

Article

Framework for Water Management in the Food-Energy-Water (FEW) Nexus in Mixed Land-Use Watersheds in Colombia

Camilo Torres ^{1,2} , Margaret Gitau ^{1,*} , Jaime Lara-Borrero ²  and Diego Paredes-Cuervo ³ 

¹ Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN 47907, USA; torre185@purdue.edu or c-torresp@javeriana.edu.co

² Department of Civil Engineering, Pontificia Universidad Javeriana, Bogotá 110231, Colombia; laraj@javeriana.edu.co

³ Department of Basic Environmental Sciences, Universidad Tecnológica de Pereira, Pereira 660003, Colombia; diparede@utp.edu.co

* Correspondence: mgitau@purdue.edu; Tel.: +1-765-494-9005

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Abstract: The food-energy-water (FEW) nexus approach has emerged as an alternative for managing these resources more efficiently. Work from studies conducted in the FEW nexus in Latin America is scarce in the scholarly literature. This study aims to develop a framework for water management at the FEW Nexus, with a focus on Colombia. The study focuses on a typical mixed land-use watershed in the Andean region with specific objectives being to: (1) characterize the watershed with respect to land use, climate, water resources, and other factors pertinent to the nexus; (2) explore the relationship between factors in the FEW nexus that may affect water management in terms of quality and availability; and (3) propose a methodology for conducting a FEW Nexus analysis for watersheds located in the Andean region. The results indicate that the Pereira/Dosquebradas urban area has a significant impact on the FEW nexus components in the Otun River Watershed (ORW). Subsequently, an urban FEW nexus framework is proposed for its implementation at the watershed.

Keywords: food-energy-water (FEW) nexus; sustainable water management; urban systems; Andean watersheds

1. Introduction

The food-energy-water (FEW) nexus approach has emerged as an alternative to meet the increasing food and energy demands due to population growth. During the 2011 Bonn Conference, initial evidence showed the benefits of having a nexus approach in terms of an increment in the efficient use of resources, reduction in trade-offs, and improvement of governance among the food-energy-water sectors [1]. Since then, multiple studies and reviews have been conducted including the complete FEW nexus [2–4], elements of the nexus [5], or even an expanded nexus to include additional components such as land [6] and health [7]. These studies have presented the advantages, limitations, and challenges for using a nexus approach. This methodology is preferred because it improves the resource-use efficiency, avoids adverse impacts, [6] and provides the most benefits in inter-sectorial negotiations [8]. However, a lack of data and knowledge gaps limit the use of a nexus scheme [9]. Therefore, developing robust analytical tools, conceptual models, appropriate and valid algorithms, and robust data sets are indicated as the way forward for a nexus framework that can be used as a decision-making mechanism.

Methodologies for managing water resources have been developed in the past. One of them is known as “integrated water resources management” (IWRM). The concepts of nexus and integrated water resources management (IWRM) are closely linked; however, IWRM is water sector-oriented,

limiting the interaction with other sectors [2], and its implementation could be difficult for its lack of political leverage to enact integrated plans and policies [3]. In contrast, a nexus approach is open to more sectors, which could encourage efficiency in the use of resources [2] and address issues in a comprehensive way [3]. Studies on the FEW nexus have been conducted in different regions around the world, including countries in Europe [5,10,11], Africa [12–14], Asia [15–18], Oceania, and North America [19,20]. However, there are few articles published in peer-review journals regarding work conducted in Latin America [21–26].

Since the FEW nexus is a vast topic, Endo et al. [27] suggested five groups where peer-reviewed articles can be classified: (1) comprehensive review articles; (2) targeted review articles; (3) synthesis articles; (4) articles that assessed interlinkages, trade-offs, and/or synergies among resources; and (5) nexus case studies. Based on this classification, articles published from work completed in Latin America fall into targeted review articles [21,23,25] and case studies [22,24,26]. Paim et al. [25] indicated that nationally determined contributions (NDCs) might be a useful platform to incorporate nexus elements on a national and international scale. Mesa et al. [24] presented a FEW nexus conceptual framework in four regions in Chile with water security problems such as droughts and over-allocation of water resources.

In addition to the studies published in peer-review journals, reports have been published by international organizations, including the United Nations Economic Commission for Latin America and the Caribbean (ECLAC-CEPAL), the German Corporation for International Cooperation (GIZ), and the Global Canopy Programme [28–32]. These reports depict the current status of the nexus in Latin American and the Caribbean and provide recommendations for moving forward into using a nexus approach as a planning and decision-making tool to optimize limited resources. The recommendations include the integration of climate change risks into infrastructure design and planning [28] and the promotion of quality research in the nexus sectors that is adapted to regional requirements [29].

As it was noticeable from the literature review and indicated in publications [23,29], the FEW nexus is an area where little consideration has been given in the region. Colombia is not an exception. At the time of this study, no specific studies or reports related to the FEW nexus in Colombia were found in the literature review conducted. However, some departments, like Huila, are preparing climate mitigation and adaptation plans where water management, food production, food security, and energy resources are included as part of the thematic areas in strategic planning [33]. This study aims to develop a framework for water management at the food-energy-water nexus, with a view to providing methodologies for use in watersheds across the Andean region. The study uses a typical mixed land-use watershed in the Andean region as a pilot study site with specific objectives being to: (1) characterize the watershed with respect to land use, climate, water resources, and other factors pertinent to the nexus; (2) explore the relationship between factors in the FEW nexus that may affect water management in terms of quality and availability; and (3) propose a methodology for conducting a food-energy-water nexus analysis for watersheds located in the Andean region. The results of this study will be specific to the Andean region. Methodologies and approaches will be widely applicable.

The manuscript is structured as follows. The first part of the manuscript presents a description of key characteristics of the study watershed, which then guides the development of the framework. Subsequent parts of the manuscript provide a rationale for the focus of the framework development, descriptions of FEW nexus elements at selected sites, and interactions among the FEW nexus elements. Finally, we provide guidance for implementing the framework in the study site and the Andean region in general.

Pilot Study Area

The area selected for this study is the Otun River Watershed (ORW) (Figure 1), 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 48,062 ha ORW belongs to the Cauca hydrographical zone, which is a sub-area of the Magdalena-Cauca hydrological area. The source of the 78-km-long Otun river is the Otun

Lagoon, located inside of the Nevados National Park at an altitude of 3900 m above mean sea level and the discharge point is the Cauca River at an altitude of 825 m above mean sea level. The primary land-use land-cover, based on 2015 data, is forest (37%) and agriculture (32%), followed by grassland (18%) and urban lands (6%). The rest of the land use (7%) corresponds to water bodies, glacier zones, transportation infrastructure, rocky outcrops, and other unspecified land uses. The forest area is mainly located in the upper section of the watershed, while the agricultural and urban areas are located in the middle and lower sections. The major crops grown are coffee, plantain, corn, sugar cane, and bananas. The total sown and harvested areas for these crops are 7274 ha and 6574 ha, respectively which corresponded to the 65% and 69% of the ORW's total sown and harvested areas, respectively [34]. Most of the crops are currently rainfed with limited use of surface water sources (3.6 Mm³/year). According to the Estudio Nacional del Agua (National Study of Water) conducted by Colombia's Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) [35], the Otun River watershed is a hydrographic zone with very high-water demand stress and variability. The same study rated the water quality in the Otun River as poor based on a water quality index (WQI) that considered dissolved oxygen, chemical oxygen demand, total suspended solids, conductivity, and total nitrogen/total phosphorus ratio.

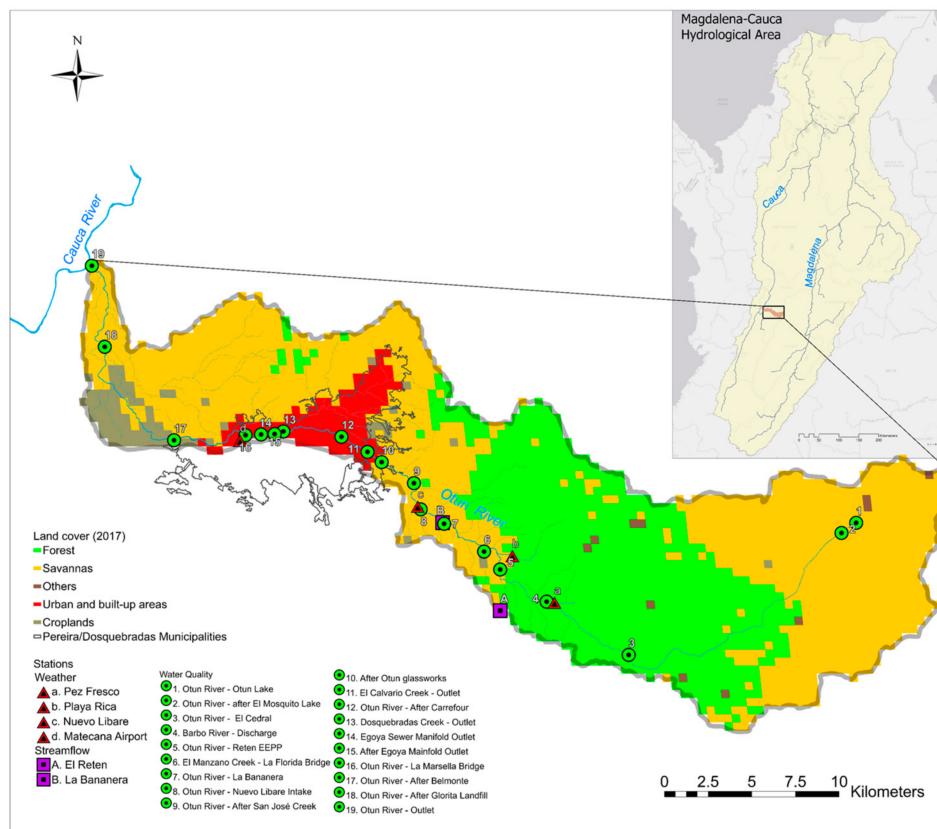


Figure 1. The Otun River Watershed (ORW) showing the location of weather, water quality, and streamflow stations.

