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Puebla City Water Supply from the Perspective of Urban Water Metabolism

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Abstract: The city of Puebla is a mid-sized Mexican city facing multiple water-related challenges, from overexploitation of water sources and extreme pollution of rivers to water conflicts and contestation processes due to the privatization of water supply. Due to the complexity of urban water systems and their relevance for urban life, a holistic and integrative perspective is therefore needed to inform policymakers addressing such challenges. In this paper, Urban Water Metabolism (UWM) has been used to offer a comprehensive understanding of current water insecurity in the City of Puebla and its metropolitan area. Water inflows and outflows have been estimated using the Material Flow Analysis (MFA) method with data either obtained from official sources or simulated with the Monte Carlo method. Our findings show that the UWM configuration in the City of Puebla and its metropolitan area is effective for generating profits for service providers and water-related businesses, yet ineffective for guaranteeing citizens' Human Right to Water and Sanitation (HRWS), a right recognized in the Constitution of Mexico. We conclude that to advance towards an inclusive and sustainable long-term provision of water, economic goals must follow socio-ecological goals, not the other way around. We consider UWM accounting useful for informing policy and decision-making processes seeking to build a new water governance based on both the best available knowledge and inclusive and vibrant social participation.

Keywords: Urban Water Metabolism; city of Puebla; urban sustainability; human right to water and sanitation; water governance

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1. Introduction

More than half of the world's population currently lives in cities [1]. By 2050, the urban population is expected to reach 68.4% of the total population due to the addition of 2.43 billion urban inhabitants [2]. By the same year, the urban population in Latin America and the Caribbean is projected to reach 90% of the total population [3]. Under a tendential scenario, population growth will translate into a higher demand for resources, including water [4]. Water availability is compromised due to overexploitation, pollution, and the impacts of climate change in mid-latitudes [5–7]. In the case of the volcanoes in the vicinity of the city of Puebla (Popocatepetl and Iztaccihuatl), the main climatic factor causing glacier retreat is the decrease in precipitation [8]. A trend towards the disappearance of glaciers will be observed in the coming decades, and this is expected to imply a decrease in the availability of fresh water [9].

Part of the Megalopolis Central Region, the City of Puebla and its metropolitan area (which comprise the State of Tlaxcala) are the fourth largest metropolitan areas in Mexico after those of Mexico City, Monterrey, and Guadalajara [10]. Its population has grown consistently from 1.76 million inhabitants in 1990, 2.27 million in 2000, and 2.72 million in 2010, up to 2.94 million inhabitants in 2018 (of whom 1.67 million resided in the "central city" or the municipality of Puebla) [11]. Due to population growth and the advancement of industrial activities, water sources have been increasingly exploited, quickly reducing the average annual water availability of the local aquifer from 44.64 Mm^3/yr in 2015 to 20.66 Mm^3/yr in 2020 [12,13].

To move towards a long-term sustainable use of water and certainly to address urban sustainability, a comprehensive perspective is required to grasp the complexity of the challenge [14]. Urban Metabolism (UM) is an appropriate approach that has its historical origins in the concept of "social metabolism" in Marx's economic theory [15,16]. This concept regained relevance when applied to cities due to Abel Wolman's article "The Metabolism of Cities" [17]. The UM metaphor implies understanding a city analogously to a living organism that feeds, accumulates, and excretes energy and matter, involving the use of certain information for decision-making (scare and poor information presuppose limited capacities for decision-making) and, in some cases, considering mechanisms for "closing cycles", which are at the base of urban circularity [18]. This holistic approach to urban metabolism accounting helps to interweave into a central model urban energy and material inflows, distribution, outflows, and the potentiality for circularity, allowing us to understand much better the regulating functions that shape such metabolic processes and the associated multidimensional impacts, synergies, and trade-offs. According to Kennedy et al., UM is defined as "the total sum of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste" [4]. Similarly, Urban Water Metabolism (UWM) refers to the UM metaphor applied only to water flows.

UM and UWM studies have been frequently associated with engineering notions of water management and, thus, more traditional industrial ecology approaches, yet there has been a hybridization with other inter and transdisciplinary disciplines and fields of knowledge [19,20]. Studies vary from the assessment of multiscale institutional programs [21], the evaluation of city water (in)efficiency [22–24] or the integration of the urban nexuses approach to UM or UWM studies (e.g., Water-Energy-Carbon Nexus) [25–28], to the analysis of climate change implications and health impacts of pollution in UM and UWM [29–31]. Some of them include returning flows and moving from linear to circular UM approaches [32–35]. Some UM and UWM studies have also analyzed economic, political, and sociocultural aspects that have triggered injustices and conflicts in different historical and spatial contexts [36–40].

In Latin America, the number of UM studies is noticeably lower compared to Europe, the USA, or Asia [41], and only a fraction of them specifically deal with water. Some works critically apply the concept without actually quantifying its flows, such as the case of the peri-urban planning of the metropolitan areas of Guadalajara and Ocotlán [36], the analysis of power relations associated with water distribution in Cuautla [42,43], the case study of the metabolic rupture in Morelia [44], the study of disputes related to the pollution of the Santiago River in Guadalajara [45], and the case dealing with the socio-economic drivers and implications of the complex urban growth of Mexico City [44]. Other studies, such as the study of energy use in Mexico City's water supply [46] include some quantitative elements of the MHU. Other studies, such as the MHU analysis of the Central and Western Metropolitan Areas in Colombia [47], the water-energy-pollution nexus study in Purísima del Rincón in Guanajuato [48], and the studies of climate vulnerability in the geographic space of Mexico City [49] and Kingston [50] provide more detailed information on the internal processes of their systems. Some other studies present a material balance of the entire system and its sub-processes; for example, this study focused on wastewater management in Tepic Nayarit [51] and the MHU study of two water-dependent megacities in regions such as Mexico City and Los Angeles, California [52].

In the case of the city of Puebla, the historical evolution of the appropriation of water and its relationship to power struggles, wars, and socioeconomic transformation were analyzed within the framework of social metabolism [53,54]. Besides water availability and quality studies [55–70], a study evaluating the potential for rainwater harvesting in parking lots, utilizing a system dynamics model, is the most similar quantification exercise, yet it only pays attention to one fraction of urban water flows in the city of Puebla [71].

Many UWM studies conducted in Latin American cities are critically biased given the prevailing urban informality and the persistent inequalities of their populations, both features usually not considered in UWM study design. In addition, the common lack of public information and issues with the consistency of the existing data may also contribute to the limited number of quantitative UM and UWM studies. Furthermore, most of the UM and UWM case studies have focused on large cities, neglecting the analysis of small and medium-sized cities, even though the latter are expected to grow the most in the coming decades [41]. Less than half of the studies mentioned above incorporate analysis of water flows from bottled and tanker trucks, and no one analyzed elements of the HRWS with a quantified UWM model. No UWM studies have been identified for the case of the City of Puebla and its metropolitan area, neither in Scopus, the Web of Science, nor Google Scholar. We aim to contribute to filling the aforementioned gaps with the first accounting of UWM in the city of Puebla, as said, a medium-sized city struggling with limited water availability, increasing exploitation of the Puebla Valley Aquifer (PVA) [68–70,72], inefficient and inequitable distribution of water [40,71], service cuts to dwellings due to non-payment, excessive charges for users [73], water contamination, and prevalence of diseases in communities nearby contaminated water bodies [55,56,58,63,74–76], as well as with water-related socio-environmental conflicts [38,77] within the context of privatization of the public water service (which legally took place in December 2013).

Water flow accounting and balancing were based on the Material Flow Analysis method, which was supplied with official data. To fill in the non-existing data on bottled and trucked water flows, we used a Monte Carlo simulation. Rainfall and runoff over the urbanized surface have been estimated in accordance with the national standard NOM-011-CONAGUA-2015 [78] (CONAGUA is the acronym for the National Water Commission, whose main objective is to manage, regulate, control, and protect all of Mexico's water resources). Its jurisdiction is nationwide. The UWM approach applied to the city of Puebla has allowed us to grasp the diversity and complexity of urban water issues from a systemic perspective, relating the magnitudes found through the model to HRWS-related water problems or those associated with expressions of social contestation. We believe that the UWM model has the potential to empower stakeholders by providing relevant data and information, ultimately enabling, yet not guaranteeing, transformative processes that may lead to more sustainable, inclusive, and equitable urban water governance [79].

2. Materials and Methods

The MFA method was applied to estimate the UWM of the City of Puebla and its metropolitan area [80], with the support of the software STofflussANalyse (STAN) version 2.6 developed by the Vienna University of Technology (https://www.stan2web.net/, accessed on 30 June 2023). Water loss by electrolysis was considered negligible. Energy flows and CO_2e emissions, the distribution and drainage networks' weight, and materials related to drinking and wastewater treatment, which were estimated only for the water utility's processes, were calculated. The consumption of virtual water and indirect energy consumption associated with the UWM of the City of Puebla and its metropolitan area were not estimated.

2.1. UWM Conceptual Model and Its Energy and Carbon Nexus

Our water system model is composed of two subsystems: a biophysical subsystem and a social subsystem. The first one corresponds to natural water dynamics, i.e., the hydrological cycle. The second one relates to the social dynamics that shape and reshape our first subsystem and the system as a whole. Those dynamics, following González de Molina and Toledo [81] are appropriation, transformation, circulation, consumption, and excretion.

Appropriation refers to withdrawals from the surface, groundwater, and rainwater harvesting. Importation refers to water appropriated from outside the spatial limits of this study and consumed within the city. Transformation refers to the water utility's potable and wastewater treatment processes and the Local Purified Water Companies (LPWC) (see the following article for more information on LPWC in the city of Puebla and their water quality issues [82]). Circulation refers to water distribution, either through pipe networks, water trucks, or bottles, from its sources to consumption and excretion. It is at this stage that the Human Right to water may or may not be guaranteed to all urban inhabitants. Consumption refers to the multiple uses of water and is the process that drives the rest of the UWM processes. The excretion process alludes to the return of treated or untreated water to the biophysical subsystem through evaporation, leakages, and losses along the distribution network or within dwellings. In this last stage, the Human Right to Sanitation is in play. See Figure 1.

