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Urban FEW Nexus Model for the Otun River Watershed

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Abstract: The food–energy–water (FEW) nexus has emerged as an alternative for managing resources in the food, energy, and water systems. However, there are limited case studies applying this approach in the Latin American and Caribbean region. This region stands to benefit significantly from the FEW nexus approach due to its heavy reliance on hydropower for electricity generation and unevenly distributed and poorly managed water resources. In this study, an urban FEW nexus framework was used in the Otun River Watershed (ORW) to evaluate changes in food, energy, and water demand for four scenarios. Additionally, regional climate models (RCMs) were used to forecast water availability in the ORW from 2030–2039. The results show that water demand could increase by 16% and energy demand will increase by roughly 15% for scenario 2, while water demand in scenario 3 will likely remain unchanged in relation to the current conditions (base scenario). Enhancing water resources management in the ORW will involve a variety of measures, including: implementing practices to reduce water losses in distribution systems, developing green infrastructure and decentralized wastewater systems, and embracing urban and peri-urban farming. Successful application of urban FEW nexus solutions requires involvement from stakeholders across the food, energy, and water systems.

Keywords: food–energy–water nexus; water resources management; water sustainability; climate change

Citation: Torres, C.; Gitau, M.W.; Lara-Borrero, J.; Paredes-Cuervo, D.; Daher, B. Urban FEW Nexus Model for the Otun River Watershed. *Water* **2024**, *16*, 3405. https://doi.org/10.3390/w16233405

Academic Editors: José Baltazar Salgueirinho Osório De Andrade Guerra and Yejun Xu

Received: 21 August 2024
Revised: 22 September 2024
Accepted: 27 September 2024
Published: 27 November 2024

1. Introduction

The food–energy–water (FEW) nexus is a research area with increasing interest since the initial Nexus conference in Bonn [1]. Concerns about population growth, climate change, and food security have been considered drivers for more holistic and interdisciplinary approaches to address these issues. Moreover, review articles on the FEW nexus showed a growth in the number of academic publications related to this area, especially from 2015 [2–6]. Despite the progress in the area, recent reviews pointed out the need for new methods and tools to display available conceptual frameworks [7] and accessible tools to be used by a broader range of researchers [8]. The need is even greater in the Latin American and Caribbean (LAC) region because the region falls behind in research and implementation of the FEW nexus [9]. Additionally, ref. [10] pointed out the need to generate high-quality information to make informed decisions about natural resources management. As the LAC region has deficient planning capacity and poor natural resources management and control [10], a FEW nexus approach would improve the usage of these resources.

Some challenges facing implementing a FEW nexus approach in the LAC region are associated with specific traits like high urbanization and dependence on hydropower. Reports related to the FEW nexus in LAC indicated the need for water to be in the center of the nexus interactions since energy and food security are water-dependent [9,11], and both food and energy production impact water availability and quality [9]. Moreover, future water scarcity has been identified as impacting energy, water, and land. The water challenges identified in the LAC region are associated with multiple sectors' supply and demand dynamics; as a result, ignoring reservoir storage expansion, climate change, population growth, and agricultural requirements will cause stakeholders to ignore relevant planning scenarios [11]. Adopting a nexus approach will benefit the region to implement actions for sustainable resources management and meet the national plans and agreements signed at international venues [12].

In the case of Colombia, the Andean region is the most populated, accounting for almost 60% of the population. Most of the population lives in urban centers, and the three major Colombian cities are located in the region (Bogotá, Medellin, Cali). Even though the region has plentiful surface water sources, poor water resources management has caused many of the rivers to be classified with a very high potential water quality alteration index [13]. Additionally, climate phenomena like El Niño and La Niña may impact the amount of water available with extended drought or flooding periods, which, like other climate-related events, have been more intensified due to the warmer temperatures in the oceans. Since most of the agricultural systems in the Andean region are rainfed, a deficit or excess in precipitation can potentially affect crop yield. Furthermore, as 69% of the electricity in the country is generated by hydropower, extensive drought seasons have the likelihood to cause a strain on the country's electricity grid. Due to the close interconnectedness of the food–energy–water systems in the Andean region, a FEW nexus approach may be valuable to optimize the limited resources involved in the three systems.

Different tools have been used for modeling the FEW nexus in local ([14,15], regional [16], national [17,18], and multi-national scale studies. Ref. [19] analyzed different FEW nexus modeling tools (CLEW, WEF Nexus Tool 2.0, WEAP/ LEAP, MuSIASEM, GLOBIOM, PRIMA, NexSym) to identify their benefits and limitations and demonstrate the potential application considering different future climate change scenarios. The assessment conducted as part of the previously mentioned study included seven criteria (availability and accessibility, user-friendliness and simplicity, flexibility, comprehensiveness, predictive component, economic component, and water quality), which were used in a multi-criteria decision analysis (MCDA). The MCDA ranked the WEF Nexus Tool 2.0 in first place due to its user-friendliness, accessibility (open access), intuitiveness, and amount of inputs required. Tools used to model the FEW nexus allow decision-makers to conduct assessments in an affordable manner [19]. Moreover, decision-makers can compare the effect of different actions in the physical model when a tool combines the physical model with a scenario analysis [7], and optimized outcomes between various sectors and stakeholders may be reached [20].

In this regard, existing FEW nexus models might not be suitable for the LAC region since they are generally not comprehensive (WEAP/LEAP), water-centric (WEF 2.0 Nexus Tool), nor open-access (WEAP/LEAP), and some require a large amount of data (CLEW, MARKAL/TIMES). Due to the limitations of existing tools, we propose a water-centric tool in this study that uses elements adapted from the WEF 2.0 Nexus Tool, material and energy flow analysis (MEFA), and water footprint analysis. This tool allows accounting for and integration of typical processes occurring in urban areas like water and energy demand per capita, energy consumption in water treatment and distribution systems (MEFA), water and energy consumption for raw products produced and consumed in the ORW (WEF 2.0 Nexus Tool), and water quality impact of non-treated urban sewage (water footprint analysis). This model addresses the previously indicated gaps and has the advantage of being created based on a FEW nexus framework for the Colombian Andean region [21]. Additionally, the following distinctive attributes of the Andean region are considered in the model: food products are transported to distribution centers located in the largest metropolitan areas, where they are redistributed to intermediate urban areas; hydropower is the main source of electricity generation due to steep slopes and year-round rainfall; and water quality issues in surface waters associated with wastewater discharges.

This study is an initial implementation of the urban FEW nexus framework developed by [21] with specific objectives being: (1) estimate the future food, energy, and water demand in the Otun River Watershed (ORW) using base information reported by local, regional, national agencies; (2) estimate the water quantity and quality in the ORW under different climate change scenarios; (3) provide water resources management recommendations that may aid to offset the adverse impacts of climate change in the ORW. By filling the existing gap in modeling tools for the FEW nexus in urban contexts of LAC, this study significantly contributes to the field. It provides a foundation for future research and policies aimed at sustainable water resources management under an urban FEW nexus framework.

2. Materials and Methods

2.1. Study Site

The study site selected for the implementation of the urban FEW nexus framework is the Otun River Watershed (ORW), which is located in the Risaralda region in the central-western part of Colombia (4.80° N–75.38° W, 4.91° N–75.91° W). The ORW has an area of 48,062 ha and belongs to the Magdalena-Cauca hydrological area. The land-use land-cover in the watershed is mainly forest (37%) followed by agriculture (32%) and grassland (18%). The urban area corresponds to the Pereira/Dosquebradas metropolitan area and covers around 6% of the watershed's total area. The total population living in the metropolitan area is 590,118, accounting for 70% of Risaralda's total population [22]. The labor statistics show that 22% of the population works in retailing and vehicle repair, 15% in public administration, health, and education, and 13.5% in manufacturing. The agroindustry is significant in the ORW and Risaralda, and it represents 64% of Risaralda's total exports, with the primary commodities being coffee, plantain, corn, sugar cane, and bananas. Since most of the food produced in the ORW is exported, Pereira and Dosquebradas need to import food to meet its demand. In 2019, about 84% of the food received in the ORW main food distribution center was imported, with 58% coming from domestic markets and 26% from international markets [23]. Energy consumed in the Pereira/Dosquebradas mainly comes from outside of the ORW. From the total energy required, less than 1% is produced inside the watershed. There are two small run-of-the-river hydropower plants installed in the Otun River and seven photovoltaic systems. The remaining electricity demand is met through the interconnected national grid. Oil and natural gas come from outside the watershed through pipelines and tanker trucks from the Llanos and La Guajira regions. Regarding water, the Otun River is the major water source for Pereira and Dosquebradas. The water supply intake for Pereira/Dosquebradas is located in the Otun River, three kilometers upstream of the Pereira/Dosquebradas urban area. Pereira's annual water demand is estimated at 449.8 Mm^3, corresponding to about 93% of the ORW total water demand. This watershed was selected because it is a mid-sized watershed, with only one main river that is a tributary of the Cauca River, and the food–energy–water systems were clearly identified, simplifying the analysis of the intersections between the systems. Additionally, Pereira/Dosquebradas is the largest urban center located in the coffee axis region, a very representative Colombian region due to coffee production.