2. Characterization of the Otun River Watershed (ORW)

The characterization of the study site was conducted based on analyses of climate data, changes in land use/land cover, the Otun River's streamflow and water quality, population, and a general account of FEW nexus elements in the watershed. Data to complete the characterization of the ORW was obtained from Colombian governmental sources as well as other official sources like the U.S. Geological Services (USGS) and the National Oceanic and Atmospheric Administration (NOAA). Weather and streamflow data were obtained from stations operated by the IDEAM, (<http://dhime.ideam.gov>.

[co/atencionciudadano/](#), Figure 1) and NOAA. For the land-use/land-cover analysis, images from the MODIS Land Cover Type Product (MCD12Q1, USGS EarthExplorer) covering the years 2001–2017 were used. The water quality station locations (Figure 1) and data were provided by the regional environmental agency (CARDER). The complete list of weather, streamflow, and water quality stations can be found as Supplementary Materials (Supplementary Materials Table S1).

2.1. Climate

Of the stations for which climate data are available in the IDEAM meteorological network, four (Pez Fresco, Playa Rica, Nuevo Libare, and Matecaña Airport) are located inside the watershed. These stations were selected because they have at least a 15–20-year period of record and are still active (Table S2). For the rainfall data analysis, the data used were from 01/01/1994 to 12/31/2019 for Playa Rica, Pez Fresco, and Matecaña Airport. Even though Nuevo Libare has a shorter period of record (9/1/2004–6/30/2019), we included the data from this station because of their completeness (100%). For long-term analysis, we used data from Matecaña Airport (1/1/1960–12/31/2019). For temperature, data from Matecaña Airport (1/1/1965–12/31/2019) were used since it was the only station reporting temperature in a consistent manner. Temperature data were obtained from two sources: the IDEAM (daily minimum and maximum) and the NOAA (average daily). Data from the IDEAM were used preferentially since this dataset had 38 years of complete data. Average daily temperatures were estimated from the IDEAM dataset as the average between the maximum and minimum daily temperatures. These average values were then used in the analysis. The NOAA dataset was used to complete any missing data in the IDEAM-derived dataset. Both rainfall and temperature data were checked for annual completeness based on the Expert Team on Climate Change Detection and Indices (ETCCDI) criterion on data quality [36], which indicates that only years with four or five missing values must be preserved. The strict criterion is necessary as serial completeness of the data may affect extreme analysis. For monthly completeness, the criterion indicated by the PRISM Climate Group [37] was used. This criterion indicates that monthly data are complete if there are at most two missing days per month.

- Rainfall Patterns

Data completeness for the rainfall data obtained varied depending on the station. Matecaña Airport was the station with the longest and more complete data in the watershed. From the 60 years of data, 52 years (87%) met the ETCCDI criterion, with the longest consecutive span being 15 years (2003–2017). Likewise, there were 707 months with complete data (98%) within the 60-year period. These data met the 30-year period indicated by the World Meteorological Organization (WMO) as appropriate for a climatological normal reference [38]. Therefore, the data were found sufficient for use in the planned analysis. Seasonality analysis of Matecaña Airport rainfall based on the Walsh and Lawler [39] seasonality index (Equation (1)) showed that rainfall in the area was equable but with a definite wetter season ($\bar{SI} = 0.20\text{--}0.39$). This kind of rainfall pattern favors permanent shrub and herbaceous crops like coffee, green onions, and fruit trees. In the study region, these crops are mostly rainfed, with a few exceptions where other water sources are used. However, this rainfall pattern may cause water quality concerns due to associated wash-off of nutrients, pesticides, and herbicides to surface or ground waters.

$$\bar{SI} = \frac{1}{\bar{P}} \sum_{n=1}^{12} \left| \bar{P}_n - \frac{\bar{P}}{12} \right| \quad (1)$$

where

\bar{SI} : seasonality index for the study period

\bar{P} : average annual precipitation for the study period

\bar{P}_n : mean monthly precipitation for month n over the study period

The distribution of the median monthly rainfall for the area (Figure 2a) confirmed that there is a distinctive wetter period (January–June, herein termed Wet1 and September–December, herein termed Wet2), split by a short drier period (July–August, termed Dry). Graphs of mean rainfall vs. day of the year for all the stations confirmed this rainfall pattern (Supplementary Materials, Figure S1). A deeper analysis of the Matecaña Airport data showed that the annual seasonality index (SI_a) did not follow a particular trend, indicating that no substantial changes in seasonality had occurred over the past 60 years (Figure 2b). Low SI_a values were observed in the late 80s and early 90s (1989 = 0.19, 1991 = 0.23, 1992 = 0.28), indicating a very equitable rainfall regime ($SI \leq 0.19$) or one that was equitable but with a definite wetter season (0.20–0.39). These low points correspond to a period with low rainfall in the country, potentially intensified by the 1992 El Niño event [40]. The effect of El Niño/La Niña events on precipitation varies in Colombia; while an El Niño event did occur in 1991–1992, for the study area, events in 1965–1966 and 1997–1998 were more severe and were responsible for a reduction in annual precipitation in the area [41]. The correlation between SI_a and total annual rainfall was weak (Figure 2c; $\rho = -0.276$), consistent with Montealegre [41]. Results showed an increasing trend in annual rainfall at Matecaña Airport (Figure 2d). However, total rainfall amounts for 1965 and 1997 were 1642 mm and 2044 mm, which were below the mean total rainfall (2311 mm) for the analysis period, confirming a rainfall deficit associated with El Niño events occurring in these years as reported by Montealegre [41].

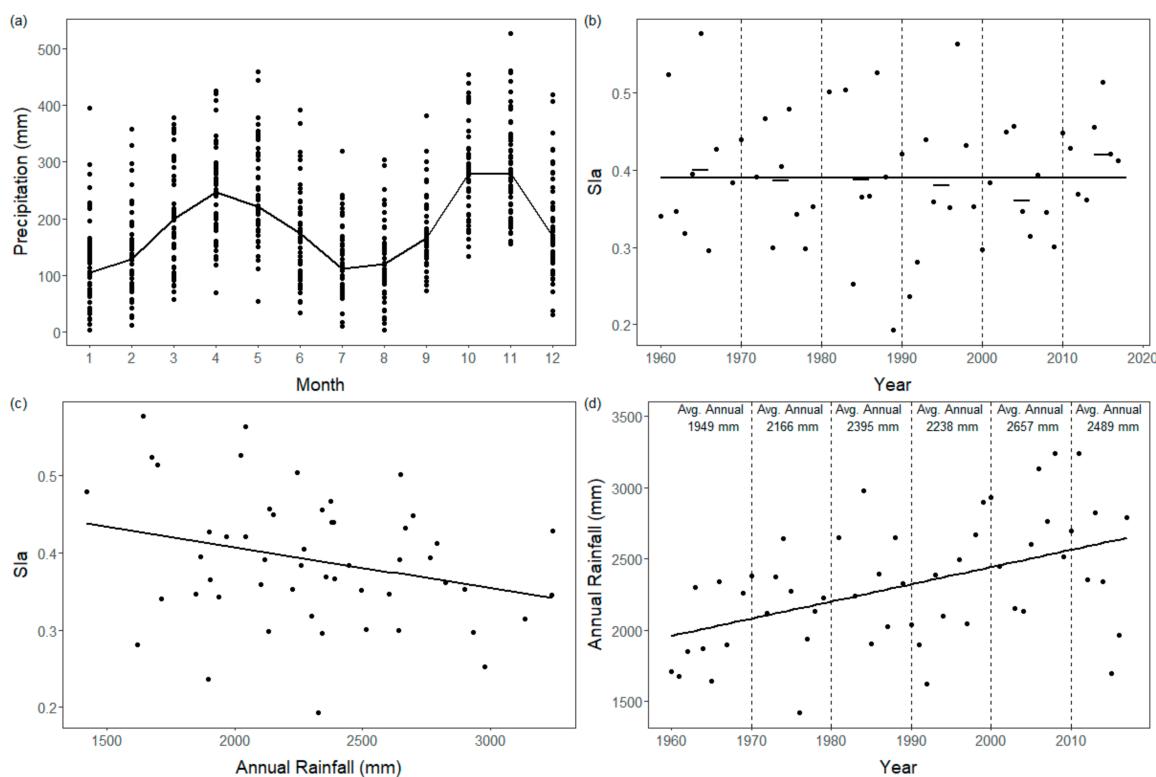


Figure 2. (a) Median monthly rainfall; (b) Trends in annual seasonality index (SI_a). Solid line: mean of data. Short horizontal lines: averages for the respective decades; (c) Relationship between annual seasonality index (SI_a) and annual rainfall; (d) Trends in annual rainfall. Values on top: average annual rainfall for each decade.

Statistical properties including minimum, maximum mean, standard deviation, median, and interquartile range, and essential characteristics [42] including one-day maximum rainfall, number of wet days, and number of days with rainfall greater than the 95th (wet day) and 99th (very wet day) percentile for seasonal rainfall for the watershed are provided as Supplementary Materials (Table S3). These metrics were selected because they are part of the extreme indices defined

by the ETCCDI. This methodology has been recommended by the WMO [43] and is widely used as a tool to monitor and assess climate changes in extremes. For this study, a wet day was defined as a day where daily precipitation equaled or exceeded 1 mm to avoid biases that can be introduced by under-reporting of small rainfall amounts [44]. These statistical properties were estimated for the period between 2005–2019, since this was the period in common for the four stations used for this analysis (Pez Fresco, Playa Rica, Nuevo Libare, and Matecaña Airport).

The statistical properties show that Pez Fresco is the station with the lowest average rainfall during July and August (Dry), while Nuevo Libare is the station with the highest average rainfall during the same period. Even though the average rainfall for Dry within stations was fairly substantial, ranging between 42 mm and 118 mm, any reductions could have an appreciable effect on water availability in the ORW, especially during the years where the climate is affected by El Niño events. During 2015, for example, several municipalities including Pereira and Dosquebradas reported water shortages, especially in rural areas [45,46]. The number of wet days varied across seasons, with a difference of wet days between Wet1 and Wet2 that ranged from 6 to 26 days. The relationship between the number of wet days and total annual rainfall exhibited a linear correlation (Supplementary Materials, Figure S2) except for years with rainfall greater than 4000 mm. Thus, the increase in annual rainfall was associated, at least in part, with an increase in the number of wet days. A trend analysis completed for the rainfall at Matecaña Airport showed that the strength of the monotonic relationship (Kendall's tau) was higher for the number of wet days ($\tau = 0.653$) than for the percentage of rainfall from extreme events ($\tau = 0.241$). These results are consistent with Mejia et al. [47]. In Colombia, the pluviographic optimum occurs at an elevation of 1500 m above mean sea level. This optimum corresponds to the point with the highest rainfall between the base and the summit of a mountain ridge. Stations located in the watershed's mid-section (Playa Rica, Pez Fresco, Nuevo Libare) are near in elevation to the pluviographic optimum [48]; overall, more rainfall was reported at these higher elevation stations compared to what was reported at the station located in the lower-section of the watershed (Matecaña Airport), consistent with expectations.