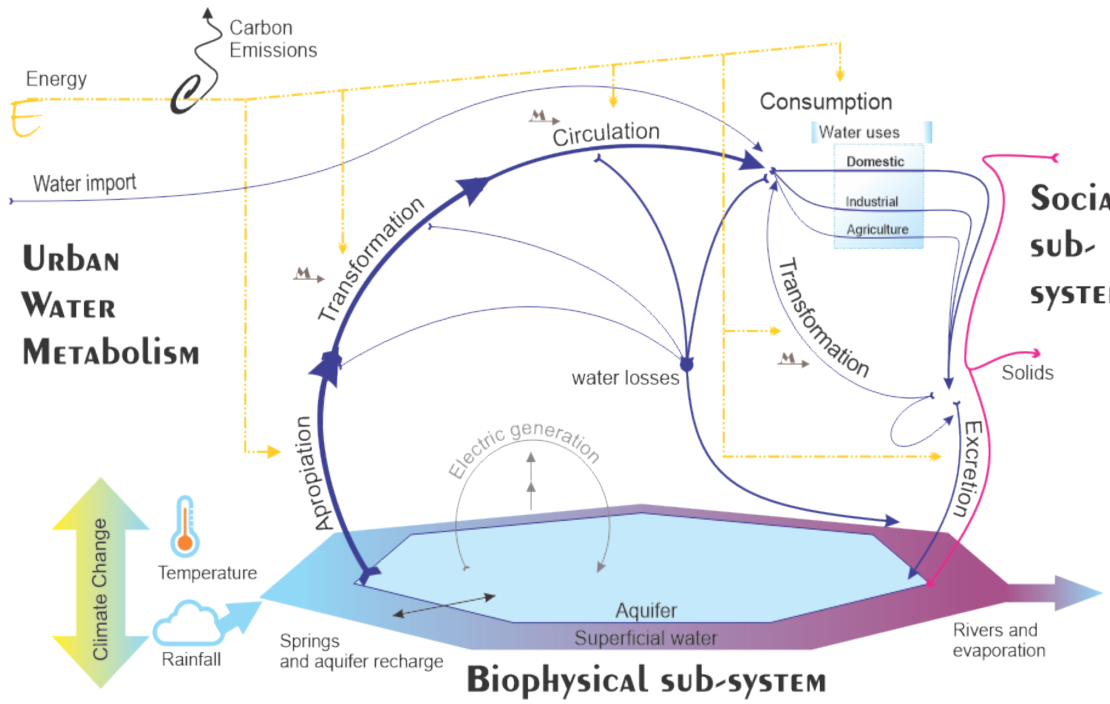


Figure 1. Urban Water Metabolism and its nexus with energy and carbon conceptual model. Authors' own elaboration.

It is to be pointed out that due to the complex dynamics of the natural water cycle, the spatial unit of analysis does not correspond to or is not limited to the urbanized area but rather the local aquifer area, as explained further in the following section.

2.2. Study Area Delimitation

The model was built in two resolutions due to the irregular quality of the available data: the first, with lower resolution, corresponds to the 25 municipalities outside the central city but within the Puebla Valley Aquifer (PVA) area; the second, with higher resolution, corresponds to the Municipality of Puebla or the central area of the City of Puebla; see Figure 2.

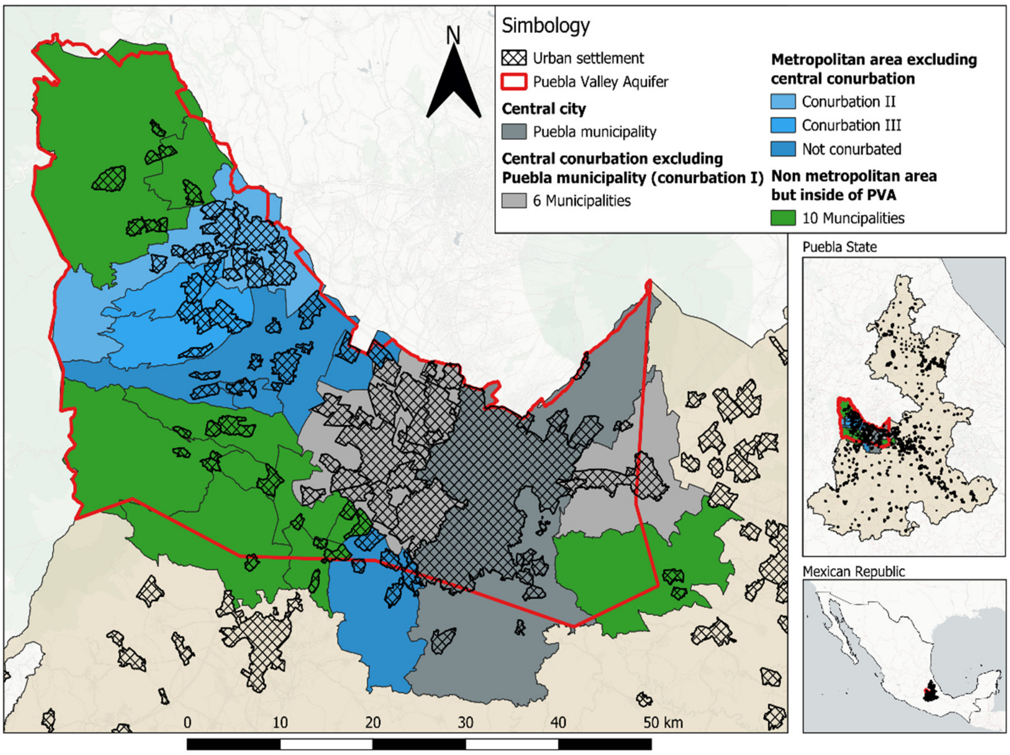


Figure 2. Delimitations of the study area. Authors' own elaboration.

The PVA extends approximately 2025 km^2 and intersects with 26 municipalities; 20 of them are within the model's delimitation, and six are partially within [13]. The considered area was subdivided into zones according to their degree of urbanization:

- Non-metropolitan area within the PVA
    - Ten municipalities outside the metropolitan area of the City of Puebla: Calpan, Cuautinchan, Nealtican, San Gregorio Atzompa, San Jerónimo Tecuanipan, San Matías Tlalancaneca, San Nicolás de Los Ranchos, Santa Isabel Cholula, Tianguismanalco, and Santa Rita Tlahuapan
- Metropolitan area outside of the central conurbation
    - Ten municipalities in the metropolitan area of Puebla have urban settlements with no adjacency to the central conurbation.
        i. Conurbation II: San Martín Texmelucan, San Salvador el Verde
        ii. Conurbation III: Chiautzingo, San Felipe Teotlalcingo
        iii. Non-conurbated: Domingo Arenas, Huejotzingo, Ocoyucan, San Miguel Xoxtla, and Tlaltenango.
- Central conurbation
    - Five municipalities contiguous to Puebla central city comprise our conurbation I: Amozoc, Coronango, Cuautlancingo, Juan C. Bonilla, San Andrés Cholula, and San Pedro Cholula.
- Puebla central city
    - Puebla is a "historical" city located in the municipality of Puebla. Its surface area is approximately the same as the one covered by the water utility system called "*Sistema Operador de Agua Potable y Alcantarillado de Puebla*" (SOAPAP). SOAPAP is the acronym for Sistema Operador de los Servicios de Agua Potable y Alcantarillado del Municipio de Puebla, a decentralized public organization

of the State of Puebla whose purpose is to provide drinking water, sewerage, and sanitation services. Its jurisdiction is the municipality of Puebla and part of the surrounding municipalities; however, its functions are concessioned to a private company (a water utility). This decentralized agency regulates the private concessionaire company that provides potable water service in Puebla City.

2.2.1. Estimation of the Hydrological Cycle in PVA

Groundwater use data for 2020 was obtained from the National Water Commission—CONAGUA [13] and was balanced with precipitation and surface runoff water flows, which were calculated according to the Mexican official standard NOM-011-CONAGUA-2015 [78] with precipitation historical data from 14 meteorological stations (21,065, 21,248, 21,120, 21,163, 29,170, 21,101, 21,247, 21,034, 21,249, 21,016, 21,046, 21,167, 21,223, 21,214) of Mexico's National Metrological Service and soil type information for the region. Data was processed using Geographic Information Systems (GIS); see Figure 3. In the PVA region, surface runoff entering from surrounding regions was not integrated due to a lack of information. The method used to estimate surface runoff has also been used by Martínez-Austria [71].