2.2. Estimation of Food–Energy–Water Demand in the ORW

Food–energy–water demand for the selected study area was estimated using a FEW nexus model that includes elements of the WEF Nexus 2.0 tool, material and energy flow analysis (MEFA), and the water footprint methodology. The distinguished features from each tool/methodology used in the model used in this study are presented in the following sections.

2.2.1. WEF 2.0 Nexus Tool

The WEF 2.0 Nexus tool was developed by Daher and Mohtar [17] as a comprehensive tool using a scenario-based framework. The tool estimates the water and energy demand required for locally grown (domestic) and imported food products. Moreover, the tool includes total financial cost and carbon emission components, which provide additional information for comparison among the different scenarios. Qatar was used as an initial case study since the country has an abundance of oil and natural gas but faces water management challenges related to water scarcity. The tool is currently available online (http://www.wefnexustool.org/login.php, accessed on 24 October 2020).

The model started by identifying the nationally consumed food products, distinguishing which products are locally produced and which ones are imported. Local food products have water and energy demands, while imported products have energy demands associated with their transportation and virtual water, which is the water used in food production outside the watershed. The water demand is quantified for each of the sources available in the region. The water options included in the model are: surface water, groundwater, treated water, treated wastewater, and desalinated water. The energy demand is broken down into energy associated with agricultural practices (tillage, fertilizer production, harvesting, and local transport) and energy required to obtain the water used in agriculture (pumping, water/wastewater treatment, and desalination). The tool includes a sustainability index—comprising seven resource indexes (water, land, local energy, local carbon, financial, energy imported, carbon imported)—for use in decision making and which can be modified depending on the region or the analysis scale. The equations used to estimate the total water and energy demand were:

$$\boldsymbol{DWU} = \sum_{i}^{n} \boldsymbol{DOM_i} \times \boldsymbol{WP_i} \quad (1)$$

$$\boldsymbol{VWI} = \sum_{i}^{n} \boldsymbol{IMP_i} \times \boldsymbol{WP_i} \quad (2)$$

$$\boldsymbol{E_{local}} = E_{till.T} + E_{harv.T} + E_{fert.T} + E_{local\ tr.T} \quad (3)$$

$$\boldsymbol{E_{imp}} = \mathrm{DIST}_i \times E_{tr(\mathrm{i})} \quad (4)$$

where:

DWU: Total amount of water needed for domestic production of food products (m^3);
DOMi: Local consumption of food product (i) domestically produced (ton);
VWI: Virtual water import (m^3);
IMPi: Local consumption of food product (i) from import (ton);
WPi: Water requirement of product grown locally or in similar environment (m^3/ton);
Elocal: Local energy demand for tillage, harvest, fertilizer production, and local transport (GJ);
Etill.T: Total energy needed for tillage/land preparation (GJ);
Eharv.T: Total energy needed for harvest (GJ);
Efert.T: Total energy needed for producing the required amount of fertilizer (GJ);
Elocal tr.T: Total energy consumed for transport of products from field to market (GJ);
Eimp: Total energy consumed for transport of imported products (GJ);
DISTi: Distance between the importing location and the receiving site (km);
Eimp tr.(i): Energy consumed in the transport of imported food (GJ/km). It depends on the method of transportation and the type of fuel used.

The list of the main food products produced and consumed (commercialized) in the Pereira/Dosquebradas area can be found in Table 1 and it was compiled using data obtained from the 2014 National Agricultural Census [24] and Pereira's Chamber of Commerce [23]. The data reported by Pereira's Chamber of Commerce distinguished between the food products commercialized locally and imported in the ORW's main food distribution center, which were used in the model as the DOMi and IMPi, respectively. The products selected to be included in the model were raw produce. These products accounted for 70% of the total crop production in the Otun River Watershed and 55% of the total food products received at the major food distribution center in the watershed. The water requirements for the products included in the model were obtained from [23].

Table 1. Water requirement for the main food products commercialized in Pereira.

Food Product	Water Requirement (m^3/kg)	Source
Apple	0.561	[25]
Banana	3.25	[26]
Coffee	15.249	[25]
Corn (white and yellow)	0.947	[25]
Onion	0.176	[25]
Orange	0.401	[25]
Plantain	3.25	[26]
Potato (parda pastusa, unica, and yellow)	0.191	[25]
Rice	1.146	[25]
Sugar cane	0.139	[25]
Tomato	0.108	[25]

The total domestic energy demand is defined as the sum required in tillage (Etill, T), harvesting (Eharv, T), fertilizing (Efert, T), and local transportation (Elocal tr, T) of the crop products. Equations (5)–(8) show how the different energy components were estimated.

$$E_{till.T} = \sum E_{till.land(i)} \times \frac{1}{\mathbf{Yield}_i} \times DOM_i \quad (5)$$

$$E_{harv.T} = \sum E_{harv.land(i)} \times \frac{1}{\mathbf{Yield}_i} \times DOM_i \quad (6)$$

$$E_{fert.T} = \sum E_{fert.land(i)} \times FERT_i \times DOM_i \quad (7)$$

$$E_{local\ tr.T} = \sum E_{local\ tr(i)} \times 2d \times \frac{DOM_i}{TC} \quad (8)$$

where:

Etill.T: Total energy needed for tillage/land preparation (GJ);
Etill.land(i): Energy needed for tillage per hectare of land growing product (GJ/ha);
Yield(i): Product yield (ton);
DOMi: Local consumption of food product (i) domestically produced (ton);
Eharv.T: Total energy needed for harvest (GJ);
Eharv.land(i): Energy needed for harvesting per hectare of land growing product (GJ/ha);
Efert.T: Total energy needed for producing the required amount of fertilizer (GJ);
Efert.land: Energy required for producing a kilogram of fertilizer (GJ/kg);
FERT(i): Amount of fertilizer applied per ton of product produced (kg/ton);
Elocal tr.T: Total energy consumed for transport of products from field to market (GJ);
Elocal tr (i): Energy consumed by transfer vehicle per kilometer (GJ/km);
d: Distance between field and market (km);
TC: Truck capacity (ton).

Table 2 shows the energy needed for tillage, harvesting, and fertilizing. Yield values were estimated based on the results obtained from the National Agricultural Census [24]. The amounts of fertilizers applied to each crop were taken from Colombian sources (chambers of commerce, research centers, associations) or respected international sources (research centers, university extension departments) [27–32]. The energy consumed by transfer vehicles was estimated using the fuel efficiency reported by the Ministry of Transportation [33]. The distance between field and market was estimated using the ruler tool in ArcGIS Pro as an average between the furthest agricultural zones in the watershed and downtown Pereira. For the transportation of imported food, only ground transportation was considered because most of Pereira's food is transported by truck. The weighted average distance from the five main cities (Bogotá, Cali, Ibague, Manizales, Pasto) that distribute food to Pereira was used as the distance between the importing location and the receiving site. The truck selected for this analysis was a 3-axle truck with a load capacity of 17 metric tons (mton). This type of truck is one of the most commonly used truck configurations in Colombia.

Table 2. Energy requirements for agricultural processes.

Process	Energy Requirement (kJ/kg)	Source
Tillage	29,851 *	[34]
Production, packaging, transporting, and application of nitrogen	78,230	[35]
Production, packaging, transporting, and application of phosphorus	17,500	[35]
Production, packaging, transporting, and application of potassium	13,800	[35]
Harvesting	39,802 *	[34]

Note: * kJ/ha.

2.2.2. Material and Energy Flow Analysis (MEFA)

Material and energy flow analysis (MEFA) is commonly used in industrial ecology and it is the systematic assessment of the state of and changes in flows and stock of materials in a system during a specific period [36]. Some form of material flow analysis has been included in urban FEW nexus modeling as indicated by [4]. Ref. [36] indicated that MEFA is suitable for decision making and assessment since it is based on a mass-balance principle, making it a reliable, reproducible, and transparent tool. Additionally, it provides comprehensive system analysis, uses a simple uniform metric, and allows for early recognition of stock changes.