- Temperature Patterns

In general, temperatures showed slight variations (17°C – 27°C) across seasons, with the highest (33°C) and lowest (13°C) temperatures occurring during Wet1. These results confirmed that temperatures in the region do not depend on the time of year; instead, they depend on the altitude—decreasing gradually with an increase in altitude which is consistent with what is reported about temperatures in Colombia [48]. Even though daily average temperature changes do not seem to be significant, the main concern is associated with the temperature effects on sensitive crops. Of the main crops grown in the ORW, coffee is the most sensitive because it has the largest production and is less resistant to increments in temperature, which can affect coffee's thermal time accumulation—the determinant for coffee production.

Thermal time accumulation is defined as

$$\Delta UT = \sum T_{avg} - T_{base} \quad (2)$$

where

ΔUT : Thermal time accumulation ($^{\circ}\text{C}$)

T_{avg} : Average daily temperature ($^{\circ}\text{C}$)

T_{base} : Base temperature (10°C for coffee crops)

Based on studies conducted at the Centro Nacional de Investigaciones de Café (National Center for Research in Coffee, CENICAFE), coffee requires 3250°C ΔUT for a six-month-old bush to reach its first flowering, 2500°C ΔUT from flowering to first fruit development, and 4139°C ΔUT to complete flowering and fruit filling for the subsequent harvest cycles [49,50]. In the traditional Colombian

coffee growth regions (Quindío, Risaralda, and Caldas), the average time to reach the first flowering is 224 days and 550 days for fruit development. The initial harvest cycle occurs between 1 January and 31 March, and subsequent cycles occur from 1 April to 31 March [49–51]. The coffee crop has a life expectancy of up to 25 years, thus the need to understand temperature patterns in the region. For the period of study, there was a tendency for the number of thermal accumulation units to increase ($\tau = 0.55$, p -value < 0.0001, Figure S3), which could have both positive (yield increases up to a point) and negative (yield decreases associated with temperatures > 33 °C) impacts on production based on Sachs et al. [52].

2.2. Land-Use Land-Cover Changes

The MODIS Land Cover Type Product (MCD12Q1) used in this study contained land cover classification for the study area for the period 2001 to 2017, with an image resolution of 500 m, and five legacy classification schemes. For this study, the International Geosphere-Biosphere Programme (IGBP) 17-category classification system was used. To facilitate characterization, the 17 IGBP categories were aggregated into five categories: forests, grasslands, urban land, croplands, and other (permanent wetlands, permanent snow/ice, and barren). An evaluation of changes in land use/land cover (LULC) across five-year time periods showed that changes primarily occurred in the ORW middle and lower sections. The main changes observed were an increase in grasslands and a loss of forest and croplands from 2001 to 2005, and a subsequent gain of forest area, especially in the Otún River's riverbank for the following periods (Figure 3, Supplementary Materials, Figures S4 and S5). An additional analysis to estimate the magnitude and nature of the LULC based on Aldwaik et al. [53], Pontius et al. [54], and Gitau and Bailey [55] showed that forests and urban areas had a positive net gain of 1.2% and 0.8% respectively, while grasslands and croplands had a negative net change of −0.6% and −0.8%, respectively (Supplementary Materials, Table S4). These results showed that during the period of study there were no significant changes in the land cover/land use in the ORW. The slim increase observed in forest area may be associated with areas restored near streams used as water sources for human consumption in rural areas. From 1997 to 2015, 240 ha were restored in 20 streams, some of which are the Otún River's tributaries [48].

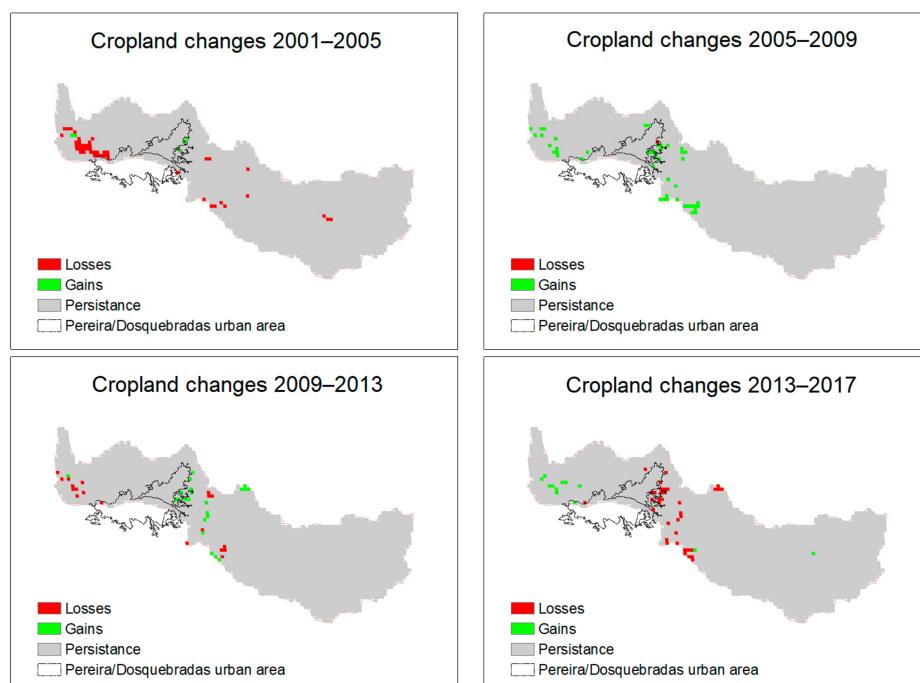


Figure 3. Change in cropland in the Otún River Watershed for the periods 2001–2005; 2005–2009; 2009–2013; and 2013–2017.

Changes in cropland area (Figure 3) showed that the largest losses occurred between 2001 and 2005. These losses occurred in the area located to the west of the Pereira/Dosquebradas urban area. This area has been designated as an area of urban expansion in the Pereira Land Use Ordinance Plan [56]. Changes in the following periods were dispersed across the ORW. These changes can be associated with a reduction in transitory and permanent crops and its subsequent transition to grasslands. The Updated Otun River Watershed Management Plan [48] indicated that a reduction of 7.2% in permanent crops and a gain of 3.1% in grasslands occurred from 1997 to 2015. Overall, while some changes were discerned in the land use land cover and, in particular, with respect to cropland, results tended to be somewhat ambiguous due to the low-resolution of the original datasets. For example, over the last 20 years, coffee farms located in the outskirts of the Pereira/Dosquebradas urban area have been replaced by recreational houses and luxury condominiums [57], a change that is not readily discernable from the existing datasets. Furthermore, some of the changes observed could be attributed to misclassification.

2.3. Streamflow and Water Quality

- Streamflow

Data used to conduct this analysis was from La Bananera station (Streamflow station B, Figure 1) which is located upstream of the water utility and energy utility companies' combined water intake. The daily mean streamflow data were available from 1971–2013. The estimated mean streamflow for this station is $12.8 \text{ m}^3/\text{s}$, with a maximum registered flowrate of $103.5 \text{ m}^3/\text{s}$ and minimum streamflow of $0.4 \text{ m}^3/\text{s}$. Water demand in the watershed was reported as $15.4 \text{ m}^3/\text{s}$ [48]. The highest demand was for industrial purposes ($11.7 \text{ m}^3/\text{s}$), including electricity generation at two small hydroelectric power (SHP) plants located in the Otun River. In 2015, CARDER increased the water rights for electricity generation at the Nuevo Libare's small hydroelectric power (SHP) plant to allow a maximum flowrate of $7.2 \text{ m}^3/\text{s}$ (up from $5.0 \text{ m}^3/\text{s}$). These water rights were conditioned on streamflow downstream of Pereira's energy utility company being sufficient to meet the environmental and the water utility company's streamflow demand, which are $3.0 \text{ m}^3/\text{s}$ and $2.4 \text{ m}^3/\text{s}$, respectively. As water availability for energy production and domestic use is a concern in this area, a reliability–resiliency–vulnerability (R-R-V) analysis [58] was conducted as part of this study.

Reliability was defined as the probability α that a system is in a satisfactory state

$$\alpha = \text{Prob}[X_t \in S] \quad (3)$$

where X_t denotes the system's output state or status, and S the set of all satisfactory outputs.

Resilience (γ) describes how quickly a system is likely to recover from failure once failure has occurred

$$\gamma = \frac{\rho}{1 - \alpha} = \frac{\text{Prob}[X_t \in S \text{ and } X_{t+1} \in F]}{\text{Prob}[X_t \in F]} \quad (4)$$

where ρ is the probability of the system being in a satisfactory state for some period t and going to an unsatisfactory state (F).

Vulnerability (ν) is the likely magnitude of a failure, if one occurs. The equation used to estimate vulnerability was adapted from Sandoval-Solis et al. [59] with a view to identify long-term trends and critical periods where there may be a water deficit

$$\nu = \frac{\left(\sum_{t=0}^{t=n} D_t \right) / \text{No.of times } D_t > 0 \text{ occurred}}{\text{Water Demand}} \quad (5)$$

where D_t is the deficit at time t . The result obtained from the sum of D_t divided by the number of times $D_t > 0$ is divided by the daily water demand to obtain a dimensionless value for vulnerability.