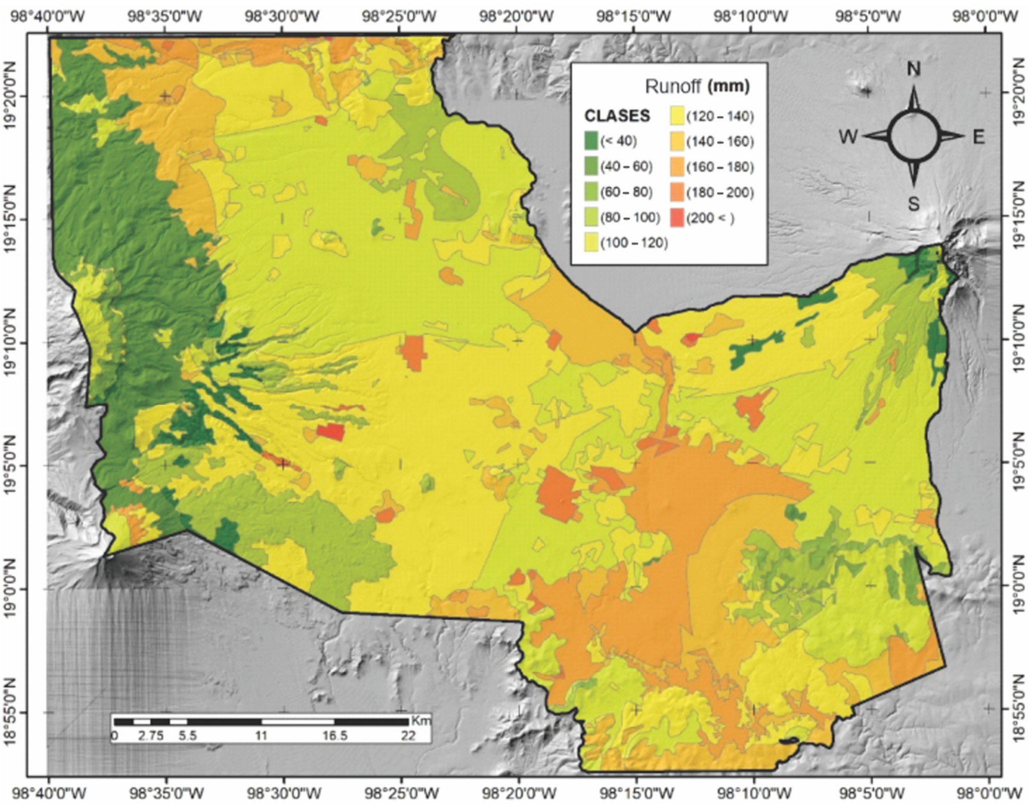


Figure 3. Water runoff in PVA. Authors' own elaboration.

2.2.2. Estimating UWM in the PVA, Excluding the Central City of Puebla

A balance of water inflows and outflows was carried out. Water use and discharge data for 2019 was obtained from CONAGUA's National Registry of Water Rights (*Registro Público de Derechos de Agua*—REPDA, for its acronym in Spanish). (REPDA is the acronym of the Public Registry of Water Rights and is a platform created by the National Water Commission (CONAGUA), in which are registered the titles of concession, transfer, and authorization of water use in Mexico, as well as their renewals, suspensions, terminations, and acts related to the total or partial transfer of the rights covered by the titles and authorizations) available at https://app.conagua.gob.mx/ConsultaRepda.aspx, accessed on 30 June 2023. Due to the absence of empirical data, the withdrawal and discharge concessions were considered a proxy for actual flows. CONAGUA also determines water availability per aquifer using the REPDA (in the following link, you can find the latest official document called "the update of the average annual water availability of the Puebla Valley aquifer" [13]). https://sigagis.conagua.gob.mx/gas1/Edos_Acuiferos_18/puebla/DR_2104.pdf, accessed on 15 July 2021.

2.2.3. UWM Estimation for Puebla Central City

A balance of water inflows and outflows was made with 2018 and 2019 data obtained from SOAPAP through both direct contact with the institution's personnel and public solicitations of information (www.plataformadetransparencia.org.mx, accessed on 30 June 2023). Due to the lack of official records on bottled water consumption and water distributed by tanker trucks, such data was estimated using a Monte Carlo simulation.

2.3. Estimation of Water Flows without Official Records with Monte Carlo Simulation

Due to the lack of official records, a Monte Carlo simulation was utilized to estimate the volume of bottled water and water transported by tanker trucks. Figure 4 summarizes the induction method used. For further details, see the Supplementary Materials document.

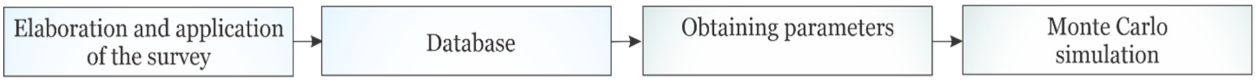


Figure 4. Summary of induction method for tanker truck and bottled water flows. Authors' own elaboration.

2.3.1. Survey Data Collection

Two surveys were designed to collect quantitative and qualitative information:

- The first survey comprised 30 questions addressed to the general public with the objective of collecting information on water service and consumption in dwellings. It was distributed online using Google Forms to informants selected using a snowball method (we acknowledge that a probabilistic sampling method is preferable to the non-probabilistic snowball sampling we used). The survey was written in colloquial language with multiple-choice answers accompanied by images to facilitate understanding by the non-specialized public. It was structured according to different thematic axes referring to information on dwelling infrastructure, water storage habits, and the intensity of water consumption obtained through tanker trucks and bottled water. In 2021, the survey was conducted on 256 residents in the context of COVID-19 pandemic preventive measures. Using this sampling method along with online tools like Google Forms helped us overcome the challenges imposed by limited research resources and pandemic health constraints. Other studies in the same context have successfully used a similar methodology [83].
- The second survey consisted of seven questions applied on-site to five LPWCs in 2021 to gather information on their purification processes and water supply areas.

2.3.2. Monte Carlo Simulation for Water Flow Induction

The Monte Carlo simulation was performed using the 64-bit Crystal Ball version 11.1.2.4.900 in Excel [80]. The following postulates and assumptions were established for information processing:

Postulates: The maximum possible amount of water distributed by a tanker truck to a dwelling is equal to the maximum water storage capacity of the dwelling; a fraction of the total dwellings require water service by tanker truck and bottled water; hence, we must approximate that fraction to approximate tanker truck water consumed.

Assumptions: Based on field observations, we determined to add 500 L of storage capacity to the city's dwellings that store extra water in sinks, floor-level water tanks (*tinacos*), barrels, jars, or buckets. To deal with the water shortages and intermittent water service in the city, households often store additional water. Intermittent water service is commonly referred to as "tandeo" and can range from daily to only a few hours per week. The average capacity of a tanker truck is 10,000 L; The capacity of carboys is 20 L, the average capacity of a carafe is 5 L, and that of a bottle is 1.5 L. Sugared and carbonated beverages were not considered. The average price in 2021 of a big brand (the term "big brand" bottled water refers to water sold in supermarkets, many of them belonging to large companies such as Nestlé or Coca-Cola, among others) water carboy (Bonafont, Epura, Ciel, etc.) was USD1.90, while the average price of other carboy brands was USD1.70. The average price of a bottle of water and that of LPWC carboys was USD0.60. In 2021, the exchange rate was around 20 Mexican pesos for every 1 USD.

The Monte Carlo simulations followed the next procedure. First, the maximum, minimum, mode, and correlation between variables' statistical parameters were estimated for the data collected in the survey, which were used to parameterize the probability distributions of each variable shown in Table A4. Two probability distributions were used, and the selection criterion was that for the Beta PERT distribution. It is considered more confident that the values are concentrated around the mode, while with the triangular distribution, there is more dispersion in the data. Subsequently, 20,000 simulations were applied.

2.3.3. Estimated Flow Rates Distributed by Tanker Truck in the Central City

The total water storage capacity for each dwelling is the sum of the water tank capacity plus the water cistern capacity (C_{wt+cis}) and the extra storage capacity per dwelling (C_{extra}) Equation (1).

$$C_{dwelling} = C_{wt+cis} + C_{extra} \quad (1)$$

The dwellings were classified into two groups according to how they accumulate water. The first group refers to multifamily dwellings that usually store water in water tanks or elevated cisterns (commonly multifamily apartments). The second group relates to dwellings with a cistern (commonly single-family dwellings).

Equations (2)–(4) were then operated on with Monte Carlo simulation (Table A1).

$$Q_{tanker-t,\mathrm{cis}} = Ac * Pc * Rc * Mcp * V/10^9 \quad (2)$$

$$Q_{tanker-t,\mathrm{wt}} = At * Pt * Rt * Mtp * V/10^9 \quad (3)$$

$$Q_{tanker-t} = Q_{tanker-t,\mathrm{wt}} + Q_{tanker-t,cis} \quad (4)$$

2.3.4. Estimation of the Accumulation Capacity in City Dwellings

To estimate the accumulation capacity in the dwellings with a water tank (A_{wt}) and a cistern (A_{cis}), we suppressed the terms for the number of tankers (*Pc*, *Pt*) from Equations (2) and (3), resulting in Equations (5) and (7).

$$A_{cis} = Ac * Rc * Mcp * V/10^9 \quad (5)$$

$$A_{wt} = At * Rt * Mtp * V/10^9 \quad (6)$$

$$A_v = A_{wt} + A_{cis} \quad (7)$$

2.3.5. Bottled Water Flow Estimation

The flow rate of bottled water consumed in each dwelling surveyed (L_v) was estimated by multiplying the number of containers purchased in each dwelling. (*E*) by the storage capacity of each type of container (*cap*). The resolution of the information allowed us to differentiate between containers (carboys, carafes, and bottles from big-brand purifiers). Equations with subscripts 1 to 3 refer to water from big-brand purifiers, and equations with subscript 4 refer to carboys from LPWCs (Equations (8)–(11)). A distinction was made between the magnitudes of big brands and LPWC bottled water to estimate and compare their costs.

$$l_{v1} = E_1 * cap_1 \tag{8}$$

$$l_{v2} = E_2 * cap_2 \tag{9}$$

$$l_{v3} = E_3 * cap_3 \tag{10}$$

$$l_{v4} = E_4 * cap_4 \tag{11}$$

For each dwelling surveyed, the liters consumed (l_v) were calculated, followed by a Monte Carlo simulation to estimate the total flow rate (Q) for each type of container (Equations (12) and (15)). The total flow of bottled water supplied in the city is equal to big-brand bottled water plus bottled water from LPWCs (Equations (16) and (17) and Table A2).

$$Q_{em1} = l_{v1} * Rba * V * 365/10^9 \tag{12}$$

$$Q_{em2} = l_{v2} * Rba * V * 365/10^9 \tag{13}$$

$$Q_{em3} = l_{v3} * Rba * V*365/10^9 \tag{14}$$

$$Q_{er} = l_{v4} * Rba * V * 365/10^9 \tag{15}$$

$$Q_{em} = Q_{em1} + Q_{em2} + Q_{em3} \tag{16}$$

$$Q_e = Q_{em} + Q_{er} \tag{17}$$

2.3.6. Estimating the Costs of Water Distributed in Tanker Trucks and Bottled Water

Under the assumption that tanker and bottled water are distributed in containers of known capacities (C), it is possible to approximate the number of containers needed (R) to move the water flow (Q) (Equations (18)–(22)). Monte Carlo simulation was not applied in this procedure.