Material and energy flow analysis (MEFA) was used to estimate the water and energy demand for household, institutional, and industry uses in the Pereira/Dosquebradas area. The methodology used in this study follows the methods developed by [15]. These researchers defined the inputs, interprocess flows, and outputs for the food, energy, and water systems in an urban area. The food system was not included in this study since that information is obtained from the analysis conducted using the WEF 2.0 Nexus Tool. The water system included water treatment, storage and distribution, water usage, wastewater collected and treated, and residual processing. The energy system included fossil fuel extraction, liquid fuel/coke production, electricity/gas production, storage and distribution, and usage. In Pereira/Dosquebradas, both water and energy systems were simplified since there are not wastewater treatment facilities and the only source of energy generated in the cities is electricity from the small hydropower plants (SHPs) installed in the Otun River and solar power facilities. The water demand for electricity generation was considered negligible since run-of-water hydropower plants are often considered having "zero water footprint" [37].

The water withdrawn and supplied to Pereira/Dosquebradas was obtained from Pereira's water utility company [38] and Risaralda's information and statistical website [39]. The water utility company published monthly reports of the water withdrawal from the Otun River and water treated in its treatment plants. Risaralda's information and statistical website http://siete.risaralda.gov.co/ (Accessed on 25 March 2021) displays the annual volume of water withdrawal, water treated, water supplied, and percentage of water losses for each municipality. Supplementary information like monthly water demand per household and household size was obtained from a report presented to the Water and Wastewater Regulatory Commission [40].

Data for energy are from Pereira's electricity utility company [23,41,42]. Pereira's electricity utility company reported the amount of electricity generated by the two hydropower plants installed in the Otun River and the photovoltaic plants installed in Pereira. The PCC summarized the monthly electricity and natural gas consumed in Risaralda from 2005 to 2018. The report elaborated by the Ministry of Mines and Energy shows the volume of liquid fuels (gasoline and diesel) dispatched to Pereira and Dosquebradas from July 2017 to June 2018.

2.2.3. Water Footprints

Introduced by Hoekstra [43], the water footprint is a freshwater indicator that considers direct and indirect water uses. It has three components: blue water, green water, and grey water. Blue and green water footprints are associated with water consumption, where blue water refers to surface and groundwater consumption and green water to the consumption of rainfall that does not become runoff. In contrast, grey water is associated with water pollution, and it is defined as the volume of freshwater required to assimilate the pollutant loads based on natural concentrations [44]. Water footprints can be assessed at different scales (watershed, regional/national, or global), which will dictate the data requirements to conduct the assessment. As limitations for the water footprint, ref. [44] highlighted that it does not address issues that are not water scarcity related (e.g., lack of water supply and distribution infrastructure) or environmental issues. For this study, the water footprints were assessed at the local (Pereira/Dosquebradas urban area) and the watershed scale (ORW) since there were available data on both scales. Using both scales allows us to characterize better the interactions and processes between the urban and rural areas in the ORW.

Water footprints were used as input to estimate the water demand for the food and energy produced and consumed in Pereira/Dosquebradas, as well as for estimating the water quality impact in the Otun River. Reports and research articles were used as a source to obtain the water demand for food and energy [13,25,45,46]. Water quality was estimated by calculating the grey water footprint using the methodology developed by [44]. Equation (9) was used to estimate this footprint.

$$\boldsymbol{WF_{grey}} = \frac{\boldsymbol{Effl \times c_{effl} - Abst \times c_{act}}}{\boldsymbol{c_{max} - c_{nat}}} \tag{9}$$

where:

Effl: Effluent volume (L/s);
c_{effl}: Pollutant concentration (mg/L);
Abst: Volume of water abstraction (L/s);
c_{act}: Actual pollutant concentration at the intake (mg/L);
c_{max}: Maximum permissible concentration (mg/L);
c_{nat}: Background (or natural) concentration (mg/L).

Data used to estimate the baseline grey water footprint were obtained from the water quality monitoring data collected by the Regional Environmental Authority (CARDER). The concentrations at the Otun River's source (Otun Lake) were used as background concentrations, while the data used for the volume of abstraction and actual pollutant concentration at the intake corresponded to Pereira's water utility intake location (3 km upstream of the urban area). The effluent volume and pollutant concentration were taken from El Egoya sewage outfall, the city's main sewage outfall to the Otun River. El Egoya sewage outfall is located in the watershed's mid-section at approximately 14 km upstream of the Otun River discharge point to the Cauca River. For future scenarios, flowrate and concentrations for biological oxygen demand (BOD_5) and total suspended solids (TSS) were extracted from El Paraiso wastewater treatment plant (WWTP) environmental assessment of the discharge. It is important to note that El Paraiso WWTP is the proposed wastewater treatment facility to be built in the ORW, which is expected to be operating by 2026. Nine future scenarios were used, based on discharging flowrates (0.73, 1.42, and 1.62 m^3/s) and operating conditions (regular operation, primary treatment only, contingency causing non-treatment).

2.2.4. Urban FEW Nexus Model for the Andean Region

Figure 1 shows the urban food–energy–water flows for the Pereira/Dosquebradas urban area as presented by [21]. Water is used for residential, commercial, and industrial uses in the Pereira/Dosquebradas urban area, while agriculture has the largest demand in the remaining area of the ORW. Water to supply the urban area demand comes mainly from the Otun River. In contrast, the water used for agricultural purposes comes primarily from rainfall. Groundwater is used in some areas but its contribution is negligible compared with the water contribution coming from rainfall. Water is also used for electricity generation. Pereira's electricity utility company (Energía de Pereira) has two run-of-the-river hydropower plants installed along the Otun River. The remaining electricity required in the Pereira/Dosquebradas urban area comes from Colombia's interconnected system. Additional sources of energy used in the Pereira/Dosquebradas urban area are natural gas and liquid fuels, which all come from outside of the ORW. Food production requires water and agricultural supplies. Crops in the ORW are mostly rainfed, and fertilizers, pesticides, and herbicides are widely used, especially in coffee and green onion crops. Colombia does not produce urea, di-ammonium phosphate (DAP), or potassium chloride (KCL); therefore, these supplies come mainly from the United States and Russia. Finally, water quality in streams located in the ORW is affected by agricultural activities and wastewater discharge from the urban area [21]. Currently, Pereira/Dosquebradas does not have a wastewater treatment facility; as a result, raw sewage is directly discharged into the Otun River and the Dosquebradas Creek.

Based on the above-mentioned framework and the elements adapted from the WEF 2.0 Nexus tool, MEFA, and water footprint methodology, the urban FEW nexus model for the Andean region was developed. In this model, key inputs include the distribution (locally produced or imported) of the main food products consumed in Pereira/Dosquebradas and its population. Based on this information, the water and energy demands are estimated. Water-related outputs include: volume of water used in food and energy production; volume of water used in the city; and the grey water footprint. Outputs related to energy demand comprise energy demand for food production, electricity generation, natural gas extraction and distribution, and transportation. An additional feature of this model is the option to estimate the water and energy demand under different scenarios. For the purpose of this study, four scenarios were created.

Description of Scenarios

The four scenarios evaluated in this study were:

Base Scenario: The base scenario was created with data from 2017. This year was selected since it was the last year with complete data for food production, energy, and water demand for Pereira/Dosquebradas. This scenario is used as the basis on which to appraise the changes occurring in the food, energy, and water systems in Pereira/Dosquebradas.

Scenario 1—Impact of population growth in 2035: This scenario considers the increase in food, energy, and water demand due to population growth based on the projection reported by [22]. Food commercialized in Pereira was adjusted using the same population growth rate. Energy for transportation was estimated by using the national growth rate indicated by the UPME.

Scenario 2—Impact of population growth in 2035 and reduction in food production in the ORW: This scenario considers the increase in food, energy, and water demand due to population growth based on the projection reported by [22]. Agricultural production is expected to be reduced by 21% due to an increase in temperatures [47]. Energy for transportation was estimated by using the national growth rate indicated by the UPME. The deficit in locally harvested food was replaced by imported food products, except for coffee, since all coffee grown in the ORW is exported.