Using the water demand indicated by CARDER as a basis, the overall reliability (α), resiliency (γ), and vulnerability (ν) were 0.39, 0.09, 0.38; and 0.89, 0.17, 0.24 for scenarios 1 (considering water demand

for electricity generation, human consumption, and environmental streamflow) and 2 (considering water demand for human consumption and environmental streamflow), respectively. Loucks [60] indicated that R-R-V values should be defined based on economic, ecological, environmental, and social criteria established by the water system's stakeholders. Based on the results obtained for R-R-V, it is possible to indicate if a system is sustainable (sustainable system: reliability and resiliency increase and vulnerability decreases over time). In the case of the ORW, it is expected that the critical R-R-V values ($\alpha < 0.5$, $\gamma < 0.5$, and $\nu > 0.5$) occur in seasons or years with lower rainfall and higher temperatures compared to the average values, for example, $\alpha = 0.12$, $\gamma = 0.02$, $\nu = 0.59$; and $\alpha = 0.37$, $\gamma = 0.06$, $\nu = 0.29$ for scenarios 1 and 2, respectively, obtained for 1997.

Figure 4a,c,e shows that reliability and resiliency had upward trends while vulnerability showed a downward trend. These results are consistent with the findings reported by Kjeldsen and Rosbjerg [61], which indicated that reliable systems tend to have a higher degree of resiliency and tend to be less vulnerable. Figure 4b,d,f shows the R-R-V distributions for each season. Even though the median values for reliability and resiliency in scenario 2 were higher than 0.5 for the most part, there were values below 0.50, especially during the dry season. Values of reliability and resiliency below 0.5 indicate that there was a probability that, at least half of the time, the daily demand would not be met, and the system would not recover in a reasonable amount of time following a failure [60]. For scenario 1, reliability and resiliency were mostly below the 0.5 threshold, indicating the substantial pressures that the SHPs put on the water resource system in the ORW. However, vulnerability values were mostly below 0.5 for both scenarios. Reliability and resiliency were higher in the Wet2 compared to the Wet1 and Dry seasons, indicating that Wet2 is the season with the highest probability that the system will meet all water requirements without interruption and without the risk of a potential water shortage. Overall, results were consistent with the Updated Otun River Watershed Management Plan [48], where the Otun River was classified as having a high hydrological vulnerability index (HVI) in the upper and lower sections and a medium HVI in the middle section. The HVI is a qualitative indicator that measures a hydrological system's ability to meet the water demand for all its intended uses in normal conditions and extreme drought conditions. A high HVI indicates that there is a high risk of water shortage during extreme climate events, while a low value indicates that there is a low risk of water shortage during extreme climate events.

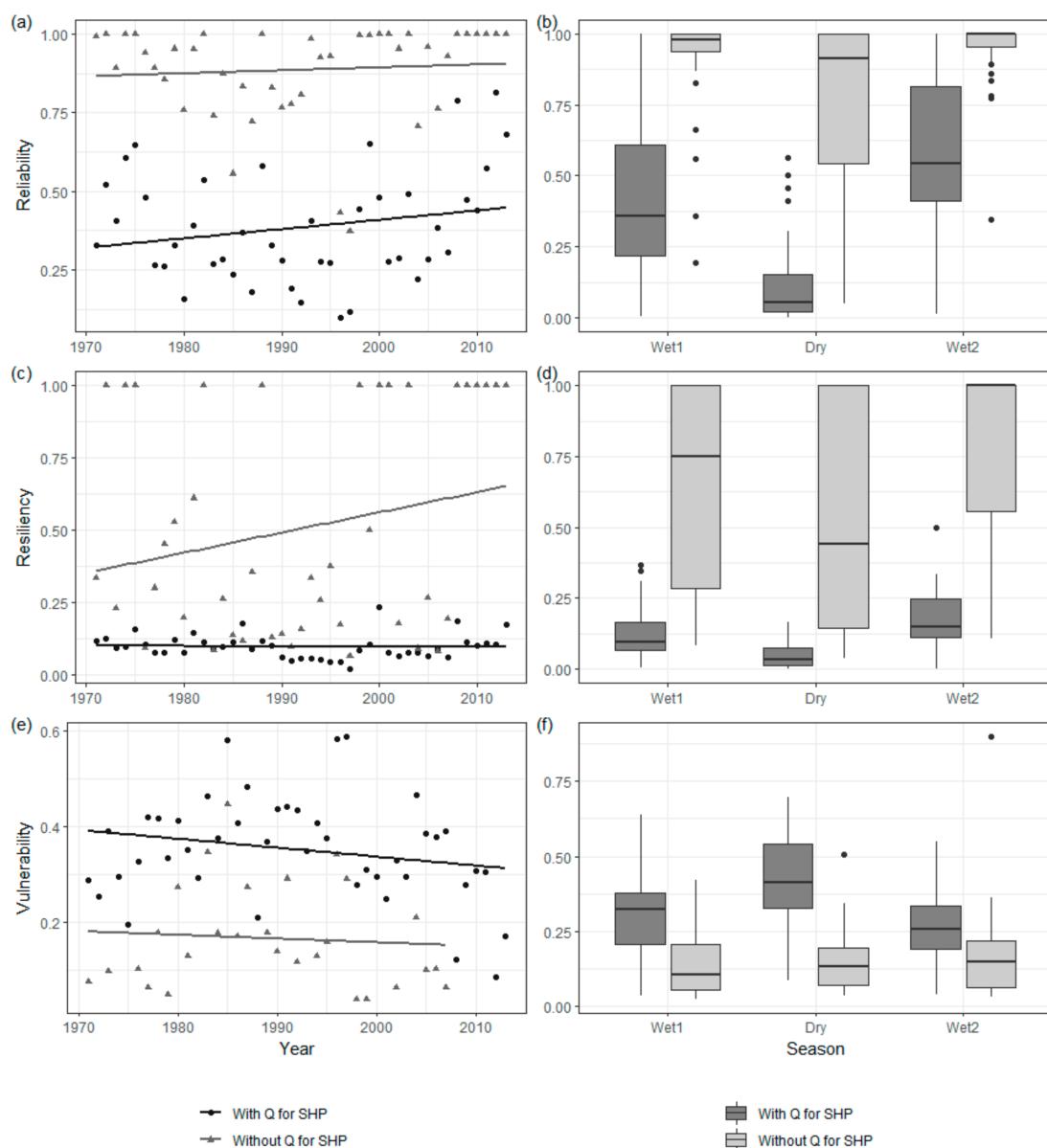


Figure 4. Temporal and seasonal changes in reliability, resiliency, and vulnerability for the Otun River at La Banarera station (1971–2013). Scenario 1: Considering water demand for electricity generation, human consumption, and environmental streamflow (With Q for SHP). Scenario 2: Considering water demand for human consumption and environmental streamflow (Without Q for SHP). Q; Withdrawal flowrate; SHP: Small hydroelectric power plant. Subgraphs: (a–c) Temporal change for reliability, resiliency, and vulnerability under Scenarios 1 and 2; (d–f) Seasonal change for reliability, resiliency, and vulnerability under Scenarios 1 and 2.

- Water Quality

For the Otun River, CARDER has implemented a sampling protocol where three samples are taken in a year for each of the 19 sampling points in the watershed. The first sample is taken between February and March (Wet1), the second between July and September (capturing Dry), and the third between October and December (Wet2). Data were available for the years 2010 to 2018, with an average of 46 entries per year for each of the 20 parameters measured. A graphical exploratory analysis of a selected number of water quality parameters—pH, dissolved oxygen (DO), total suspended solids (TSS), total solids (TS), nitrates+nitrites ($\text{NO}_2\text{--}_3$), BOD, *E. coli*, stream temperature,

and total coliforms—(Figure 5) showed that water quality degraded along the river path. In particular, concentrations of total solids, nitrates+nitrites, BOD, total coliforms, and *E. coli* increased from station 1 (river source at Otun Lagoon) to station 19 (outlet into the Cauca River). Data from stations 4, 6, 11, 13 (located in Otun River tributaries), and 14 (a sewer discharge point) were excluded from Figure 5 as they are not located on the mainstem of the Otun River. However, concentrations at these points (Figure S6) are important to Otun River water quality and were thus considered in the analysis. The thresholds included in Figure 5 were extracted from Colombian water regulations (Ordinance 1076, 2015) unless thresholds were not defined in the Colombian regulations, in which case commonly used thresholds reported in the literature were used [62].

For all parameters, except nitrates+nitrites, the peak median values were reached in the urban area. Higher concentrations in the urban area were primarily associated with the discharge from Pereira's sewer manifolds (primarily station 14), since the city does not have a wastewater treatment facility. The marginally higher concentrations for nitrates+nitrites downstream of the urban area might be associated with an increase in agricultural activities in that part of the ORW. Mann-Kendall's tau values (Supplementary Materials, Table S6) were positive and ranged from 0.250 and 0.531 (*p*-values < 0.0001) for TSS, TS, NO₂₋₃, BOD, *E. coli*, and total coliforms, indicating a significant positive trend. For pH and DO concentrations, results indicated a tendency to decrease along the Otun River ($\tau = -0.250$ and $\tau = -0.147$, respectively; *p*-value < 0.0001). pH concentrations ranged from 6.5 to 8.3, which is within the acceptable limits to support most aquatic organisms. However, DO concentrations were at times lower than the acceptable limits to support aquatic life, attributable to sewer discharges coming from station 14. The U.S. EPA indicates that concentrations below 3 mg/L should be avoided to prevent acute mortality in fish species [63]. Nonetheless, the Otun River showed a tendency to recover quickly from this oxygen depletion, largely due to the rapid mixing afforded by the steep gradient of the river channel.

TSS concentrations were also noticeably higher in the urban region, with median values ranging from 15.8 to 177 mg/L in this area compared to a range of 3.2 to 26.0 mg/L in other parts of the Otun River. High TSS concentrations can have negative effects on water resources, including damage to fisheries and ecological habitats, transport of pollutants, and acceleration of nitrification processes [64]. Higher NO₂ concentrations can accelerate nitrification, which has the potential to reduce DO levels available for aquatic life, leading to eutrophication in water bodies (as cited in [64]). BOD is a water quality parameter that describes the amount of oxygen required for the decomposition of organic matter [65]. Elevated BOD concentrations are typical in raw sewage as is the case with station 14, and can run as high as 100, 200, and 300 mg/L for weak, medium, and strong municipal domestic wastewaters, respectively [66]. High BOD concentrations can reduce the amount of DO in a stream, affecting aquatic life diversity [65]. *E. coli* and total coliforms concentrations (indicators of fecal contamination) generally increased along the Otun River. *E. coli* and total coliforms concentrations were also higher in the urban area attributable to the higher human activity in the area.