$$R_{tanker-t} = Q_{tanker-t}/C_{tanker-t} \tag{18}$$

$$R_{em1} = Q_{em1}/C_{em1} \tag{19}$$

$$R_{em2} = Q_{em2}/C_{em2} \tag{20}$$

$$R_{em3} = Q_{em3}/C_{em3} \tag{21}$$

$$R_{er} = Q_{e4}/C_{em4} \tag{22}$$

The total costs for water distributed by tanker truck and bottled water resulted from multiplying the total number of containers by the unit price of each container (Equations (23)–(29) and Table A3).

$$Pt_{tanker-t} = Pu_{tanker-t} * R_{tanker-t} \tag{23}$$

$$Pt_{em1} = Pu_{em1} * R_{em1} \tag{24}$$

$$Pt_{em2} = Pu_{em2} * R_{em2} \tag{25}$$

$$Pt_{em3} = Pu_{em3} * R_{em3} \tag{26}$$

$$Pt_{er} = Pu_{er} * R_{er} \tag{27}$$

$$Pt_{em} = Pt_{em1} + Pt_{em2} + Pt_{em3} \tag{28}$$

$$Pt_e = Pu_{em} + Pu_{er} \tag{29}$$

2.4. Energy Consumption and CO_2e Emissions of the Water Utility

Energy intensity data for each process was obtained from SOAPAP's energy consumption and flow rates [84]. Carbon emissions were estimated by multiplying the amount of water consumed by the coefficient of CO_2e emissions per unit of energy [85]. Due to a lack of information, energy consumption beyond SOAPAP processes was not estimated.

2.5. The Human Right to Water (HRW) Indicator and Efficiency (R_{HRW_E})

Calculating the ratio of bottled water and water transported by tanker trucks as a function of total water consumption for domestic use (Qc_{dom}) provides an idea of water acceptability, accessibility, and sufficiency. This, in turn, results in higher water costs and impacts water affordability. This indicator also provides information on decreasing energy efficiency since these two alternative water supply options involve the use of motor vehicles and, in the case of bottled water, the addition of the purification and bottling processes. If the ratio is zero, it indicates that tap water service is likely to provide sufficient, accessible, and acceptable water. As the percentage increases, it suggests that the city's inhabitants face more significant challenges with HRW due to prevailing challenges with water acceptability, accessibility, and sufficiency, hand in hand with increasing household expenditure on water.

$$R_{HRW\_E} = \frac{Q_{tanker-t} + Q_{em}}{Q_{Cdom}} \tag{30}$$

Calculating the HRW indicator for the city from the UWM perspective shows that this approach also helps to identify and thus enable mechanisms that may prevent the undermining of the social floor in Kate Raworth's terms [86].

3. Results and Discussion

In the following section, UWM accounting for the City of Puebla and its metropolitan area is described, starting with the hydrological cycle of the PVA according to the delimitations illustrated in Figure 2.

3.1. The UWM as an Embeded Element of the PVA Hydrological Cycle: The Biophysical Subsystem

The UWM of the City of Puebla and its metropolitan area operates within the hydrological cycle of the PVA region. This region receives 2011.21 Mm^3/yr of precipitation, which feeds the surface runoff of the region with 305.95 Mm^3/yr, while 1588.75 Mm^3/yr is evapotranspired. The runoff coefficient calculated using the method specified in NOM-CONAGUA-2015 was 0.152, and it refers to the entire study area, which includes crop fields, forests, rural settlements, and the built-up area of the city. For the built-up area of the central city of Puebla in particular, the runoff coefficient was estimated to be around 0.238, although it could be higher considering that other cities have a higher value. Other studies conducted in the city of Puebla reported a lower runoff coefficient of 0.116 for vegetated areas and 0.169 for covered areas [71]. In a similar study in Mexico City, the exact runoff coefficient was not specified, but it is estimated to be around 0.26 based on the model data [87]. In other UWM studies, the runoff coefficients for Sydney, Melbourne, South East Queensland, Perth, and Bangalore are 0.29, 0.22, 0.38, 0.22, and 0.38, respectively [22,23]. The values for the last five cities were taken from other studies [88,89].

The PVA receives 116.5 Mm^3/yr as vertical recharge, plus 196.8 Mm^3/yr that enters as a horizontal flow into groundwater from the surrounding aquifers; 43.62 Mm^3/yr have an anthropogenic origin produced by leaks in the distribution or drainage networks and irrigation. The above three flows total 356.92 Mm^3/yr of total PVA water recharge.

The aquifer's water storage decreases by 38.29 Mm^3/yr, causing a decrement of the annual average static water level of 2 m. In some areas in the south of Puebla's central city, the static water level has decreased by up to 80 m between 1973 and 2002, or an average annual decrease of 2.75 m [13,69]. The current decline in water levels should be more severe, compromising regional water security [66,67]. Overexploitation of the aquifer implies risks in soil mechanics, which can generate soil subsidence and mega-sinkholes such as the one that appeared in 2021 in Santa María Zacatepec (Santa María Zacatepec is a town in the municipality of Juan C. Bonilla, adjacent to Puebla municipality) [90].

The University Center for the Prevention of Natural Disasters (Cupreder) (Cupreder is the acronym of the University Center for the Prevention of Regional Disasters, a dependency of the Autonomous University of Puebla, whose mission is to study the processes that generate disasters and the calamitous experiences that have occurred in the region) discovered irregularities in the PVA's official data update documents. The document, which provides information to policy officials on whether new water permits can be issued, reported a 20 Mm^3/yr increase in PVA recharge from 2013 to 2016 (from 339 Mm^3/yr to 360 Mm^3/yr) [12,91–93]. Such an increment has once again been reported in CONAGUA's 2020 update [13]. The update concludes that the same 20.6 million cubic meters per year are available for new concessions. CONAGUA's data would imply the occurrence of improbable factors such as an increase in annual precipitation, a decrease in urban sprawl, and/or changes in the geophysical conditions of the aquifer. If the recharge of the PVA were based on what was indicated for the year 2013, our analysis indicates that there would no longer be available water for new concessions, which would be highly problematic for keeping pace with the real estate market's dynamism, mostly residential housing and industrial parks [94–98]. The total surface water and groundwater inflows to the PVA region are 662.88 Mm^3/yr.

The UWM model is a valuable tool for analyzing water sustainability. It combines groundwater and surface water availability analysis with water demand and aquifer recharge through rainfall, as Scott suggests [31]. This conjunctive analysis is crucial within the context of climate change and the necessary adaptation strategies in a city like Puebla, where the aquifer, as the main source of water, will be affected by rainfall patterns, glacier preservation of surrounding volcanoes, and indeed by potential changes in water consumption patterns.

3.2. Urban Water Metabolism in the PVA Region

As shown in Figure 5, water extracted from the environment totals 671.83 Mm^3/yr, comprising 300.16 Mm^3/yr of surface water and 334.01 Mm^3/yr of groundwater. Of the withdrawn water, 35.2% is excreted as concession discharges, 8.4% as flows related to induced recharge, and 56.5% are undefined discharges between evaporation, electricity generation discharges, or non-concession discharges. Flows with a magnitude of 1.505 Mm^3/yr and 36.156 Mm^3/yr correspond, respectively, to imported water from outside the aquifer plus the aboveground rainfall runoff estimated for the central city.

3.2.1. UWM outside the Central City of Puebla

Total appropriated water in settlements outside the central city was 352.56 Mm^3/yr of water, composed of 110.37 Mm^3/yr of surface water, 185.76 Mm^3/yr of groundwater, and 56.43 Mm^3/yr of surface water for power generation. Of the total water withdrawn and then used, it is discharged as follows: 33% of the discharges are concessioned (discharge permits); 4% correspond to induced vertical recharge because of agriculture and leakages in distribution networks; 16% are related to electricity generation; and the remaining 46% correspond to undefined discharges (it may include evaporated water, water that constitutes the products of agriculture, or informal discharges). See Figure 6.

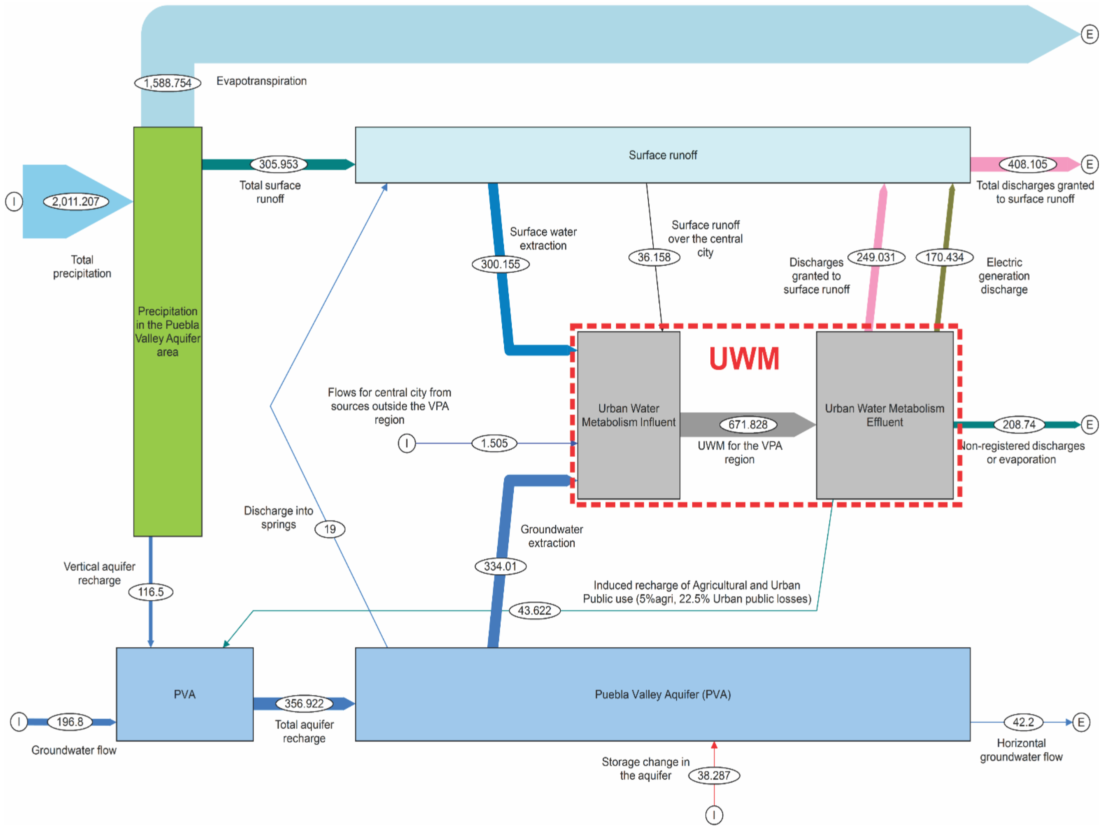


Figure 5. UWM of the City of Puebla and its metropolitan area. Authors' own elaboration. Note: The letters "I" and "E", indicated in the diagram, represent import and export flows. These two flows connect the environment outside of the system boundaries with the processes inside.