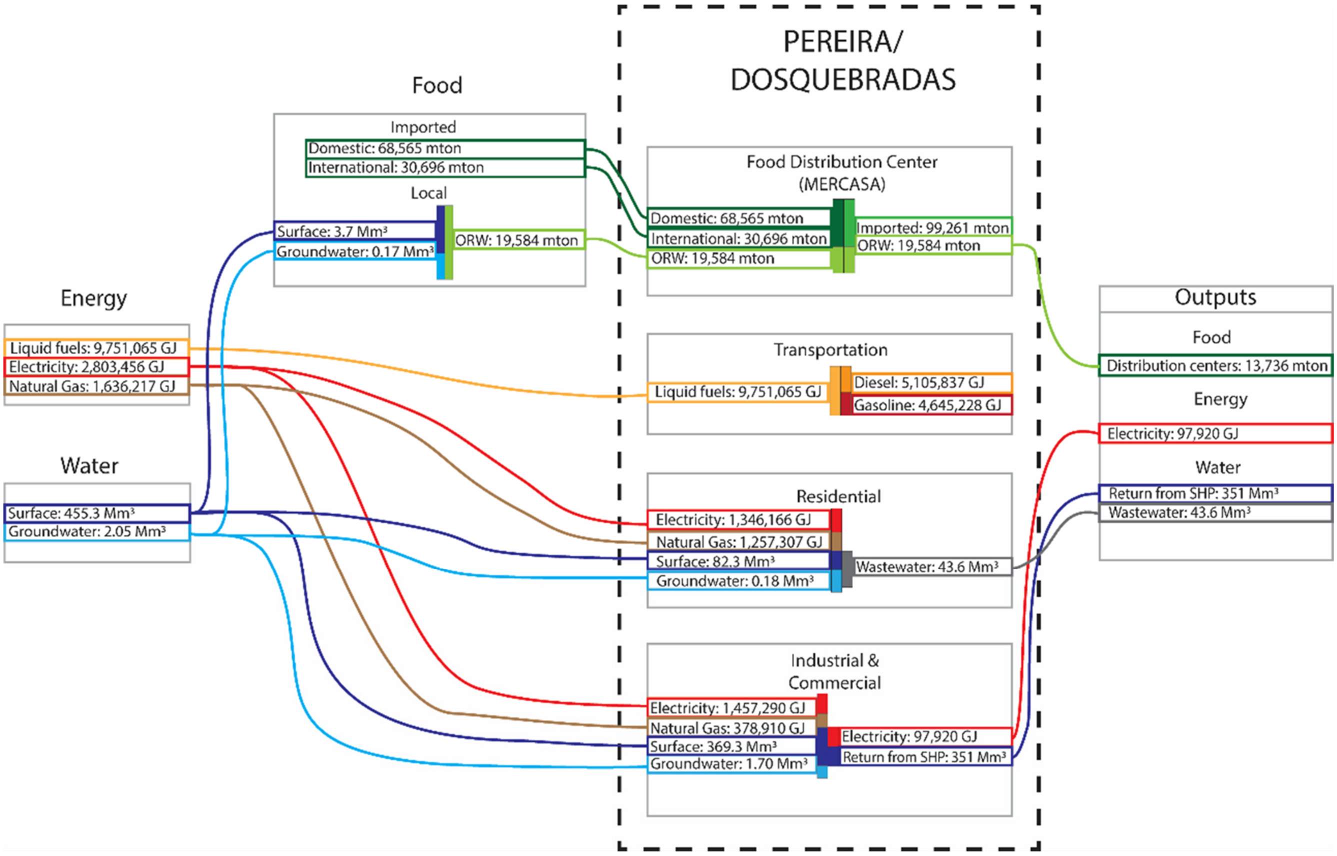

Figure 1. NEST diagram showing details of FEW nexus components and their interactions for the Pereira/Dosquebradas urban area of the Otun River Watershed. Reprinted from Framework for Water Management in the Food-Energy-Water (FEW) Nexus in Mixed Land-Use Watersheds in Colombia by Torres et al. Sustainability, 12(24), p.18. Copyright (2020) by Torres et al. [21].

Scenario 3—Impact of population growth in 2035 and increase in electricity generation in Risaralda: This scenario considers the increase in food, energy, and water demand due to population growth based on the projection reported by [22]. Additionally, it considers an increment in electricity generation due to the expansion of the Belmonte run-of-the-river plant as well as the construction of El Fenix and Senegal run-of-the-river plants. These new projects will generate an additional 35.4 MW/year.

These scenarios were developed because they provide a broad range of possible outcomes based on forecasts reported by regional and national governmental agencies. The year 2035 was selected as the future set point because the current planning documents for Colombia and Risaralda have a planning window between 2032 and 2040. Future scenarios were created using reports from different governmental agencies as references. The Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM) prepared a report on the precipitation and temperature changes occurring in Colombia due to climate change [48]. Based on this report, climate change scenarios considered in the study were RCP2.6, RCP4.5, RCP6.0, and RCP8.5 as derived from the Coupled Model Intercomparison Project Phase 5 (CMIP5). The future scenarios generated by IDEAM were 2011–2040, 2041–2070, and 2071–2100, considering 1976–2005 as the reference period. The Mining-Energetic Planning Unit (UPME) projected the demand for liquid fuels consumed in transportation until 2030 [49], and the National Department of Statistics (DANE) created the population projections for all Colombian municipalities until 2035 [22]. Table 3 shows a summary of the expected changes in climate (temperature and precipitation), population, and energy demand for liquid fuels for the Pereira/Dosquebradas urban area. Table 4 shows a summary of the scenarios developed.

Table 3. Summary of expected changes in climate (temperature and precipitation), population, and energy demand for liquid fuels for the Pereira/Dosquebradas urban area.

Parameter	Period of Comparison	Expected Change
Temp. (°C)	2011–2040	0.83–0.97
Precip. (%)	2011–2040	16.31–23.60
Population (%)	2017–2035	17
Energy demand for liquid fuels (%)	2017–2035	26–36

Table 4. Summary of the scenarios developed for Pereira/Dosquebradas urban FEW nexus model.

Nexus Component	Scenario			
	Base Scenario	Scenario 1	Scenario 2	Scenario 3
Food	Data from 2017	17% ↑ sc. 1	Total food demand: 17% ↑ sc. 1 Food locally produced: 21% ↓ sc. 1	17% sc. 1 ↑
Energy	Data from 2017	17% ↑ sc. 1	17% ↑ sc. 1	Total energy demand: 17% ↑ sc. 1 Electricity generated locally: 880% ↑ sc. 1
Water	Data from 2017	17% ↑ sc. 1	17% ↑ sc. 1	17% ↑ sc. 1

2.2.5. Water Quantity in the ORW Under Different Climate Change Scenarios

Due to the expected changes in climate in the upcoming years and its influence on the water resources in the ORW, one of the goals for this study was to estimate changes in water availability in the ORW under different climate change scenarios. For that reason, we considered that a hydrological model would allow us to identify the potential changes in water availability in the ORW. The Soil and Water Assessment Tool (SWAT+) version 60.5.2 [50] was used to create this hydrological model. Watershed delineation and creation of the hydrologic response units (HRUs) were completed using the QSWAT+ 2.1.2 plugin. Land-use data were obtained from the MODIS land cover product [51], with a spatial resolution of 500 m, and taken in 2010. Soil data used in the model corresponded to the global_usersoil database created using the FAO's global soils map [52]. Precipitation and temperature data were obtained from five weather stations (La Laguna, Pez Fresco, Playa Rica, Nuevo Libaré, and Aeropuerto Matecaña) operated by Colombia's Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM) "http://dhime.ideam.gov.co/atencionciudadano" (accessed on 13 November 2020). Precipitation in the watershed varies significantly due to the changes in elevation; one of the stations (La Laguna) did not have any data from 2005 to 2007, yet it was the only station located in the ORW upper area. To ensure data completeness, data for La Laguna station were completed using the LARS-WG stochastic weather generator [53].

For calibration and validation of the model, the periods of 2006–2010 and 2011–2014 were used, respectively. The selection of these timeframes was based on the land-cover land-use analysis conducted by [21], where small changes in land-cover land-use were observed in the region. Therefore, it was considered that the HRUs created using the land-use and soil maps remained unchanged during this time window. We used daily streamflow observations from El Reten station, which is located upstream of the Pereira/Dosquebradas urban area, for calibration and validation purposes.

As a part of the calibration process, a two-stage sensitivity analysis was completed. In the first stage, the sensitivity analysis was performed for parameters that have been identified as having a strong influence on streamflow (soil evaporation compensation factor, curve number, Manning's roughness coefficient for overland flow, pothole evaporation coefficient, plant uptake compensation factor, available water capacity of the soil layer, and moist bulk density) using the delta moment-independent measure [54]. Moment-independent methods quantify the relative influence of uncertain parameters by using the entire output distribution. This method was selected because it requires less computational time than variance-based methods and moment-independent methods have been found to identify the same influential parameters as variance-based methods [55]. Once the first stage was completed, parameters with the highest 1st order sensitivity values (higher than 0.01) were selected to continue with a sensitivity analysis using a variance-based method (Sobol). Variance-based methods measure the sensitivity of an uncertain parameter using its contribution to the model's total variance.

Once the parameters with the highest sensitivity values were identified, an automatic calibration was completed using SWAT+ Toolbox [56]. SWAT+ Toolbox uses the dynamically dimensioned search (DDS) [57], which is a global optimization algorithm that automatically scales the search to find good solutions within a user-defined number of iterations. The objective function selected for optimization was the Nash–Sutcliffe model efficiency (NSE). The number of simulations completed in the automatic calibration process was 1000. After completing the automatic calibration, manual calibration was used for fine tuning the model. The model's performance evaluation (Table S1) indicates that its performance is satisfactory for the ORW watershed on the annual scale. Table S2 summarizes the final calibration parameters for the model.