Overall concentrations of most of the water quality parameters of concern tended to be high (and low for DO) particularly in the mid and lower sections of the watershed, sometimes exceeding associated thresholds. Concentrations were higher for stations downstream from the urban area compared to stations upstream of the area, indicating residual impacts of the sewage outflow. There is also concern associated with the loads deposited by the urban area [48]. While concentrations are important for assessing ecological responses, loads provide a more accurate assessment of pollutant amounts from point and non-point source discharges, since they account for fluctuations in water quantity over time. In general, water quality is of concern in the study area, and particularly as related to the impact of the Pereira/Dosquebradas urban area. However, it is important to note that the Otun River has a high assimilative capacity, as indicated in the results reported in the Drinking Water and Basic Sanitation Environmental Impact Study (as cited in [67]). This assimilative capacity is due to the stream characteristics with high slopes in the riverbed, and thus inherently high re-aeration rates, which increases DO concentrations in the river.

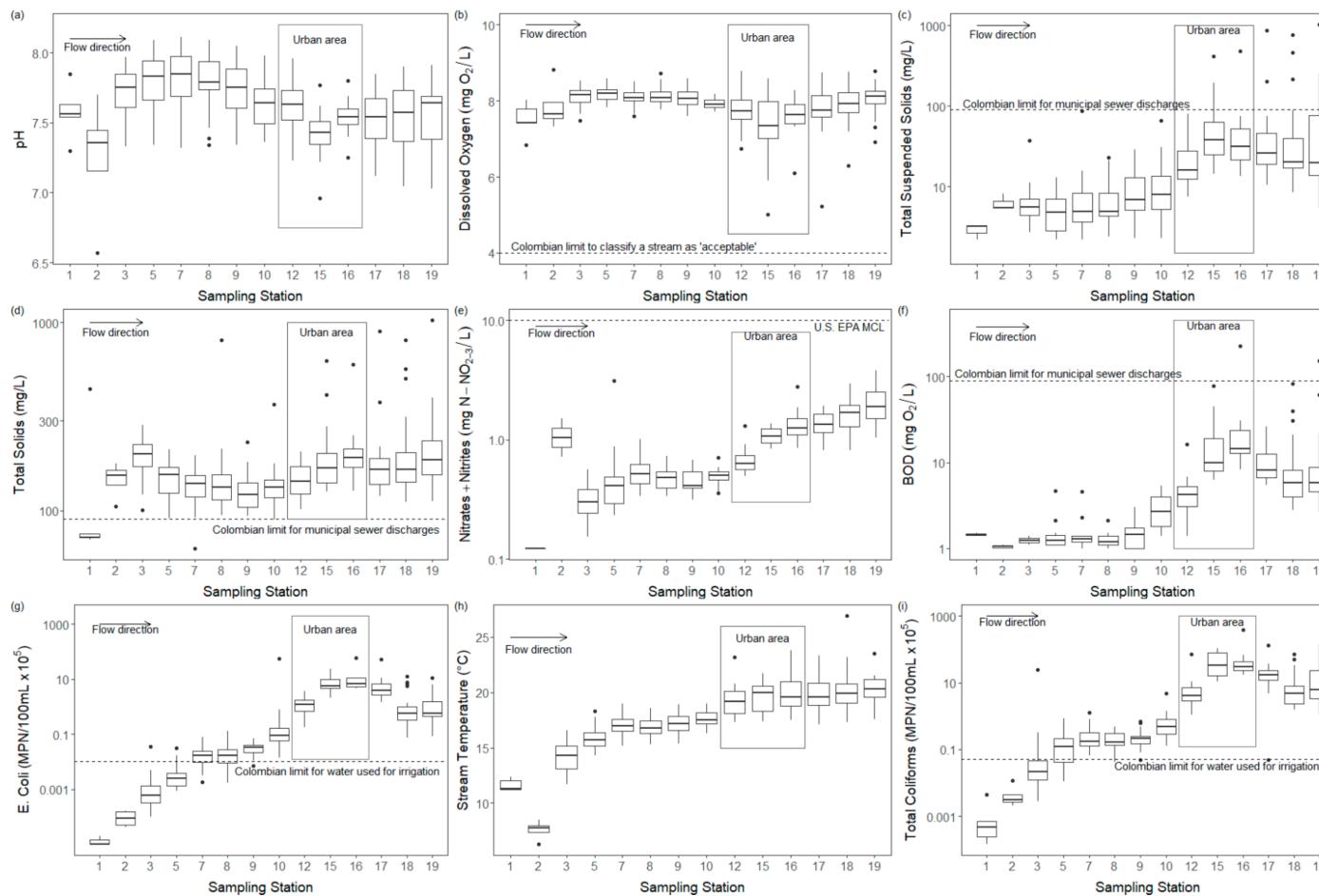


Figure 5. Water quality results at different sampling stations across the ORW. Sampling station (SS) 1: Otun River (OR)-Otun Lake, SS2: OR after El Mosquito Lake, SS3: OR-El Cedral, SS5: OR-El Reten EEPP, SS7: OR-La Bananera, SS8: OR-Nuevo Libare intake, SS9: OR-after San Jose Creek, SS10: OR-after Otun glassworks, SS12: OR-after Carrefour, SS15: OR-after Egoya sewer discharge, SS16: OR-La Marsella bridge, SS17: OR-after Belmonte, SS18: OR-after Glorita landfill, SS19: OR outlet. SS4: Barbo River-Outlet, SS6: El Manzano Creek-La Florida bridge SS11, El Calvario Creek outlet, SS13: Dosquebradas Creek-outlet, SS14: OR-Egoya sewer outlet were not included since these samples are not taken in the OR mainstream. Concentration distributions for: (a) pH; (b) Dissolved oxygen; (c) Total Suspended Solids; (d) Total Solids; (e) Nitrates+Nitrites; (f) BOD; (g) E. coli; (i) Total Coliforms; and, (h) Stream Temperature distribution.

2.4. Population

About 99% of the total population in the ORW resides in the Pereira and Dosquebradas municipalities, which together form the largest urban centers in the watershed [48]. Fifty percent of Pereira is located in the ORW, while the corresponding proportion for Dosquebradas is 93%. Figure 6 shows Pereira and Dosquebradas urban expansion from 1991 to 2014 [68] and their population growth from 1985 to 2020 [69]. From 1991 to 2001, Pereira's urban area almost doubled, with the largest expansion occurring in the southwest part of the city. From 2001 to 2014, there was a slight urban expansion in all directions. Urban growth in the region has been caused by migration from Risaralda's rural areas and other areas affected by Colombia's internal conflict, as well as growth in the coffee industry. Dosquebradas' population almost doubled between 1985 and 2013, consistent with Pereira and Dosquebradas' urban area growth. Dosquebradas' growth rate was estimated as 1.1% for 2013 and is expected to keep reducing. However, this trend may change due to national policies to incentivize the construction of housing for low-income families. Dosquebradas is the municipality with the largest growth rate compared to other municipalities in the region, with the rate being almost twice as high as that of Pereira (estimated as 0.54 for 2013). The 2016 Pereira's Revised Land Use Plan [56] indicates that the vision for the city is to consolidate it as a regional business and services hub, as well as an industrial and agro-industrial center and a tourist attraction.