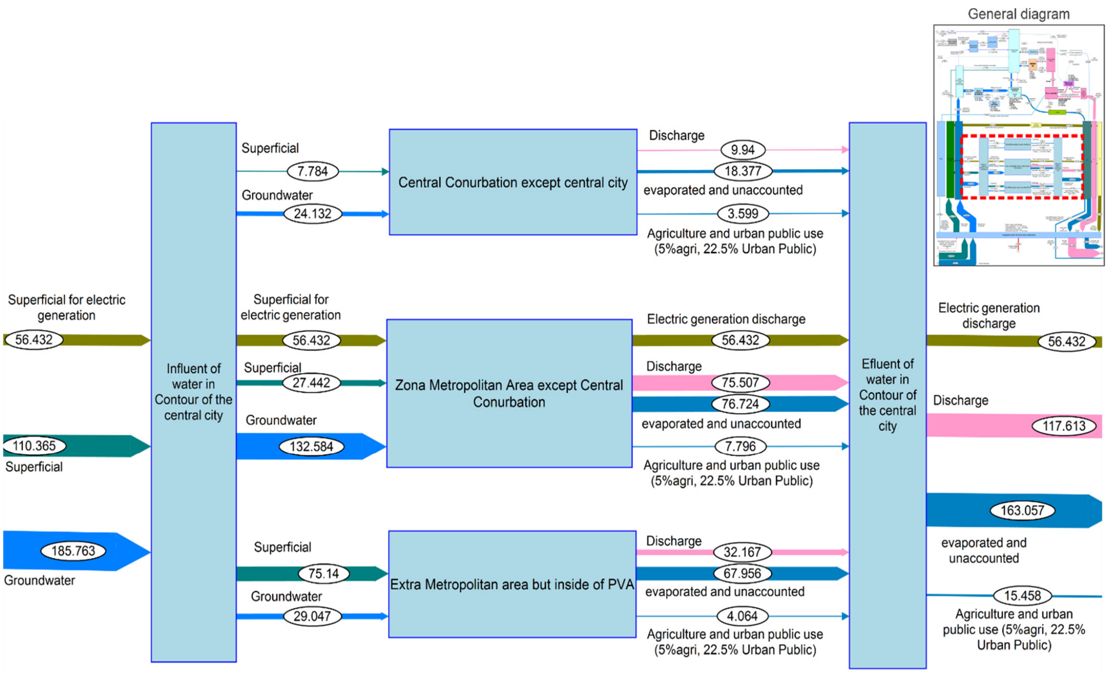


Figure 6. Urban Water Metabolism in the outskirts of the central city of Puebla. Authors' own elaboration. Note: This figure is a cropped version of Figure A1 in Appendix C.

The use of surface water gradually decreases as settlements become more urbanized because of its progressive contamination due to a lack of sanitation [99]. The Atoyac River is the primary source of runoff in the basin, concentrating the region's pollution. It is considered an "environmental hell" by the Environment and Natural Resources Secretariat of the federal government (SEMARNAT). SEMARNAT is the acronym for the Secretary of the Environment and Natural Resources, the government entity whose fundamental purpose is to establish a national environmental policy that reverses the trend of ecological degradation and lays the foundations for sustainable development in the country. Its jurisdiction is nationwide [100] as it has markedly affected the health of the population living nearby, including a greater prevalence of leukemia and cancer [55,56,63].

3.2.2. Water Appropriation for the Central City of Puebla

A total of 167.74 Mm^3/yr of water is extracted from the environment and distributed as follows: 148.33 Mm^3/yr of groundwater; 19.36 Mm^3/yr of surface water; 0.052 Mm^3/yr of rainwater harvested in dwellings; and 33.85 Mm^3/yr of rainwater runoff over the built surface discharged into the Atoyac and Alseseca rivers. Water imports, considered to be from outside the aquifer, were estimated for big-brand bottled water totaling 0.75 Mm^3/yr. In the same way, groundwater extracted outside the PVA and distributed by tanker trucks within the PVA was estimated at 1.50 Mm^3/yr. According to the survey, such water supplies 70% to 80% of local LPWCs.

The LPWCs are mainly supplied with groundwater from the area of San Pablo del Monte (Tlaxcala) and surroundings (located in the vicinity of the Malinche volcano) because it's low-hardness water, which contrasts with the high hardness of the groundwater of the City of Puebla [66,69]. Using low-hardness water helps them reduce maintenance and operating costs. Water quality in the surroundings of La Malinche therefore relates to public health in the central city due to the consumption of water distributed by LPWC. Water deterioration and thus ecosystems' deterioration in La Malinche could eventually imply importing water from farther away, leading to higher energy costs linked to greater carbon emissions, not to mention higher LPWC's water prices.

In 2019, the local water utility extracted 124.06 Mm^3/yr from the PVA, of which 63% came from the jurisdiction of the Municipality of Puebla and 37% from the surrounding municipalities (Table 1). Alternative flows to the water utility add a flow of 8.31 Mm^3/yr of groundwater, for the most part privately distributed by tanker trucks. Of this flow, 7.57 Mm^3/yr was for domestic consumption and 0.66 Mm^3/yr distributed to LPWCs. Finally, another flow of 15.96 Mm^3/yr was extracted from private wells.

Table 1. Flows extracted by the City of Puebla's water utility, subdivided by municipality of water origin.

Municipality Where Water Was Extracted	Annual Flow Extracted by the Water Utility (Mm^3/yr)	Percentage (%)
Puebla	78.657	63.4%
Cuautlancingo	11.622	9.4%
Coronango	9.988	8.1%
Nealtican	9.472	7.6%
San Pedro Cholula	4.944	4.0%
San Andrés Cholula	4.605	3.7%
Tlaltenango	4.222	3.4%
Juan C. Bonilla	0.339	0.3%
Amozoc	0.214	0.2%

Source: Authors' own elaboration based on SOAPAP's 2019 data.

3.2.3. Water Treatment of the Water Utility in the Central City of Puebla

Contamination and overexploitation of the PVA have deteriorated its water quality with heavy metals such as boron and manganese, which, in moderate to high concentrations, cause problems for human health. The presence of boron originates naturally from the weathering of rocks that contain it, but it also comes from cleaning products, industrial waste from paints and varnishes, textiles, leather tanning, and electronic devices, all of which are pollutants discharged by industries into rivers such as the Alseseca and the Atoyac [63,68]. Hardness is another water quality problem in the PVA, ranging from 286 mg/L to 1894 mg/L [72]. The presence of hardness in water often leads to the deterioration of domestic water infrastructure, incurring recurrent maintenance costs and decreasing affordability [98].

The water treatment applied by the water utility is chlorination and water softening. The first is applied to all the extracted water and is helpful in eliminating microorganisms but ineffective for other contaminants such as heavy metals. The second is applied to 7.56% of the water withdrawn (9.57 Mm^3/yr), with the operation of 3 out of 4 softening plants in 2018. However, former water utility workers imputed that the softening method is performed only with lime, pointing it out as a lax method [101]. Inconsistencies were found in the water softening information, such as consuming chemicals without reporting water softening and vice versa (Table 2).

Table 2. Flows softened by the water company in Puebla central city.

Water Softener Plant	Annual Softened Flow (Mm^3/a)	Percentage (%)	Amount of Chemicals (Kton/a)	Consumption of Chemicals (Kg/m^3)
Quetzatcoatl	5.77	60.3%	2.77	0.481
Sulfurosa	2.51	26.2%	5.99	2.388
Jint	1.29	13.5%	0	Inconsistent data
Paseo del Río	0	0%	0.07	Inconsistent data

Source: Authors' own elaboration based on data from SOAPAP 2018.

3.2.4. LPWCs Drinking Water Treatment in the Central City of Puebla

Based on the surveys carried out, 90% of respondents indicated they consume bottled water due to mistrust of tap water quality. Of such consumption, 70% corresponded to water supplied by LPWCs, which argue to apply ultrafiltration processes. LPWC's water price is less than half the price of big-brand carboys, and this fact is attractive to residents who are unable to afford big-brand bottled water. This means that access to drinkable water is stratified as a result of its price versus the household's income, a situation that unevenly affects guaranteeing the human right to water.

LPWCs are supplied with 2.25 Mm^3/yr of water transported by tanker trucks, of which 1.88 Mm^3/yr is bottled for sale and 0.38 Mm^3/yr is used for purification processes such as washing of containers, filters, etcetera. LPWCs respondents consider that more than half of these businesses are clandestine, whose products are even more affordable than the regularized ones because they do not perform the entire purification process or pay taxes. Some of the worst practices carried out by these purifiers are filling carboys with tap water or filling carboys directly from the tanker truck without treatment.