Once the model had been calibrated and validated satisfactorily, it was used to simulate the watershed water balance under different climate change scenarios. To include the future scenarios for food, water, and energy demand in Pereira/Dosquebradas, the simulated period selected was 2030–2039. Additionally, future climate models are conceived to be analyzed as a time series, not as a single moment; therefore, choosing this period will serve the purpose of capturing the fluctuations in the decade. Precipitation for the future climate change scenarios was obtained from CORDEX datasets. The CORDEX-CMIP5 datasets were obtained for the Central America (CAM) region, which includes Central America and the north part of South America. These datasets were different from the ones used by IDEAM in the Climate Change Scenarios for Colombia ([48]) since IDEAM used general circulation models (GCMs) instead of regional climate models (RCMs). There are nine regional climate models available for the region, with four models (MIROC5, HadGEM2, MPI-ESM-LR, and NorESM1-M) including the low and high representative concentration pathways (RCPs) (RCP 2.6 and RCP 8.5). Precipitation data were obtained for the grid point closest to the weather stations used to create the hydrological model and was bias corrected for each station. The bias correction method used was the empire quantile mapping (QUANT) because this method has been found to perform well in the bias correction of precipitation data [58,59]. Bias-corrected data were compared to observed data for 2006–2015 to assess the representativeness of the model data. Since the four models with both RCP scenarios displayed similar essential characteristics (mean, median, standard deviation, IQR, number of days receiving rainfall, number of days receiving rainfall in excess of the 95th and 99th percentiles) as the observed data, future precipitation data from these models were used in this study. Future temperature data were not used in the model since only one station (Aeropuerto Matecaña) has incomplete observed data and these were not enough to conduct a bias correction.

3. Results and Discussion

3.1. Water and Energy Demand for Food

Tables 5 and 6 show the water and energy requirements for food products commercialized in Pereira for the base scenario (2017), following the methodology used in the WEF Nexus 2.0 tool. The water used for products grown domestically (blue water) was more than double compared to the water used for products imported into Pereira (virtual water), even though more food was imported. The major difference in water demand is due to the coffee production in the ORW. Coffee is a crop with high water demand, requiring 15,149 m^3/ton. Results for the future scenarios can be found as Supplementary Material (Tables S1–S4). Food produced in the ORW accounted for 64% of the total energy demand for food commercialized (locally produced and imported) in Pereira.

Table 5. Water demand for food products commercialized (locally grown and imported) in Pereira for 2017.

Product	Domestic (DOM)			Imported (IMP)			Total (ton) (DOM + IMP)	Domestic Production (%)	Imported (%)
	DOM_i (ton)	WP_i (m^3/Ton)	DWU (Mm^3)	IMP_i (ton)	Wp_i (m^3/ton)	VWI (m^3)			
Coffee	3842	15,249	58.6	--	15,249	--	3842	100%	0%
Plantain	8138	1570	12.8	971	211	0.20	9109	89%	11%
Banana	6397	660	4.22	406	211	0.09	6802	94%	6%
White corn	2096	947	1.99	511	947	0.48	2607	80%	20%
Yellow corn	1921	947	1.82	17,364	947	16.4	19,285	10%	90%
Sugar cane	2625	139	0.37	--	139	--	2625	100%	0%
Rice	--	1146	--	6984	1146	8.00	6984	0%	100%
Onion	149	176	0.026	2870	176	0.51	3018	5%	95%
Apple	0	561	0	2217	561	1.24	2217	0%	100%
Orange	1758	401	0.71	3625	401	1.45	5383	33%	67%
Yellow potato	--	191	--	1768	191	0.34	1768	0%	100%
Potato (parda pastusa)	--	191	--	2068	191	0.40	2068	0%	100%
Potato (unica)	366	191	0.070	6813	191	1.30	7179	5%	95%
Tomato	2143	108	0.23	2108	108	0.23	4250	50%	50%
Total	29,434		80.8	47,703		30.7			

Notes: DOM_i: Local consumption of food product (i) domestically produced; WP_i: Water requirement of product grown locally or in similar environment; DWU: Total amount of water needed for domestic production of food products; IMP_i: Local consumption of food product (i) from import; VWI: Virtual water import.

Table 6. Energy required to produce and transport food products commercialized (locally grown and imported) in Pereira for 2017.

Product	Domestic (DOM)				Imported (IMP)	Total (GJ/Year) (DOM + IMP)
	E_{till} (GJ/Year)	E_{harv} (GJ/Year)	E_{fert} (GJ/Year)	$E_{local\ tr}$ (GJ/Year)	Eimp (GJ/Year)	
Coffee	103.32	137.76	184,534	121	0	184,896
Plantain	38.26	51.01	37,622	256	357	38,324
Banana	12.63	16.84	12,422	201	149	12,802
White corn	15.61	20.81	24,950	66	188	25,240
Yellow corn	17.38	23.17	22,861	60	6387	29,349
Sugar cane	15.83	21.11	21,256	83	---	21,375
Rice	---	---	---	---	2569	2569
Onion	0.53	0.71	2650	5	1056	3712
Apple	---	---	---	---	815	815
Orange	3.24	4.32	29,468	55	1333	30,864
Yellow potato	---	---	---	---	650	650
Potato (parda pastusa)	---	---	---	---	761	761
Potato (unica)	0.78	1.04	6037	11	2506	8557
Tomato	4.02	5.36	61,572	67	775	62,424
Total	211.60	282.13	403,372	926	17,547	422,339

Notes: Etill: Energy needed for tillage/land preparation; Eharv.land (i): Energy needed for harvest; Efert: Energy needed for fertilizing; Elocal tr.: Energy consumed for transport of products from field to market; Eimp: Energy consumed for transport of imported products.

Figure 2a–c show the water and energy demand for food production for the base scenario and different future scenarios. The water and energy demand increases by around 14% for scenario 2 (2035, only population growth is considered) compared to the base scenario. In contrast, the water and energy demand decreases by 9% and 19% from the base scenario to scenario 3 (2035, population growth and reduction in food produced inside the ORW). The reduction in water demand would be caused by an anticipated cutback in coffee production. Since all coffee in the ORW is produced to be commercialized outside of the watershed, it would not be necessary to replace the expected deficit. It is also relevant to note that, under scenario 3, the local water demand (blue water) decreases by 20%. This reduction in blue water could be beneficial for the ORW since this surplus may be used to account for the increase in water demand for human consumption and electricity generation.

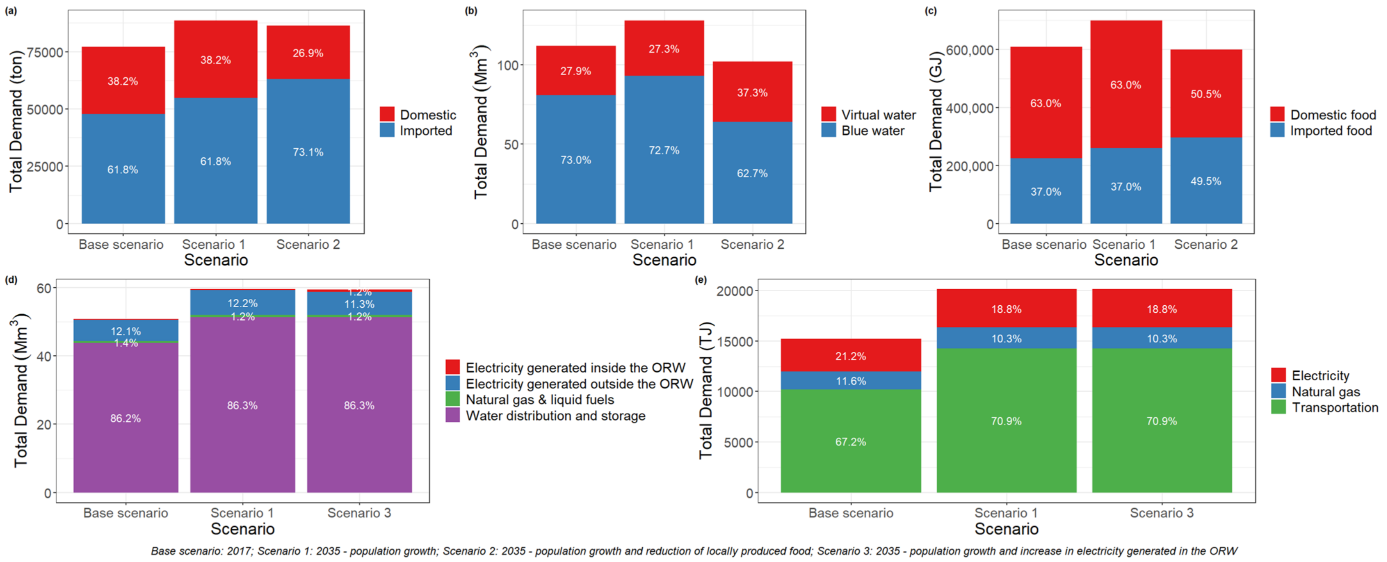

Figure 2. Water and energy demand in the ORW and Pereira/Dosquebradas urban area under different scenarios. (**a**) Total food demand in the ORW; (**b**) Total water demand for food production; (**c**) Total energy demand for food production; (**d**) Total water demand for residential, industrial, and commercial use; (**e**) Total energy demand for residential, industrial, and commercial use.