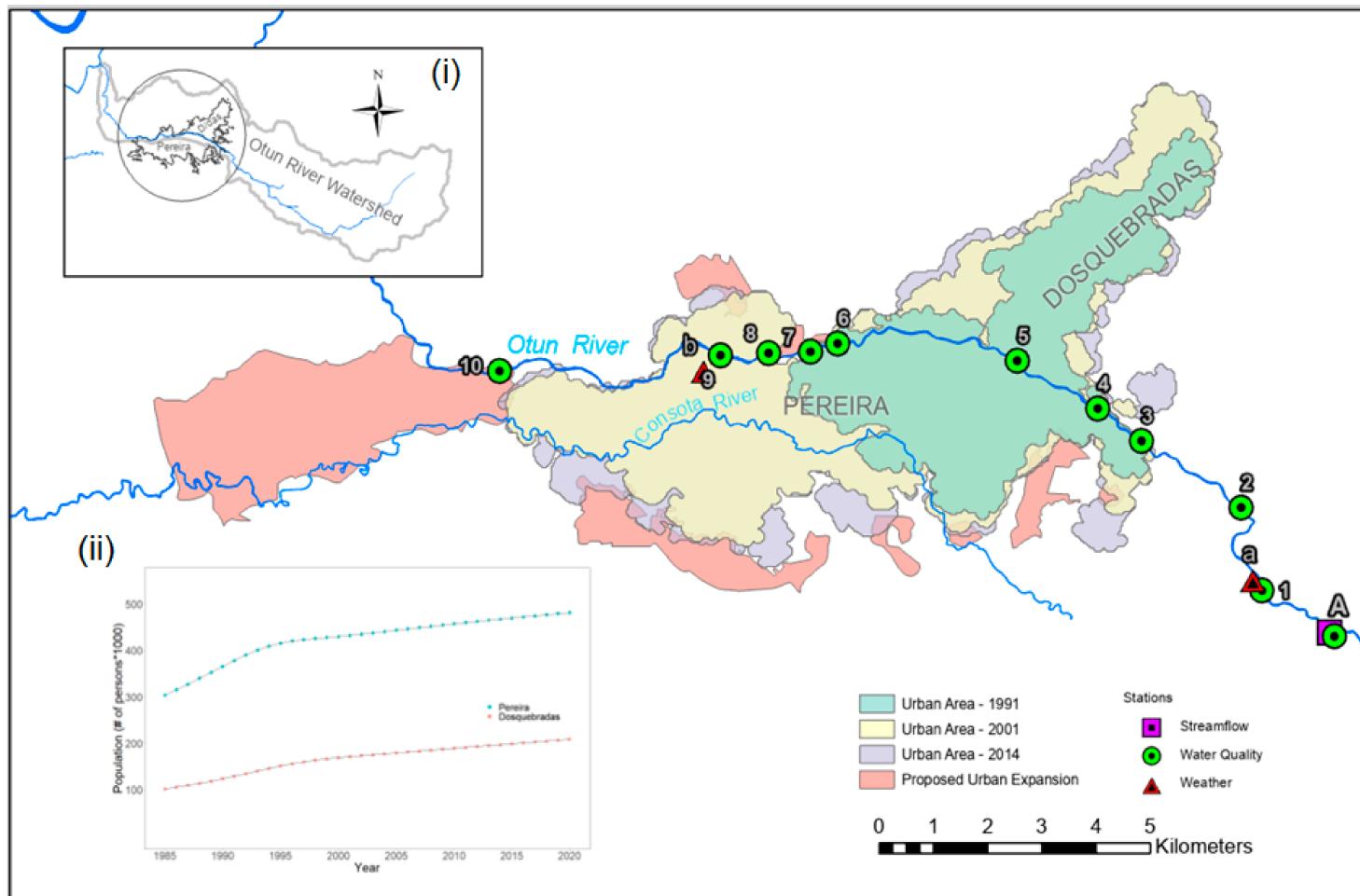


Figure 6. Pereira/Dosquebradas' urban expansion from 1991 to 2014 and proposed urban expansion (data source: Atlas de Expansión Urbana Colombia, 2020 and SIGPER, 2017). Stations. Streamflow: (A) La Bananera; Water Quality: (1) Otun River (OR) Nuevo Libare intake, (2) OR—after San José Creek, (3) OR-after Otun glassworks, (4) El Calvario Creek outlet, (5) OR-after Carrefour, (6) Dosquebradas Creek-outlet, (7) OR-Egoya sewer outlet, (8) OR-after Egoya sewer discharge, (9) OR-La Marsella bridge, (10) OR-after Belmonte; Weather: (a) Nuevo Libare. (b) Matecaña Airport. Insets: (i) Otun River Watershed; (ii) Populations in Pereira and Dosquebradas from 1985 to 2020.

3. Moving Forward to a Nexus Approach

While rainfall patterns in the study area have not changed substantially over time, average annual rainfall has tended to increase from 1960 to 2019. Additionally, the temperature analysis showed an upward trend in the number of thermal units from 1980 to 2019. All FEW nexus elements may be impacted by changes in climate patterns. Extreme climate events, especially extended dry/wet periods, heat waves, and daily extremes (wet days exceeding the 95th and 99th percentile, temperatures above 32 °C) can have a negative impact on the crops produced in the ORW as well as the water availability for human consumption and electricity generation. For example, during the last extended wet period, influenced by the La Niña event in 2010–2011, the estimated losses in Risaralda were 10,852 million Colombian pesos (approximately 5.6 million US dollars) [70]. In years influenced by El Niño events, water shortages as well as economic losses due to crop yield reductions and other negative impacts may occur, for example, as reported during the 1997–1998 and 2015–2016 El Niño events [46,71,72].

Since a third of the area in the ORW is used for agricultural purposes, activities associated with farming and animal husbandry can harm the watershed's water quantity and quality substantially. Crops such as green onion, coffee, and plantain have been identified as crops that require extensive use of agrochemicals for pest control and fertilization. Even though sown and harvested areas for green onion are small compared to other crops, the farming of this product is concentrated in the watershed's middle section, upstream of the Pereira/Dosquebradas' main water intake. The excessive use of organophosphate pesticides, which can cause damage to the nervous system, is a common practice in the region. However, information on the existence of organophosphates in the watershed's soil and water is limited. Studies conducted at the Universidad Tecnológica de Pereira [73,74] showed the presence of chlorpyrifos, dichlorvos, mevinphos, demeton, naled, disulfoton, methyl parathion, fenthion, fensulfothion, bolstar and azinphos methyl, while Beltrán Hincapié and Restrepo Martínez [75] found 53 active ingredients, including four that are classified as extremely toxic and 20 that are classified as highly toxic, in commercial products used to control plagues and plant diseases.

In addition to the risk of pollution from pesticides, water sources in the watershed can be polluted by nutrients, sediment, and biological waste. High concentrations of nitrates, suspended sediment, and E. coli were seen at stations in the watershed's middle and lower sections. While there are poultry and fish farms located along the river [48], these high concentrations were largely attributable to the urban area. In particular, the municipalities of Pereira and Dosquebradas (Figure 6), were found to be of importance; forty percent of Pereira's and 100% of Dosquebradas' wastewater is discharged directly into the Otun River or into one of its tributaries without any type of treatment.

Furthermore, these municipalities use the Otun River as the water source for human and industrial uses, as well as for electricity production in the two SHP plants located in the river. These municipalities are also the most populated areas in the ORW and in relation to urban areas in the coffee axis region (Risaralda, Caldas, and Quindío). The two urban centers are economic hubs in the region due to the coffee and garment industries, and have identified tourism, metallurgic, and agroindustry as priority areas for economic development in addition to other promising areas such as biotechnology and business process outsourcing. Due to the footprint created by Pereira and Dosquebradas in comparison to other areas in the ORW, an urban FEW nexus framework emerged as an approach to water management in the watershed and as an alternative to address the potential allocation of resources to meet current and future demands, considering trade-offs among FEW nexus elements.

Figure 7 shows the proposed FEW nexus framework considering the Pereira-Dosquebradas urban system. The FEW nexus elements and framework implementation are discussed in subsequent sub-sections.

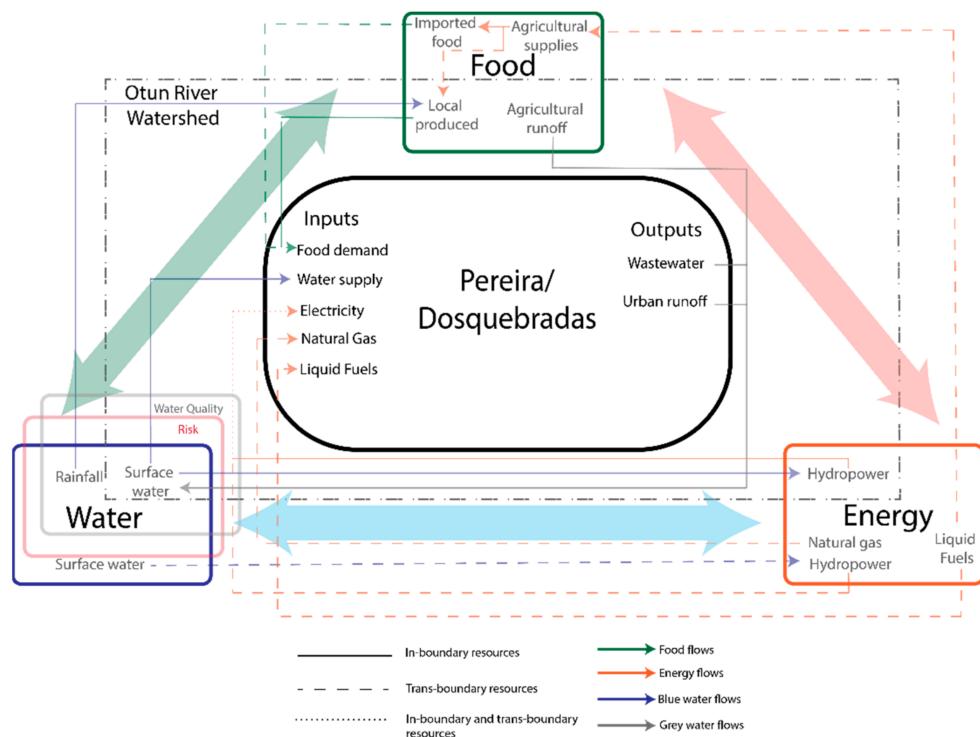


Figure 7. Framework for the food-energy-water (FEW) nexus in the Pereira/Dosquebradas urban system of the Otun River Watershed.

3.1. FEW Nexus Elements in the Pereira/Dosquebradas Area

- Food

As previously indicated, agriculture is a major economic driver in the ORW. However, the bulk of the produce—primarily coffee, plantain, corn, sugar cane, and bananas—is exported, with final destinations in other national or international markets. Food to meet the demand for Pereira and Dosquebradas mainly comes from outside the ORW; about 84% of the food received in the ORW main food distribution center (MERCASA) is imported, with 58% coming from domestic markets and 26% from international markets [76]. In 2018, MERCASA received a total 118,845 mton of food products [76]. Distribution of the food imported and exported from MERCASA is presented in Figure 8. In addition to highlighting the dependence on food products coming from outside the watershed, the 2012–2019 Pereira’s Municipal Plan for Food and Nutrition Security and Sovereignty [77] identified the use of polluted water as one of the risks to food quality and safety for products cultivated in the area. The report also indicated low food production, low agricultural competitiveness, and high use of agrochemicals as some of the factors affecting the availability of food in the municipality.

- Energy

Electricity for Pereira and Dosquebradas is provided by Energía de Pereira, which is part of Colombia’s National Interconnected System. The electricity generated by the company goes to a central grid within Colombia that redistributes it according to system needs. The company has two small hydroelectric plants (Nuevo Libaré and Belmonte) installed in the Otun River and seven photovoltaic systems. Natural gas is provided by EFIGAS, a utility company created from the merge of the Risaralda, Quindío, and Caldas regional natural gas companies. Natural gas is not extracted in the ORW; therefore, all the natural gas comes from outside the watershed through pipelines from the Llanos and La Guajira regions (Figure 8). In addition to the electricity and natural gas consumed in residences and industries, fuel for vehicles is another type of energy used in the watershed.

Hydropower is defined as a clean source of energy, since it does not produce any greenhouse gas emissions. However, depending on the size and scale of the hydroelectrical power plants, they may impact rivers' water quality and quantity. For example, in 2017, water quality at the Risaralda River was affected by the operation of the Morro Azul SHP plant when reservoir gates were open to clean the water intake screens. This maintenance caused higher concentrations of solids, increasing the river's turbidity [78]. Results of an environmental impact assessment indicated that streamflow, wildlife, natural scenery, and aqueducts might be moderately to severely impacted by this SHP [79]. Such impacts of energy production on river water quality could potentially occur in the Otun River due to the existing SHPs.