3.2.5. Water Distribution in Central City of Puebla

In the city of Puebla, network losses pose a significant challenge for UWM, accounting for approximately 40.66% (49.476 Mm^3/yr) of the water sourced from the environment. The remaining water, equal to 74.59 Mm^3/yr, meets the demands of all water uses. It is important to note that the water loss ratio is equivalent to the ratio of water imported from neighboring municipalities, which is 37%. The previous comparison (40% vs. 37%) shows an unfair scenario for the neighboring towns because the improvement of the efficiency of the distribution network is not given top priority locally, which leads to the importation of greater quantities of water to alleviate water shortages, which is also associated with losses in energy efficiency (Figure 7). This tendential scenario can eventually lead to overexploitation and pollution not only of local water sources and the local basin but of neighborhood basins as well, either for tapping fresh water or discharging increasing amounts of wastewater. Such an unsustainable water model has been identified in several cities in Mexico, from Mexico City to Monterrey, Guadalajara, San Luis Potosí and León [102].

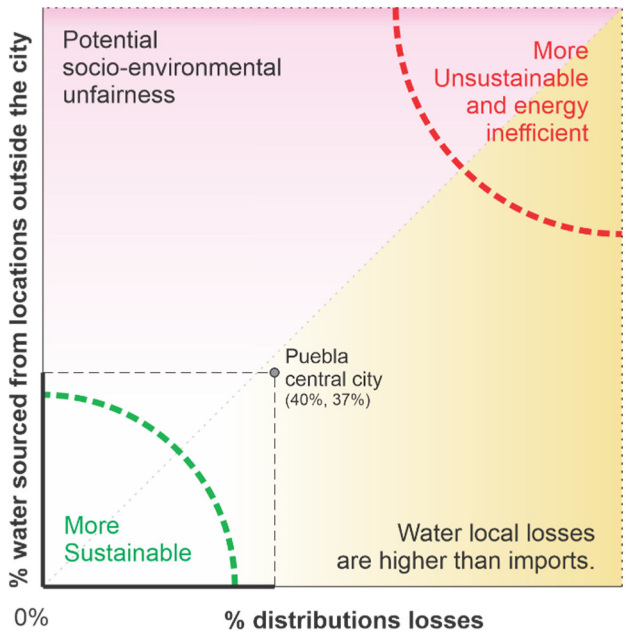


Figure 7. Graphical scheme of the comparison between distribution losses and water imported from locations outside the central city of Puebla.

Avoiding such a tendential scenario by improving physical efficiency (including here the related behavioral changes needed) could reduce the dispossession of water (and the eventual discharge of wastewater to neighbor basins), which in turn can prevent socio-environmental conflicts such as those that occurred in Nealtican or Coronango [38,40].

On the other hand, since losses in the distribution network of the city of Puebla are 6.5 times greater than water distributed in tanker trucks, by reducing losses by 15% and distributing water equitably to users, the need for tanker truck service could be minimized. If the distribution losses were hypothetically reduced to zero, the population could receive 80% more water than it currently receives from the water utility (estimation based on the current flow of 61.53 Mm^3/yr distributed by the water company for domestic use).

Distribution losses are due to water leakages resulting from the poor condition of the network and clandestine connections. In the city of Puebla, it is estimated that there are over 100,000 illegal water connections, which would represent a 20% higher number of connections than those officially served by the water company [103]. That 20% would represent a flow of approximately 14.92 Mm^3/yr, which is equivalent to 30% of the flow lost in the distribution network.

Losses in the distribution network are linked to network deterioration, but as shown above, they are exacerbated by the informal practices of users who seek access to water services, either because informal users are living in informal settlements or because they face water affordability problems that lead to water cut-offs for non-payment. The above illustrates how the causes of network losses extend beyond solely technical issues to social problems within the city, meaning that purely technical solutions for mitigating distribution losses would be inadequate. Therefore, we suggest integrating the ratio of flow related to clandestine water tapping into the network loss indicator proposed by Paul Reba et al. [23]. This would give an estimation of the incidence of social problems in distribution losses, which in turn is related to the non-guarantee of the HRW.

3.2.6. Tanker Trucked Transported and Bottled Water Flows in Central City of Puebla

Input parameters for the Monte Carlo simulation are shown in Table A4. The Big brand bottled water flow (0.75 Mm^3/yr) and the LPWCs purified water flow (1.88 Mm^3/yr) are mainly consumed in dwellings and food businesses (Table 3).

Table 3. Magnitude of water flows distributed by tanker trucks and bottled water.

Flow	Calculated Magnitude	Total
Distributed by tanker truck		7.561 Mm^3/yr
In homes with a water tank	0.526 Mm^3/yr	
In homes with a water tank and cistern	7.035 Mm^3/yr	
Big Brand bottled water		0.753 Mm^3/yr
20 L carboys	0.687 Mm^3/yr	
5 L carafes	0.066 Mm^3/yr	
1.5 L bottle	0.072 Mm^3/yr	
LPWC bottled water		1.879 Mm^3/yr

Source: Authors' own elaboration with information from Monte Carlo simulation.

The water flow distributed by tanker trucks has been estimated at 7.56 Mm^3/yr. This consumption is due to: (i) the inaccessibility of water to inhabitants that live outside the coverage of the water utility network; (ii) non-compliance with water supply frequency (which in some cases exceeds a month without water service) [104]; and (iii) water service cut-offs either due to the economic incapacity of users to pay for the service and/or the exorbitant tariffs imposed by the water utility. Some users have collectively purchased tankered water to divide the costs among their neighbors. This situation certainly represents a step back for complying with the HRW.

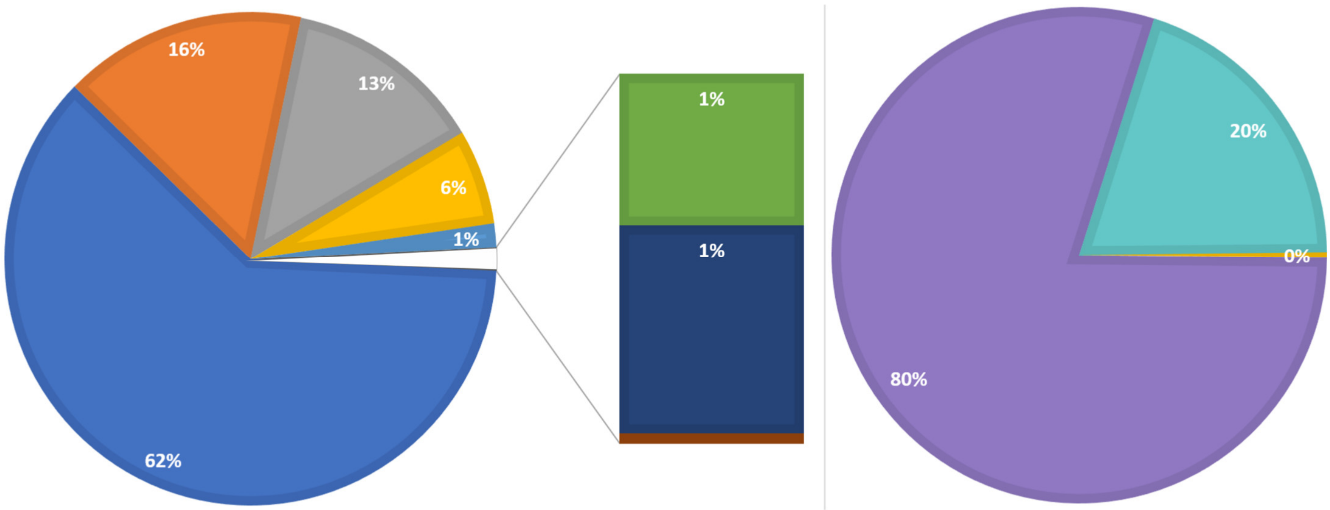
3.2.7. Water Consumption in the Central City of Puebla

After the distribution of water losses, the sum of all flows consumed in the city is 121.17 Mm^3/yr (Table 4 and Figure 8), of which only 0.85% is treated. Such flows of treated water are mostly reused for irrigating green public areas by the Municipality of Puebla. Due to the highly limited volume of water being reused, it can be said that the circularity of the UWM is practically nil. This is also supported by the constrained role played by rainwater harvesting in dwellings, which corresponds to 0.04% of the total amount of water appropriated from the environment. Even if rainwater harvesting increases up to 0.6 Mm^3/yr, as indicated by Martínez Austria [71], it would still represent 0.5% of the total water consumed in Puebla city. We believe that the rainwater harvesting data mentioned above may be underestimated. This is due to the fact that the runoff coefficient utilized by Martinez Austria [71] is significantly lower than that reported in the Council G modeling guidelines [88].

Table 4. Influent disaggregated for consumption process in the UWM of the central city of Puebla.

Influent of Water Consumed	Colors in Figure 8a	Flow Mm^3/a	Percentage of Total (%)
Water Utility		74.59	61.55
Surface water not withdrawn by the water utility		19.36	15.97
Groundwater not withdrawn by water utility		15.96	13.17
Water distributed by tanker truck to households		7.56	6.25
LPWC bottled water		1.88	1.56
Big Brand bottled water		0.75	0.69
Recycled water from WWTPs		1.03	0.85
Rainwater harvesting in homes		0.05	0.04
Total		121.17	
Consumed water effluent	**Colors in Figure 8b**	**Flow Mm^3/a**	**Percentage of total (%)**
Discharges to sewers or water bodies		97.24	80.25
Evaporation in water uses		24.31	20.06
Discharge of the water treatment process at LPWC		−0.38 *	−0.31
Total		121.17	

Source: Authors' own elaboration with information from the water flow balance (MFA method). * Negative sign because it is wastewater that does not enter the uses.



(**a**) (**b**)

Figure 8. Disaggregated percentages of consumed water, influent (**a**) and effluent (**b**).