These predictions consider that agricultural practices, dietary needs, food product harvest, and urbanization rate remain stable in the ORW. However, factors like extreme weather events, increased temperatures, changes in land use/land cover, and loss of farming land due to poor conditions for farmers may affect the prediction for future scenarios.

3.2. Water and Energy Demand in Pereira/Dosquebradas Urban Area

Figure 2d,e show a comparison of the water and energy demand for the Pereira/Dosquebradas urban area for the base scenario, scenario 1, and scenario 3 (2035, population growth and increase in electricity generation inside the ORW). The water and energy demand in the Pereira/Dosquebradas urban area is expected to increase by 17% by 2035. The major water demand is from water storage and distribution, accounting for 87% of the total water demand. The remaining water demand is for electricity generation in the SHPs installed along the Otun River. The difference between the two future scenarios analyzed is the amount of electricity generated in the ORW. Based on the Vision 2032—Risaralda Futuro Posible [47], there are proposals to install two new SHPs, which are expected to generate 25.4 MW/year. The installation of these new hydropower plants will increase the Otun River water demand by fourfold. It is important to note that the electricity generation in the Otun River is limited by the river's streamflow. As a result, there may be times during the year when the river's streamflow is too low to generate electricity.

3.3. Grey Water Footprint

Changes in grey water footprint will be susceptible to El Paraiso WWTP operation. Table 7 compares the base scenario (2017) and future scenarios with the highest flowrate discharge (1.62 m^3/s). Under normal operating conditions, the grey water footprint will decrease between 73% and 83%, depending on the selected water quality parameter. If the plant does not perform correctly, it is expected that there will be an increase of between 58% and 256% in the grey water footprint, being the worst-case scenario when there is no treatment.

Table 7. Comparison of grey water footprints for the Pereira urban area.

Water Quality Parameter	Scenario						
	Baseline	Normal Operation		Primary Treatment Only		Non-Treatment	
	Grey Water Footprint (Mm^3)	Grey Water Footprint (Mm^3)	Rel. Change (%)	Grey Water Footprint (Mm^3)	Rel. Change (%)	Grey Water Footprint (Mm^3)	Rel. Change (%)
TSS	43.5	12.0	−73	68.9	58	141.6	225
BOD_5	43.7	8.65	−83	113.1	159	155.8	256

3.4. Water Availability Under Future Climate Projections

Figure 3 summarizes the changes in hydrological variables under different climate projections for the four RCMs analyzed. Based on the results from these projections, the changes in annual average precipitation (PREC) for the simulated period (2030–2039) range from −26% to 6% for RCP 2.6 and −29% to −13% for RCP 8.5. For all models and scenarios, except MIROC5 RCP 2.6, the average annual precipitation is expected to decrease by more than 10%. These findings differ from what was reported by [48] since IDEAM used GCMs instead of RCMs. Also, the time scale reported was 30 years (2011–2040), while we used a 10-year time window (2030–2039). Moreover, IDEAM reported the results at the departmental scale, while we did it at the watershed scale. The decrease in precipitation will cause a reduction in the water yield (WYLD) as well. This reduction might cause challenges in the ORW since the Otun River is the primary water source.

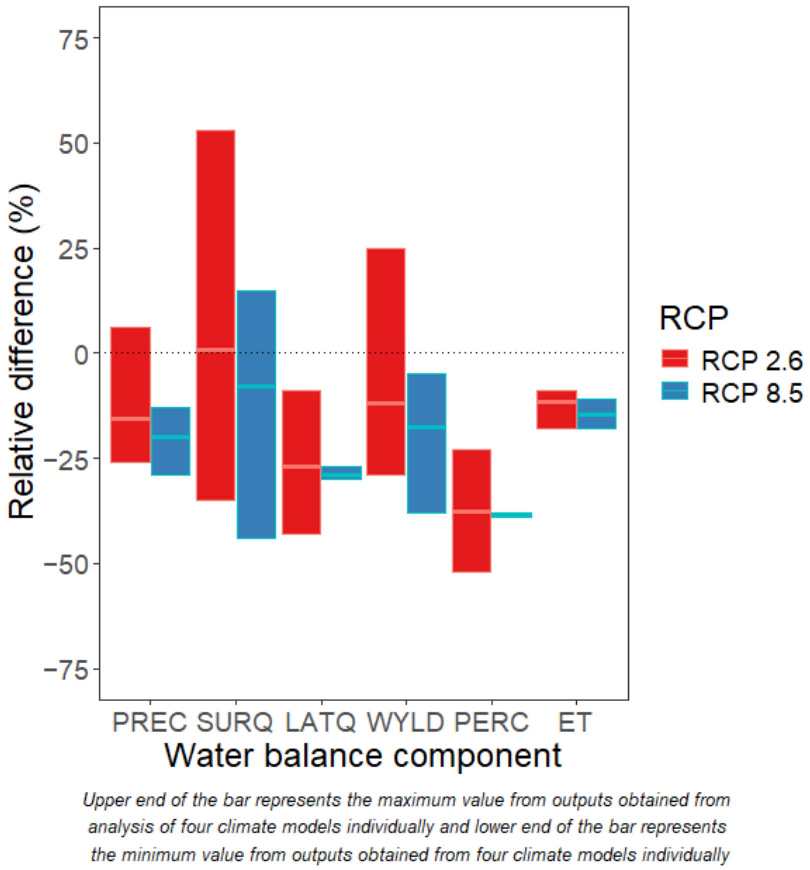

Figure 3. Changes in hydrological variables relative to the baseline scenario (2007–2012) under different climate projections (RCP 2.6 and RCP 8.5) for the ORW from 2030–2039 for the climate models used in the study. PREC: Precipitation (mm), SURQ: Surface runoff (mm), LATQ: Lateral flow (mm), WYLD: Water yield (mm), PERC: Percolation (mm), ET: Actual evapotranspiration (mm).

3.5. General Discussion

The Pereira/Dosquebradas urban area has a significant influence on the food, energy, and water systems in the ORW. Since most of the ORW population is concentrated in the urban area, population growth and expansion of the metropolitan area will increase the amount of food, energy, and water needed to meet the new demand. The water and energy demand for food production and the metropolitan area was estimated for current conditions (2017) and three future scenarios. The water and energy demand was estimated by combining methodologies used in the WEF 2.0 Nexus tool and material and energy flow analysis (MEFA). Additionally, water quantity and quality are a concern in the ORW since the Otun River has been identified as a river with a high water stress index and poor water quality. The results obtained from the FEW nexus model presented in this study capture the high dependency that urban areas have for food–energy–water resources coming from outside of their enclosed watershed. The Pereira/Dosquebradas area has a distinctive characteristic, which is the abundance of water resources to meet its water demand. Even though there are plenty of water sources in Risaralda, in recent years there has been low levels in all streams due to extended droughts and high temperatures; as a result, local authorities have implemented short-term actions to reduce water consumption. The most recent period of low streamflow levels was reported in 2020; for that reason, CARDER (Risaralda's Environmental Authority) recommended limiting the watering of gardens, shutting water faucets when not in use, and fixing leakages in indoor plumbing [60]. On the other hand, its dependency on food and energy resources from outside the ORW makes it susceptible to changes occurring outside the region.

3.5.1. Water and Energy

Results from future FEW scenarios showed different pathways regarding water and energy demand in the ORW. If only population growth is considered (scenario 2), the overall water and energy demand would increase by 16% and 32%, respectively. If population growth and a decrease in food production are considered (scenario 2), the overall water demand would not increase, and the energy demand would decrease by 19%. Even though there is no increase in water demand, there would be a 6% reduction in the volume of blue water and a 23% increase in the volume of virtual water. If population growth and an increase in electricity generation are considered (scenario 3), the overall water and energy demand would increase by the same amount as in scenario 2; however, virtual water demand would be reduced by 1%. An increase in water and energy demand could be a reason for concern for local and regional authorities in the ORW since the Otun River is already considered a highly vulnerable water body. According to Risaralda's climate change mitigation plan [61], water resources' risk and vulnerability obtained values of 0.92/1.00 and 0.98/1.00, respectively, based on an index created as part of the 3rd National Communication on Climate Change. Risaralda's climate change mitigation plan proposed actions focused on improving water regulation conditions and sustainable water usage and water resources management. Since the Otun River is one of the rivers of main concern in Risaralda, the proposed actions aim to improve the river's quantity and quality conditions.