- Water

The Otun River is the major water source for Pereira and Dosquebradas. A mixed-use water intake is located in the Otun River, three kilometers upstream of the Pereira/Dosquebradas urban area (Nuevo Libaré intake). This intake captures water for Pereira's water and electricity utilities. Another intake is located downstream of the urban area, which captures water for electricity generation (Belmonte intake). The streamflow that can be extracted at these two intakes is $9.2 \text{ m}^3/\text{s}$ and $4.5 \text{ m}^3/\text{s}$, respectively. Pereira's annual water demand is estimated at 449.8 Mm^3 , corresponding to about 93% of the ORW total water demand (Figure 8). Water demand for agricultural purposes is low since most of the crops are rainfed and, as presented in the rainfall analysis, there is plenty of rain all year round in the region. Even though the different water sources currently meet Pereira/Dosquebradas water demand, there is concern about the future status of these water sources, especially the surface water. This study identified the potential for reduced reliability and resilience, and increased vulnerability associated with excessive usage particularly during dry periods. Urban expansion and increasing population as identified also pose a threat to water quantity and quality. The *Estudio Nacional de Agua* [35] classified the ORW as a watershed with high erosion, bad water quality, and a critical area susceptible during extreme dry years. Therefore, water management solutions are needed to guarantee that requirements for Pereira and Dosquebradas can be met.

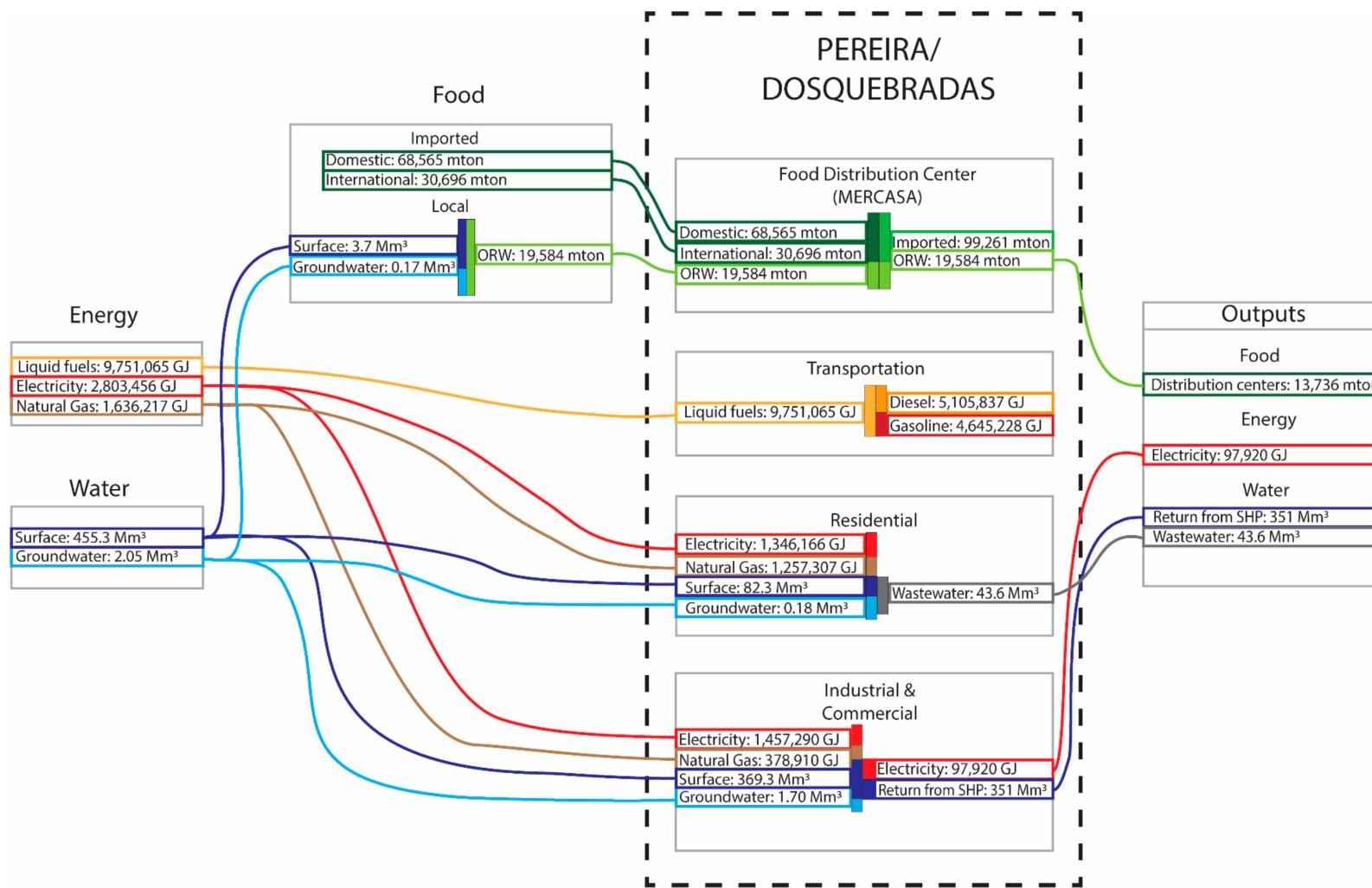


Figure 8. NEST diagram showing details of FEW nexus components and their interactions for the Pereira/Dosquebradas urban area of the Otun River Watershed. (Data sources: [48,76,80,81]; NEST concept: [82]).

3.2. Implementing an Urban FEW Nexus

The FEW nexus framework presented in this article includes the main interactions between FEW nexus components at the regional scale (ORW) and local scale (the Pereira/Dosquebradas urban area). Thus, this framework can be used to model trade-offs among FEW nexus elements and evaluate different scenarios considering anticipated changes in the area and their impacts on the water resource, as discussed in ensuing paragraphs.

As the Pereira/Dosquebradas urban area is surrounded by a rural area with significant agricultural activity, a small portion of the food consumed in the urban area comes from the adjacent rural area. However, most of the crops are grown for export (Figure S7). Even though the use of machinery is not very extensive in the farms located in the ORW, there are some pieces of equipment used to process the coffee beans such as mechanical washers, mucilage removers, threshers, and heated silos. Farm equipment and supplies required in the rural area might be acquired in Pereira/Dosquebradas due to its proximity. These equipment and machinery use electricity, natural gas, or liquid fuels, all of which are provided through the Pereira/Dosquebradas area. Some pesticides and fertilizers are produced in the Pereira/Dosquebradas area, while some are imported through this area. It is not clear what percentage of the total demand for agrochemicals is met locally, but it is expected that a significant portion of these products come from outside the ORW since some of the largest manufacturing plants are located in other regions, especially in the Caribbean region. Regardless, production and import activities related to fertilizers and pesticides in the watershed have implications on energy usage by the agricultural sector. Most of the crops do not require any irrigation since rainfall is plenty in the area all year round. However, changes in climate patterns may be problematic in the near future. The climate characterization completed in this study showed a tendency for average temperature to increase, which might have implications in the future.

Water from the Otun River and its tributaries is used for human consumption and industrial processes, as previously discussed. Water withdrawals are conditioned on Otun River streamflow, based on CARDER's established minimum flow of $5.4 \text{ m}^3/\text{s}$ as required for ecological purposes and human consumption. Water availability could be compromised due to changes in climate patterns, which could increase or decrease the Otun River streamflow. Potential threats include flooding in areas along the riverbank and potential water shortages in Pereira/Dosquebradas, similar to what occurred during the 2015–2016 El Niño event [45,46,71,83]. Due to human activities in the ORW, Otun River water quality has deteriorated and the River is considered a river of concern [35,48]. The river receives untreated wastewater discharges from Pereira's and Dosquebradas' sewer manifolds and, beyond the urban area, has high levels of pesticides and nutrients attributable to agricultural activities conducted primarily in the middle and lower sections of the watershed. Water treatment plants operated by Aguas y Aguas de Pereira use aluminum sulfate, chlorine, caustic soda, and hydrated lime in their operation [84] which has implications for water, since there are losses associated with these processes, and energy due to the energy required to produce these chemicals. Moreover, electricity is used to operate the pumping equipment used to conduct water to the storage tanks.

Due to the dependency on imported food, external factors may have an impact on the availability and prices of some products. In 2016, the consumer price index (CPI) for food in Pereira reached a maximum of 15.4% due to a national trucker strike [85]. Another factor that can impact the prices and availability of food products is the devaluation of the Colombian peso (COP), which can increase the price of some food products. In 2019, the COP shed 20% of its value compared to the U.S. dollar [86]. As an alternative to improve the urban area's food sovereignty, urban agriculture has emerged as a food source, especially for perishable goods. In many cases, food production in cities has been a response to inadequate, unreliable, and irregular access to food, and also the lack of economic means to buy it [87]. Implementation of urban agriculture requires a trade-off among the FEW nexus components; food production uses water and energy that may be hard to access in places where these resources are limited or expensive. However, producing food within the city limits can help to achieve better economic, social, and environmental conditions for urban areas as well as the surrounding rural

areas. Dubbeling et al. [88] indicated that urban and peri-urban agriculture and forestry areas could: reduce “food miles” by producing food near urban markets; reduce urban organic waste by using it as fertilizer; reduce the urban heat island effect by increasing the green surface area; and reduce stormwater runoff by storing and infiltrating the excess water.

The Pereira/Dosquebradas urban area was identified as the center for activities related to the FEW nexus. As a regional hub, these two municipalities have attracted people from Risaralda and other Colombian regions due in part to the buoyant coffee and garment industries, especially during the late 1980s and early 1990s. The population growth and the urban area expansion have put increasing pressure on watershed resources. The occurrence and negative impacts of untreated urban sewer discharges were identified in the ORW characterization. The construction of a wastewater treatment plant in Pereira was included in the city’s 2003–2018 Water Sanitation Plan. Initially, the project was scheduled to be completed by 2025 but due to the regional importance of the project, local and regional authorities decided to expedite its construction. The new schedule indicates that the primary treatment facilities will be completed in 2022 and the secondary treatment in 2025. The wastewater treatment plant is expected to considerably improve the water quality in the Otun River and its tributaries, which receive sewer discharges (Consota River and Dosquebradas Creek). However, it is essential to build additional infrastructure in the urban area to reduce common problems such as those associated with combined sewer overflows (CSOs). A report published by the U.S. EPA [89] indicated that CSOs contain pollutants that are harmful to the environment and human health. Stormwater green infrastructure (SGI) has emerged as an alternative to reduce CSOs, as well as a flood control mechanism in urban areas. SGI includes rain gardens, detention ponds, bioswales, and green roofs, and has been implemented in several cities around the world. Integrating SGI with urban agriculture practices where feasible might reduce the effects of excess urban runoff while also reducing the cities’ high dependency on exported food.