The licensed surface water flow for electricity generation in the Municipality of Puebla is 114.00 Mm^3/yr. This flow was included in the UWM model but was not included in Table 4 due to two inconsistencies: the first is that power generation processes require a higher quality of water than drinking water, which is improbable in a place where surface water is highly polluted; secondly, it is also unlikely that the amount of water licensed for power generation exceeds the amount of water withdrawn by the water utility each year. The only power generation plant of the *Comisión Federal de Electricidad* (CFE) (CFE is the acronym for Comisión Federal de Electricidad, the state-owned company responsible for the generation, management, and marketing of electricity throughout Mexico) in the municipality of Puebla is the *San Lorenzo Potencia* plant, which consumes 0.021 Mm^3/yr of water because of its zero-discharge technology design. The electricity generation plant is located one kilometer from the Jint Softening Plant, which is operated by the water company, so it is more probable to use softened water instead of surface water for energy generation.

3.2.8. Water Uses in the Central City of Puebla

Of the total central city water withdrawn, 42% is for domestic use, 29% for other uses, and losses in the network are 29%. If the comparison excludes distribution losses, domestic use represents 58.96%, and the remaining 41.04% is distributed for other uses as detailed in Table 5.

The imbalance between the inputs and discharge, as presented in Figure 9, was compensated with a flow called "unidentified flow" (data from REPDA). For example, industrial discharges corresponded to 34.46% of the water consumed for such uses. The remaining 65.54% of such industrial water inflow has, as a counterpart, an unidentified outflow to the environment. In the context of the serious contamination problems in the study area, "balance" flows in discharges could be a challenging issue due to the lack of adequate monitoring and the existence of informal discharges.

The micrometering percentage reported by the water utility is 19.18% of the total users in the central city [105], and this is a measurement issue that implies potential deficiencies in the estimation of water consumption and losses. A higher percentage of micro-metering would increase the certainty of the lost volume of water and its location. However, users reject micro-meter installation due to the associated costs and their distrust of the water utility, which is related to the current excessive rates of water. Measurement is thus seen as a mechanism that will make the water service even more expensive than it already is, particularly for the urban poor [106–108].

Table 5. Water Flow consumed in the central city of Puebla by uses.

Consumption	Annual Flow (Mm^3/yr)	Percentage of Total
Domestic	71.45	(58.96%)
Public	17.75	(14.65%)
Commercial	13.05	(10.77%)
Industrial **	10.44	(8.61%)
Services	5.99	(4.92%)
Aquaculture	0.596	(0.49%)
Different Uses	0.514	(0.42%)
Domestic not supplied by SOAPAP	0.050	(0.04%)
Livestock	0.032	(0.03%)
Bottled water in non-domestic uses	0.263	(0.22%)
Recycled water for irrigation of municipal gardens	1.03	(0.85%)
Electric power generation	114.00 *	

Source: Authors' own elaboration with information from CONAGUA 2019 and SOAPAP 2019. * Electricity generation was not included in the percentage of uses. ** In the information obtained from SOAPAP, we noticed some industrial consumption accounted as domestic, so the industrial consumption is probably higher than the one indicated.

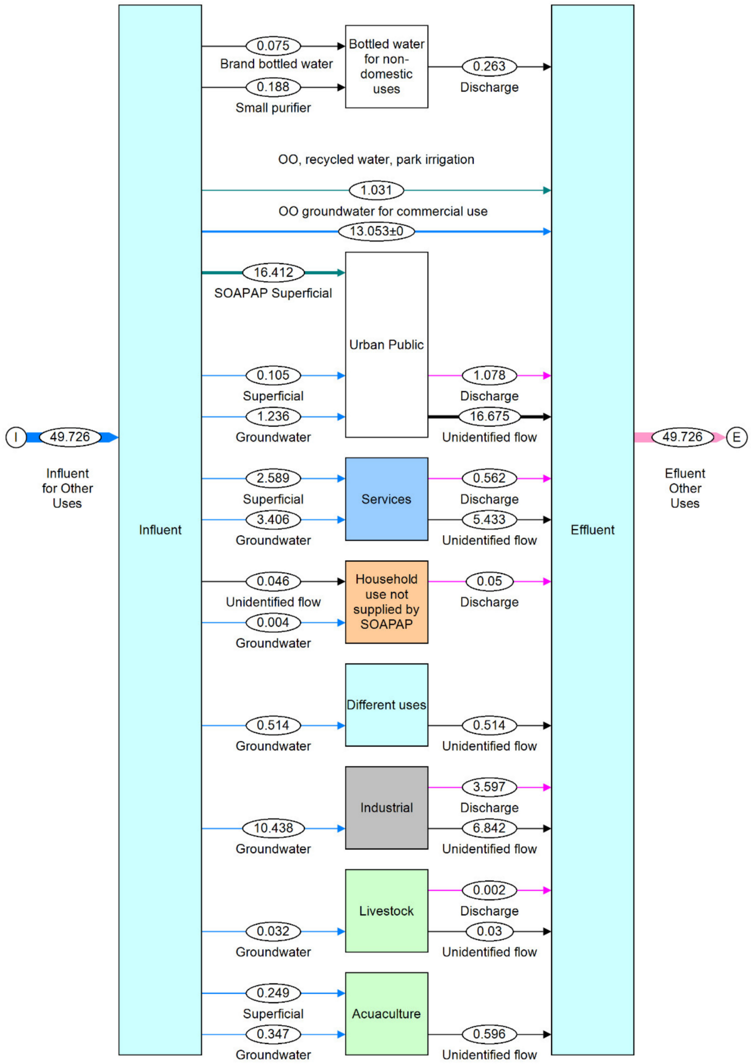


Figure 9. Water uses in the central city. Authors' own elaboration. Note: The letters "I" and "E", indicated in the diagram, represent import and export flows. These two flows connect the environment outside of the system boundaries with the processes inside.

Excessive water bills have caused non-payment of service, leading to water cut-offs for delinquent users [109–111]. Water cut-offs cause social conflicts as they challenge guaranteeing HRWS, as has been pointed out by organizations such as the "Asamblea Social del Agua", "Colectiva por el Bienestar Social", independent activists (i.e., Omar Jimenez Castro), former officials (i.e., Francisco Castillo Montemayor), and a diversity of scholars [112–117].

The total storage capacity in the water utility's water tanks is 0.246 Mm^3, and the total water accumulation capacity in the dwellings was estimated at 2.33 Mm^3. The sum of the water storage capacity of the water utility plus the total dwelling's storage capacity totals 2.57 Mm^3. Figure 10 shows two probability distributions: the first on the left refers to the dwellings without a cistern that store water in tanks plus barrels or buckets, and the second on the right relates to the dwellings with a cistern.

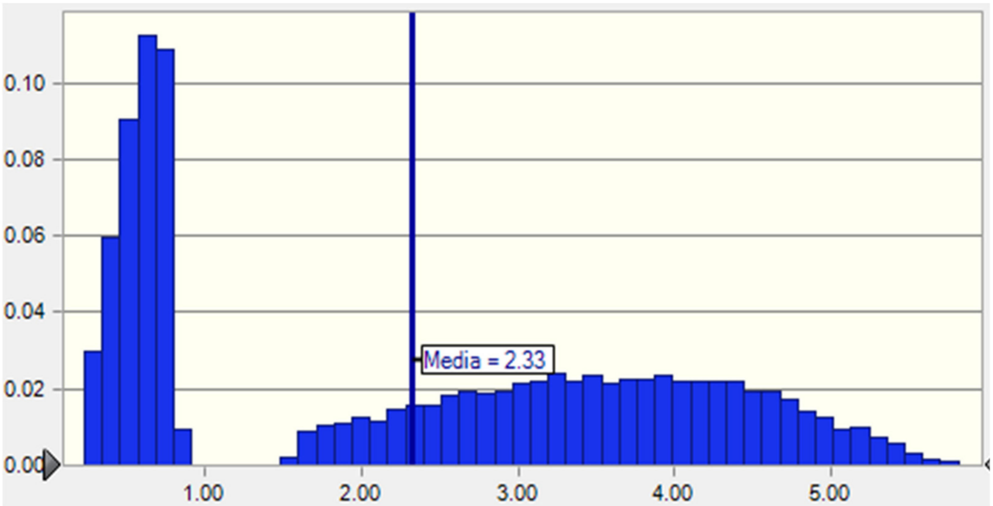


Figure 10. Probability of water accumulation capacity in city dwellings. Authors' own elaboration. Note: Units on the abscissa axis are Mm^3, and the ordinate axis refers to probability.

3.2.9. Water Excretion in the Central City of Puebla

In Puebla City, drainage and sewerage share the same infrastructure, where rainwater runoff and domestic and industrial discharges confluence. In that water, pollutants found include pharmaceuticals [118], microplastics [61,119], other emerging contaminants [119], and heavy metals [56]. Their confluence allows them to mix and produce chemical reactions that might result in new mixtures of pollutants, which may not be treated by WWTPs [120].

A maximum of 97.24 Mm^3/yr of wastewater flowed into the drainage-sewerage network, plus 33.85 Mm^3/yr of rainwater runoff, totaling 131.09 Mm^3/yr. The utility's WWTP treated 63.91 Mm^3/yr while 67.18 Mm^3/yr flowed untreated into the environment. The amount of treated water in the industrial sector is unknown. The sum of treated and untreated discharges was estimated at 129.90 Mm^3/yr.

The drainage-sewerage network exchanges water with its surroundings through the phenomena of infiltration and exfiltration [121]. Their magnitude in the City of Puebla is unknown; however, it is essential to be aware of them since the quality of the aquifer water is transcendental for the City of Puebla's water sustainability.

3.2.10. Wastewater Treatment in the Central City of Puebla

The total installed capacity of the five WWTPs is 116 Mm^3/yr. In 2018, WWTPs operated at 55% of their total capacity (63.91 Mm^3/yr). 1.03 Mm^3/yr of the total wastewater was treated in the only WWTP with secondary treatment, and that water was reused for irrigation of public green areas at the municipality's expense. The other four WWTPs treated 62.72 Mm^3/yr with primary treatment; 51.31 Mm^3/yr were discharged to the Atoyac River and 11.41 Mm^3/yr to the Alseseca River (Figure 11).