Fossil fuels will remain the primary energy source in Colombia for the next 30 years [62]. However, renewable energy seems set to become the primary source of electricity generation, accounting for about 40% of the total electricity generated by 2050 [62]. In the ORW, the electricity utility company (Empresa de Energia de Pereira) is transitioning to solar power as an alternative for electricity generation. Currently, there are more than 20,000 photovoltaic solar panels installed with a generation capacity of 13.6 GWh/year. The goal is that the company will generate 20% of Pereira's total electricity demand from solar power within five years [63]. The implementation of renewable energy sources would reduce Pereira/Dosquebrada's dependency on hydropower. As temperatures are expected to rise and drought periods will tend to be longer [48], this switch to renewable energies will increase the resiliency of the electrical grid and will reduce the chances of blackouts. Additionally, these new power sources will support the increase in energy demand due to population growth. Moreover, using these new energy sources may reduce the amount of electricity generated by the SHPs located along the Otun River. Therefore, more water would be available for other intended uses. Furthermore, the impacts on the environment associated with run-of-the-river hydropower plants, like reducing riverine habitat and disruption of longitudinal connectivity [64], will diminish if the hydropower plants' operation times decrease.

3.5.2. Water and Food

Regarding the effect of climate change on food production, the actions considered in the climate change mitigation plan include replacing the current crops with crops that may be more suitable for future temperatures and precipitation patterns. Additionally, Risaralda plans to install irrigation systems in the areas with the highest temperature rises. Unfortunately, coffee will be one of the crops that may be more affected by changes in temperature and precipitation. Even though the importance of agricultural activities in Risaralda has decreased in the past 30 years, it remains a relevant economic sector, accounting for 8% of Risaralda's gross domestic product [24], and coffee is the crop with the largest cultivated area. Additionally, coffee is the largest commodity exported by Risaralda, accounting for USD 170 million in 2020, while sugar was the second product with USD 36.4 million [65]. Due to the potential decrease in coffee production in the ORW, alternative crops should be considered to replace coffee as the primary agricultural product. One crop that has emerged as a substitute for coffee is avocado, reflected by the increase in the area cultivated in the region. Even though avocado is also susceptible to future changes in climate patterns, the future suitability for growing this crop in Colombia remains mostly unchanged by 2050 [66]. Additionally, avocado is a polyculture crop, allowing the optimization of the available land for agriculture. Moreover, its blue water footprint is almost 20 times lower than coffee's blue water footprint [25]. Even though growing avocado may be beneficial for the ORW, it is important to learn from previous experiences as in the Michoacan region in Mexico. The boom in avocado production in Mexico led to an increased use in agrochemicals since this crop is highly susceptible to plagues and diseases, contaminating the surface and groundwater sources [67]. Furthermore, avocado crops should be cultivated in areas where no or limited irrigation is required. Ref. [68] concluded that a large percentage of current and potential avocado growing areas in Colombia require at least one month of irrigation during the year. According to the previously mentioned study, the area where the ORW is located requires irrigation from one to four months. Since the whole purpose of substituting coffee plantations for other crops is to reduce water consumption, avocado should be cultivated in areas where rainfall would be sufficient to meet its water requirements.

3.5.3. Water Footprints

Considering the grey water footprint results, it is valuable to emphasize the need for the construction and proper operation of El Paraiso WWTP. According to El Paraiso WWTP's assessment of the discharge report [69], if the plant is not operating in normal conditions (primary and secondary treatment), water quality in the Otun River at the location of the plant would not meet the river's water quality target for BOD_5, as set in the 2015 ORW Water Management Plan (BOD_5 concentrations below 10 mg/L by 2035). Moreover, the expected grey water footprints were estimated assuming that all domestic wastewater is collected and transported to the WWTP. Therefore, the grey water footprints would be higher if there were still some direct dumping of raw sewage into the Otun River's tributaries, reaching a BOD_5 pollutant load of 155.8 Mm^3, which is an increment of 256% compared to the baseline scenario. Furthermore, the Otun River's self-depuration capacity may decrease during periods of low streamflow.

3.5.4. Recommendations for Water Resources Management for the ORW Under Future Climate Change Scenarios

Based on the future climate scenarios developed in this study, water availability in the ORW may decrease due to the potential changes in the precipitation ranging from −26% to 6%. As a result, Pereira/Dosquebradas should consider the improvement of their existing water distribution system, the implementation of water conservation practices, and the use of alternative water sources to meet its demand. The current water distribution system for Pereira has estimated water losses of 29% and the indicator of losses per billed consumer is 7.9 m^3/month [70]. Pereira is close to the 25% of admissible water losses established by Resolution 330 of 2017 [71]. Even though the city is in better shape compared to other Colombian cities, it is still desirable to limit these losses. The most common methods for detecting and locating leakages are acoustic techniques; however, these techniques are expensive and labor-intensive [72]. Ref. [73] developed an algorithm that detects and estimates background leakage outflow in a water distribution network, which could be a valuable tool for water utility companies since currently used methodologies for detecting water losses only are effective to detect leakages from burst pipes. Advancements in communication technology could provide additional resources to detect leakages. Ref. [74] presented different approaches where wireless sensor networking (WSN) has been used to detect leakages in underground pipes. Adopting new methodologies for detecting leakages will help Pereiras/Dosquebradas water utility companies reduce their water losses in the distribution network.

Cities that are currently facing water scarcity have set a blueprint for sustainable water practices that can lead to substantial water savings. Common practices include the use of water-efficient fixtures, reuse of stormwater, grey water recycling, and black water recycling. Ref. [75] concluded that a 54% water reduction could be achieved by using water-efficient fixtures, dry cooling in power plants, and grey water and black water recycling in Karachi (Pakistan). From all the strategies, the authors indicated that water-efficient fixtures were the best water reduction strategy, contributing 59% of the total water reduction. Ref. [76] reported that the potential water savings were 18.5% when rainwater was used in toilets and 40.8% when rainwater was used in toilets and washing machines in Joinville (Brazil). Due to the sizable water savings that can be reached by implementing different conservation practices, the ORW, and especially the Pereira/Dosquebradas urban area, will benefit from implementing any of the approaches previously mentioned.

An additional water source to meet the future water demand in the ORW is groundwater. The watershed is located on the Glacis del Quindio aquifer. Based on the National Water Study [13], the estimated water volume of this aquifer is 4000 million m^3 (Mm^3). The aquifer is mainly undisturbed and it is estimated that only 17 Mm^3/yr is consumed for human consumption and agricultural purposes. Therefore, groundwater could meet the future demand during the drought periods.

Extreme weather events are another potential risk in the ORW and the Colombian Andean region. According to [77], Colombia has the highest recurrence of extreme events in South America, and from 1980 to 2020 there was an average of 77 flooding events per year. Even though changes in high-impact events in the Andean region have not been assessed for future climate change scenarios [78], it is expected that the current trend will continue and more extreme weather events will occur. As a result, cities should be prepared to handle the additional runoff volume under these scenarios. One of the most common practices in cities around the world is the implementation of green infrastructure (GI), which is designed to reduce runoff volume and peak flows. Some of the most common GI alternatives are bioretention cells, buffer prairie zones, retention/detention ponds, permeable pavements, and bioswales. A limitation for the implementation of GI is associated with the high construction costs and uncertainty about their performance [79–81]. Even though there are constraints that have restricted the extensive construction of GI, problems associated with climate change and extreme events can be drivers for cities to rapidly adopt this type of infrastructure. Pereira and Dosquebradas have suffered extensive damage due to flooding and landslide events caused by heavy rainfall. The areas more susceptible for flooding along the Otun River are located in La Suiza, Bananera, Libare, and Porvenir sectors, as well as Pereira's urban area riverbank. Ref. [82] reported that about 31% of Pereira's natural disasters are associated with flooding. Additionally, these researchers indicated that, from 2007 to 2017, 1008 houses were damaged by floods and rainfall, affecting more than 3000 people. Damage in Risaralda associated with the 2010–2011 rainy season was estimated as COP 28,665 million (about USD 15 million).