The urban FEW nexus framework developed provides a comprehensive diagnosis of the state of the nexus elements and their interconnections considering: the multiple connections among the food, energy, and water components; the complexity of drawing system boundaries between the Pereira/Dosquebradas urban area and the rest of the ORW; and the need to adapt to future conditions such as those related to population growth and climate. This framework can also be used to develop integrated modeling and decision-making tools that can help policy-makers and local authorities to create alternative water management plans by allowing them to evaluate different future scenarios. Such FEW nexus modeling, however, needs to consider limitations related to availability and reliability of data. Schull et al. [90] evaluated different FEW modeling tools using seven criteria (user-friendliness, flexibility, comprehensive, availability, predictive element, economical component, and water quality). From this evaluation, the GCAM, NexSym, and WEF Nexus Tool 2.0 were selected for further assessment because these tools did not need financial input, extensive data, or multiple software. WEF Nexus 2.0 concepts can be used in the Pereira/Dosquebradas area to estimate the water, energy, and land requirements associated with local and external crop production, and model different scenarios to meet food demand in the urban area. Since the WEF Nexus 2.0 tool is a food centric model, it is necessary to combine it with additional approaches such as material and flow energy analysis (MEFA) and water-centric methodologies to fully explore FEW nexus components as identified and options for water management as relevant to Pereira/Dosquebradas.

The framework developed captures attributes and concerns specific to the ORW. These attributes are also reflective of the Andean region: food production is mainly concentrated in areas located in the eastern part of the country; most of the food products are transported to distributions centers located in the three largest metropolitan areas (Bogotá, Medellin, and Cali), where they are redistributed to intermediate urban areas; hydropower is the main source of electricity generation due to steep slopes and year-round rainfall (which allows the formation of mountain rivers) and deep, narrow valleys that are ideal for the construction of hydropower reservoirs; and surface water is the main source of water while groundwater usage is limited. Thus, the proposed framework can be extended more broadly

to the Andean region. Due to the similarity in the relationships between food, energy, and water in the ORW and Colombia, we expect that the proposed FEW nexus framework could also be used in larger and more complex watersheds in the country. Water quality in streams associated with wastewater discharges is an area of concern in several watersheds. Some cities do not have centralized wastewater treatment facilities; as a result, there are raw sewage discharges into the streams. Currently, only approximately 42% of the wastewater receives any type of treatment. The national government expects that by 2022 the wastewater treated will reach 54%, with priority watersheds including the Otun River Watershed. Additionally, as hydropower is the major source of electricity in the country, increasing energy demand will require construction and/or installation of new hydropower infrastructure. From the 94 active projects reported in July 2020 by the Mining Energetic Planning Unit (UPME), 89 projects are run-of-the-river hydropower plants. These projects are expected to be operating within the next five years.

3.3. Caveats

Water quality characterization revealed that the degradation occurring in the Otun River was largely due to the urban area. The available data were, however, limited and might not have provided a complete representation. For example, some of the higher concentrations observed for some of the selected water quality parameters could be attributable to agricultural activities upstream of the urban area (e.g., releases from the aviary or fisheries farms and/or wash-off of agrochemicals used in green onion crops). Furthermore, there were indications of pesticide contamination from agricultural areas based on the literature, yet data were not available to enable areas of concern to be established definitively. Another phenomenon occurring at the ORW is that seasonal sampling may be overlooking the impact of informal urban settlements on the river's water quality. One seasonal sample showed concentrations for TS, TSS, and turbidity 50 times higher than the median concentrations at the Quebrada El Calvario station (station 11). This station is located in an informal development area. In 2010, the city of Pereira reported that a decrease in DO levels and an increase in TSS concentrations may have been due to direct discharges of residential wastewater into the stream [91]. Otun River degradation may cause a large impact downstream since this river is a tributary of the Cauca River, an important river in the Magdalena-Cauca hydrological area. For this reason, it is necessary to increase the sampling frequency and include pesticides in the monitoring, especially as related to areas that have previously been flagged as possible sources of contaminants. The current sampling protocol implemented in the ORW consists of taking seasonal water samples (3 per year) at the 19 sampling stations selected by CARDER. Seasonal sampling does not include samples taken from April through June. Since April was identified as the month with the most rainfall in the ORW, samples taken in April/May might be more representative of the Wet1 season.

The characterization completed for the ORW included an assessment of land-use/land-cover changes in the watershed. Due to the coarse nature of the land-use data obtained for the region, all changes in land use/land cover could not be captured. Therefore, it was not possible to conduct an in-depth analysis of the impact of land use on the Otun River's water quality. Regardless of this limitation, we were able to identify the urban area as the major source of contaminants in the Otun River. Moving forward, it is necessary to conduct a detailed land-use evaluation of the ORW using datasets with a higher spatial resolution and digital images, as available, as well as in situ visits to conduct a ground-truthing.

The processes used for energy production in the region are very water-intensive. The use of biofuels, solar, and wind energy is minimal in the region; therefore, these latter sources were not included in the framework. Evaluation of alternative energy sources for the region would provide insights into potential trade-offs between energy and water. The use of alternative water sources such as wastewater reuse can also be explored.

FEW nexus methodologies and frameworks have been widely used to improve the understanding of synergies among the different nexus elements, which can help decision makers implement actions

to optimize resource use and management. However, the implementation of a FEW nexus approach is often limited by the lack of reliable data and the limited number of proven nexus framework applications, for example, in Latin American. Moving forward in the implementation of the proposed FEW nexus framework, additional models, tools, and databases will be needed to obtain a comprehensive view of the nexus and analyze trade-offs, with a view to protecting water resources in the region. A FEW nexus approach is thought to be a more suitable approach to water management than IWRM where there are multiple interactions among food, energy, and water systems [2,3]. A comparison between a FEW nexus approach and IWRM or other water management approaches would be needed in order to draw definitive conclusions for the ORW. However, such an assessment is beyond the scope of this study.

4. Summary and Conclusions

In this study, a characterization was conducted for the Otun River watershed based on which a framework for water management in the FEW nexus was developed. The characterization completed for the ORW presented a portrait that can be found in other Colombian watersheds, particularly in the Andean region. Urban growth and expansion have increased food, energy, and water demand in urban centers. The urban areas rely on food produced outside of their corresponding watershed, which makes cities vulnerable to external factors that can affect the food production chain such as extreme weather, currency devaluation, policy changes, and transportation infrastructure. On the other hand, this means that there is less pressure on water resources in the watershed related to food production. Key pressures on water resources in the study area as identified were primarily related to electricity generation and water quality impairment, both of which were attributable to population growth and associated urban expansion. Thus, the framework developed in this study revolves around the urban area and includes water quality and risks as additional dimensions in the water component. This framework provides a basis for improved water management in the Pereira/Dosquebradas urban area and is extendable to other urban areas in the Andean region of Colombia. Moreover, since a comprehensive FEW nexus analysis has not been completed in the Colombian context, results obtained from subsequent FEW nexus modeling will help provide insights applicable in a broader context considering climate, population growth, geospatial/temporal variations, and socio-economic changes. This work provides additional insights and approaches that will aid in the reduction of the existing gap in FEW nexus literature in Latin America.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2071-1050/12/24/10332/s1>, Figure S1. Mean rainfall corresponding to each day of the year (DOY) for the ORW stations (2005–2018); Figure S2. Relationship between number of wet days and total annual rainfall for weather stations in the ORW (2005–2019); Figure S3. (a) Number of days with daily average temperatures above, equal, and below coffee's optimal growth temperature (19–21 °C) based on data from Matecaña Airport. (b) Thermal time accumulation for harvest cycles from 1982 to 2019 based on data from Matecaña Airport. Harvest cycles 1-01 to 1-25 corresponded to the life cycle for the first coffee shrub and harvest cycles 2-01 to 2-11 corresponded to the life cycle for the second coffee shrub; Figure S4. (a) Change in croplands, forests, and grasslands in the Otun River Watershed from 2001 to 2005; (b) Change in croplands, forests, and grasslands in the Otun River Watershed from 2005 to 2009; Figure S5. (a) Change in croplands, forests, and grasslands in the Otun River Watershed from 2009 to 2013; (b) Change in croplands, forests, and grasslands in the Otun River Watershed from 2013 to 2017; Figure S6. Water quality results at different sampling stations across the ORW. Sampling station (SS) 1: Otun River (OR)-Otun Lake, SS2: OR after El Mosquito Lake, SS3: OR-El Cedral, SS4: Barbo River-Outlet, SS5: OR-El Reten EEPP, SS6: El Manzano Creek-La Florida bridge, SS7: OR-La Bananera, SS8: OR-Nuevo Libare Intake, SS9: OR-after San Jose Creek, SS10: OR-After Otun glassworks, SS11: El Calvario Creek outlet, SS12: OR-after Carrefour, SS13: Dosquebradas Creek-outlet, SS14: OR-Egoya sewer outlet, SS15: OR-After Egoya sewer discharge, SS16: OR-La Marsella bridge, SS17: OR-after Belmonte, SS18: OR-After Glorita landfill, SS19: OR outlet; Figure S7. Food and energy flows for Pereira; Table S1. List of Weather, streamflow, and water quality stations used in the characterization of the ORW; Table S2. Rainfall data completeness for stations during the period in common (2005–2019); Table S3. Statistical properties and essential characteristics of seasonal rainfall for ORW stations (01/01/2005–12/31/2019); Table S4. Gains, losses, net changes, and persistence of land uses in the ORW; Table S5. Non-parametric trends for selected water quality parameters at the ORW; Table S6. Seasonal Mann-Kendall test results for all water quality stations located in the ORW; Table S7. Seasonal Mann-Kendall test results for water quality stations located in the ORW's urban area.

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