Besides the benefits of GI for flood management, it can also be considered to address water quality problems. A review conducted by [81] found that 60% of the analyzed studies' results indicated a reduction in nutrient concentrations. Ref. [83] indicated that a reduction between 9% and 46% in suspended solids concentrations could be achieved depending on the GI size. Additionally, the construction of GI will improve the operation of the future wastewater treatment plant that is going to be built in Pereira. This wastewater treatment plant is expected to treat 85% and 62% of the total domestic wastewater from Pereira and Dosquebradas, respectively [84]. This plant will have a capacity of 2.5 m^3/s, and it is expected to treat sewage with a BOD_5 of 36,750 kg/d. As Pereira/Dosquebradas currently have a combined sewer system, there are potential risks for combined sewer overflow (CSO) events. Ref. [85] indicated that an increase of 20%, 30%, and 50% in the current precipitation would represent an increase of 43%, 121%, and 181% in the water volume spilling from manholes in an urban area located in Norway. Therefore, the water volume reduction provided by GI could reduce the number of CSO events in Pereira/Dosquebradas, reducing the water quality impact on the receiving streams.

In addition to GI's construction, local water resources management authorities and stakeholders in Pereira/Dosquebradas could contemplate the construction of decentralized wastewater treatment for the projected urban developing areas. Some advantages of building decentralized wastewater treatment plants are their spatial adaptability and the smaller pipe networks required [86]. These systems often rely on natural processes, reducing the energy costs related to traditional wastewater facilities [86,87]. Wetland ecosystem treatment (WET) systems have been implemented in different areas around the world. These systems could be used in agroecological systems since the high concentration of nitrogen and phosphorus in raw sewage can be utilized as nutrients. WET systems have been built in farms, where the swales used in the treatment system also are used as an environment to grow shrubs and trees [87]. Pereira/Dosquebradas could benefit from this type of system, especially in the new urban developing areas that were previously used as coffee production farms.

Another emerging strategy is urban and peri-urban agriculture. Since most of the food produced in the ORW is consumed outside of the watershed, Pereira/Dosquebradas residents could benefit from offsetting part of their food demand with locally grown products. In addition to obtaining locally grown food products, urban and peri-urban agriculture reduces stormwater runoff and excess water can be stored for later use or infiltrated to open green spaces [88]. A case study conducted in the Sydney and lower Blue Mountains basins in Australia showed that water resources security was strengthened due to the use of reclaimed wastewater and stormwater in agricultural activities [89]. Even though urban agriculture has not had an extensive application in urban settings and urban land-use planning has undermined the potential for urban agriculture [90], the Pereira/Dosquebrabas urban area could benefit from the reduction in stormwater runoff and potentially the biosolids from El Paraiso WWTP could be used as fertilizer for the urban and peri-urban farms. Further research is required to evaluate the viability and economic feasibility of using the WWTP by-products for agricultural purposes.

3.5.5. Operationalization of Food–Energy–Water (FEW) Nexus Analytics: Catalyzing Cross-Sectoral Dialogue and Knowledge to Action

Food, energy, and water systems do not exist in a vacuum. Governmental, private sector, and societal stakeholders play a role in regulating, managing, and increasing or reducing pressures on these interconnected resource systems. Despite this level of interconnectivity, planning decisions are often mainly within sectoral or institutional silos, with little coordination. Scenario analysis can play a key role in catalyzing an objective evidenced-based cross-sectoral dialogue to evaluate the trade-offs associated with different interventions under expected population growth, food production, and electricity generation scenarios. Operationalizing the food–energy–water (FEW) nexus remains an area that requires further research since most of the studies in this area have focused on the development of frameworks and tools oriented to increase the understanding of the existing relationships among the different sectors. An attempt to close this gap was completed by [91] in the San Antonio region, where the results from a survey sent to researchers and regional stakeholders revealed that increasing the communication and the information shared between agencies could improve the cooperation to address some of the interconnected challenges. The same study in San Antonio identified key barriers causing low levels of cross-sectoral communication. These barriers identified by the stakeholders included the lack of institutional mechanisms and resources to facilitate integrative planning, in addition to differences in planning horizons and lack of common goals, among others [92]. Ref. [93] concluded that disaggregating the nexus into component systems could help to make the existing connections more visible. These researchers also indicated that mapping different urban actors and the interaction among the FEW elements could lead to identifying common connections, overlapping interests, and shared knowledge, data, or resources, which may lead to a more integrated FEW nexus governance.

Based on our findings, operationalizing the FEW nexus will require the participation of the water and electricity utility companies, small and large food producers, agricultural cooperatives, CARDER, local manufacturing industries, Pereira and Dosquebradas' government, and Risaralda's government. Since this effort includes the public and private sectors at different scales, addressing these interconnected challenges will require a coordinated effort between regional and national agencies to ensure policy coherence. Moreover, a mechanism to coordinate efforts is required to manage the interdependencies in the FEW nexus. Ref. [94] examined a series of methodologies that can be used to analyze water–energy–food systems, including institutional analysis and development (IAD), network of adjacent action situations (NAAS), and ecology of games (EG) frameworks. These researchers suggested that an analytical framework based on the concept of a network of adjacent action situations could be used to operationalize the analysis of FEW nexus governance systems since it provides a procedure to formulate questions specific to different contexts and allows the assessment of the performance of a governance system based on the outcomes obtained in each context.

4. Conclusions

The ORW is expecting to have a 21% food production reduction by 2035 and a change in precipitation between −26% and 6% from 2030 to 2039. Based on the projections prepared by different regional and national governmental agencies, a FEW nexus model was created to estimate the current and future water and energy demand. The future scenarios created for 2035 show that water demand could increase by 16% and energy demand will increase roughly 15% for scenario 1, which is attributable to population growth. Water demand in scenario 2 will likely not increase in relation to the current conditions (base scenario) because of an anticipated 21% reduction in locally produced food, which will likely result in an increase in imported food. The electricity generation inside the ORW will increase by 385% due to the expansion and construction of run-of-the-river hydropower plants (scenario 3) compared to the base scenario, accounting for around 20% of the total expected electricity demand in Pereira/Dosquebradas. In terms of water quality, the Pereira/Dosquebradas grey water footprint is likely to decrease if El Paraiso WWTP operates in normal conditions. If only primary treatment is available or there is no treatment, the grey water footprint could increase between 58% and 256%. Recommendations for water resources management in the ORW include reducing water losses in the water distribution systems, adopting water conservation practices, developing GI and decentralized wastewater systems, and implementing urban and peri-urban farming practices. Moreover, operationalizing FEW nexus solutions requires the participation of the stakeholders across the food, energy, and water systems. The developed analytics could play a key role in facilitating this participation in an attempt to achieve more coordinated and coherent planning across sectors. Likewise, the 2022–2026 Colombia's National Development Plan focuses on a water-centric and environmental justice territorial development. One of the major features of this plan is to bring the local and regional population into the discussion of the territorial plans. Analysis like the one presented in this study may help governmental authorities and policy- and decision-makers to initiate the dialogue with different stakeholders since it is a more holistic approach, and a specific stakeholder does not take precedence over the others. The limitation of this study lies in the fact that the ORW is a well-defined closed system since the main stream is the Otun River, most of the water demand is met with surface water, and it belongs to only one political territorial entity. Future work includes implementing this framework in more complex watersheds that may include a combination of surface water and groundwater sources, transboundary rivers, and larger urban settlements. Additionally, more research is needed to determine the effectiveness of the different measures and their combinations to identify the most suitable practices for the area.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16233405/s1, Figure S1: Flowchart of the urban FEW nexus model developed for the Pereira/Dosquebradas urban area; Figure S2: Example of the input of the urban FEW nexus model for the Pereira/Dosquebradas urban area; Figure S3: Example of the results of the urban FEW nexus model for the Pereira/Dosquebradas urban area; Table S1: Water demand for food products commercialized (locally grown and imported) in Pereira for 2035 (Scenario 2); Table S2: Energy required to produce and transport food products commercialized (locally grown and imported) in Pereira for 2035 (Scenario 2); Table S3: Water demand for food products commercialized (locally grown and imported) in Pereira for 2035 (Scenario 3); Table S4: Energy required to produce and transport food products commercialized (locally grown and imported) in Pereira for 2035 (Scenario 3). Table S5: Water demand for food products commercialized (locally growth and imported) in Pereira for 2035 (Scenario 3). Table S6: Energy required to produce and transport food products commercialized (locally growth and imported) in Pereira for 2035 (Scenario 3).

Author Contributions: Conceptualization, C.T. and M.W.G.; Data curation, C.T.; Formal analysis, C.T.; Methodology, C.T. and M.W.G.; Validation, J.L.-B., D.P.-C. and B.D.; Supervision, M.W.G.; Writing—original draft, C.T.; Writing—review and editing, M.W.G., J.L.-B., D.P.-C. and B.D.; funding acquisition, M.W.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: Camilo Torres is grateful to the Fulbright Program and the Colombian Institute of Educational Credit and Technical Studies Abroad (ICETEX) for providing the funding for his doctoral studies under the "Fulbright-Pasaporte a la Ciencia—Foco Alimentos" fellowship program.

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

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