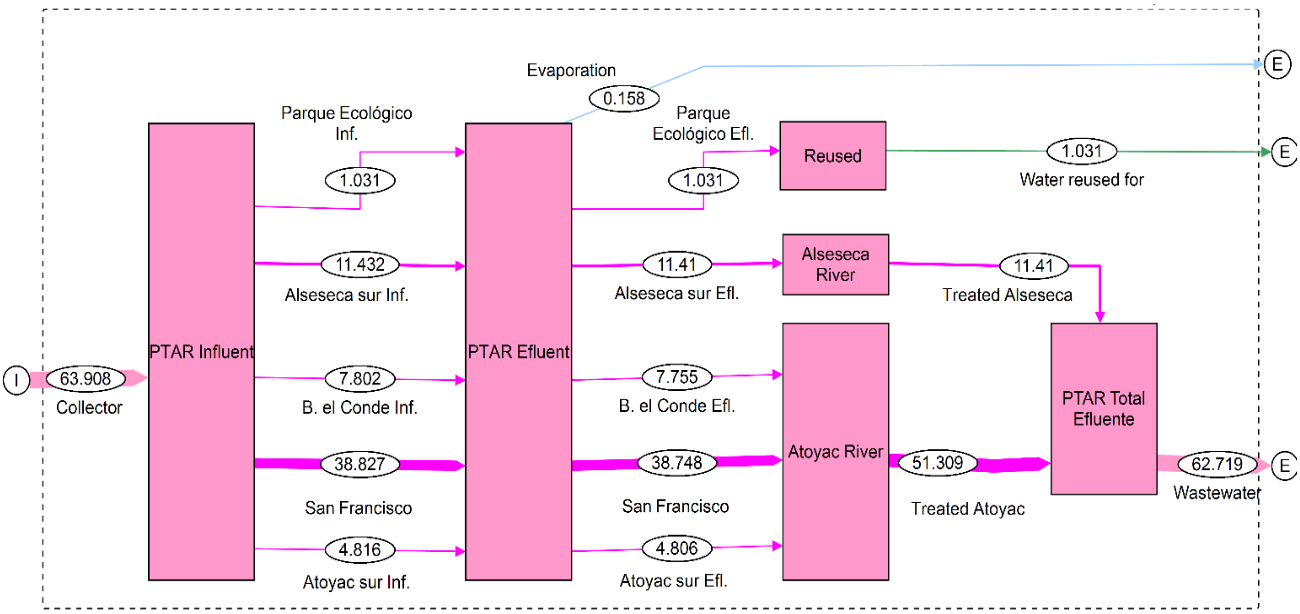


Figure 11. The wastewater treatment process at the water utility. Authors' own elaboration. Note: The letters "I" and "E", indicated in the diagram, represent import and export flows. These two flows connect the environment outside of the system boundaries with the processes inside.

Despite the above, it can be argued that UWM in the City of Puebla is mostly linear because only 1.6% of treated wastewater is used for irrigation of green areas. It is, however, possible that the WWTP "*Parque Ecológico*" is not operating, and this would translate into 0% circularity. In Mexico City, the circularity is slightly higher, where 5.26% (94.61 Mm^3/yr) of the total water discharged is treated, of which 83% is used for green space irrigation, which represents a circularity of 4.37% (78.52 Mm^3/yr) of the total water discharged in the city [87].

The Alseseca and Atoyac rivers are already highly polluted before they reach the City of Puebla. Once they flow through the city, they drain into the Manuel Ávila Camacho Dam, which in 2018 had a storage capacity of 303.1 hm^3 [74,122]. The dam acts as a sedimentation vessel, a metal scrubber due to the decrease in flow velocity, and a biofilter due to the effect of water lilies [64]. The dam's water is used for irrigation to produce food consumed in the City of Puebla, its metropolitan area, and beyond [123,124].

3.2.11. Water Evaporation in the Central City

Rainwater evaporated on the central city surface was estimated at 177.85 Mm^3/yr, and evaporation in the consumption process was estimated at 24.31 Mm^3/yr. Water pollution discharged into rivers also volatilizes into the air, forming Volatile Organic Compounds (VOCs), some of which are potentially carcinogenic and linked to diseases such as leukemia or cancer in children and young people in the metropolitan area [57,125].

3.3. Approximation to the Water-Energy-Carbon Nexus in the Central City of Puebla's Utility System

The water utility's energy consumption in 2018 was 103.36 GWh, representing 4.31% of the total energy consumed by the municipality of Puebla for the same year. Of that energy, 87.11% was consumed for water pumping and 12.46% for potable and wastewater treatment, generating total emissions of 54.47 $KtCO_2e$ of which 47.45 $KtCO_2$ are related to water pumping and 6.79 $KtCO_2e$ to potable and wastewater treatment. The estimated *per capita* energy consumption related to water was 55.15 kWh/p/yr which translates into a per capita carbon footprint of 29.06 $kgCO_2e/p/yr$ (Table 6).

Table 6. Urban Water Metabolism energy consumption and carbon emissions in the water utility.

Processes	Percentage	Consumption of Energy GWh	Mm^3/a (hm^3/yr)	KWh/m^3	$KtCO_2e$	$KgCO_2e/m^3$
Extraction	68.78%	71.09	124.06	0.5730	37.47	0.3020
Water treatment	4.69%	4.85	9.57	0.5066	2.55	0.2670
Pumping	17.71%	18.31	124.06	0.1476	9.65	0.0778
Sewage	0.62%	0.64	97.25	0.0065	0.34	0.0034
Wastewater treatment	7.77%	8.03	63.91	0.1257	4.23	0.0662
General services	0.43%	0.44	124.06	0.0036	0.23	0.0019
Water Utility		103.36	124.06	0.8331	54.47	0.4391

Source: Authors' own elaboration with information from SOAPAP 2018.

The estimated energy intensity to treat wastewater flows was 0.1257 KWh/m^3, which is lower than the average energy intensity verified for sanitation in the state of Puebla (0.60 KWh/m^3) [84]. It is also lower than the energy consumed in the city of San Purisima del Rincón (0.38 KWh/m^3) [30] and lower than that of other foreign cities such as Oslo (1.32 KWh/m^3), Nantes (0.87 KWh/m^3), Toronto (1.44 KWh/m^3) and Turin (0.94 KWh/m^3) [28].

Assuming that the energy intensity required to treat wastewater is the average in the state of Puebla (0.60 kWh/m^3), recalculating the treated wastewater flow would result in 13.39 Mm^3/yr, equivalent to 10% of the central city's total discharged water. This is significantly lower than the amount reported by the water company (63.91 Mm^3/yr). As a result, it is plausible that as much as 90% of the discharged wastewater is left untreated. This discrepancy in data reinforces the complaints made by social activists who accuse the water utility of fraud. They claim that users are charged for sanitation services that are not actually being performed [126].

Both social and environmental problems are caused by the discharge of untreated water into the Alseseca and Atoyac rivers [127]. According to Mexico's Ministry of Environment and Natural Resources (SEMARNAT), the Atoyac River is currently in an "environmental inferno", making it the second most polluted river in the country [128]. In this example, it is evident that the low energy intensity in wastewater treatment aligns with the low quality of the discharged water and its detrimental effect on the ecosystem and human health [27]. This reveals the important role that socioeconomic aspects actually play within water-energy nexus analyses, manifested in this case as the erosion of the population's right to sanitation and to a healthy environment.

On the other hand, water network losses result in a waste of 42.09 GWh of energy, leading to the emission of 22.18 Kt of CO_2e and contributing to climate change. These losses generate operating costs that the water utility ultimately passes onto its customers through tariffs, potentially impacting the affordability of water [129].

3.4. Other Material Flows Related to Urban Water Metabolism in the Central City of Puebla

The UWM is linked to other flows, including the chemicals for treatment and the materials dissolved or transported from the consumption process to sanitation and excretion. In what follows, we only pay attention to the use of water treatment chemicals.

Water Treatment Chemicals in the Central City of Puebla Water Utility

Water softening required 8824.7 kg/yr of chemicals comprising sodium chloride, sulfuric acid, calcium hydroxide, anionic polymer, cationic polymer, sodium hypochlorite, antifouling, genefloc, sodium hydroxide, and metabisulfite. Wastewater treatment required 3298.06 kg/yr of chemicals, including ferric chloride, anionic polymers, and cationic polymers. The increasing need for drinking water and wastewater treatment will generate higher requirements for water treatment chemicals.

3.5. Elements of the Human Right to Water from the UWM Model in the Central City of Puebla

According to SOAPAP data for 2019, the water utility supplied 506,024 dwellings, housing approximately 1,874,084 inhabitants. The amount of water withdrawn has been officially estimated at 181.37 L *per capita* per day (LPCD); however, such an estimation implies the absence of water losses in the networks and the absence of non-domestic uses. If non-domestic uses and network losses are subtracted from the calculation, it results in the delivery of 105.53 LPCD for domestic use, composed of 90.71 LPCD (86%) provided by the utility and 14.83 LPCD (14%) distributed in tanker trucks and bottled water.

Under the scenario of recovering the water lost in the network and distributing it equitably among the population, an extra 72.33 LPCD could be available for distribution. It is to be noted that the current *per capita* amount of water lost is greater than the average amount of water received by the inhabitants of several towns in Kenya, Tanzania, and Senegal [130,131]. This means that the opportunity to improve the system is not negligible.

Accessibility, Affordability, and Accessibility of Water in the Central City of Puebla

The R_{HRW_E} indicator shows that the water distributed by tankers and bottled water represents 14.27% of the total water consumed in the dwellings. Although the percentage may appear low, it exposes a significant issue related to the HRW as described below.

The annual costs paid by users for water distributed by tanker and bottled water was estimated at USD 200.31 million, which is 1285% higher than what the water utility collected by annual prepayment in 2019 which reached USD15.41 million (payment collection efficiency was reported to be at around 30% of the total collectable income).

The big-brand bottled water, LPWCs, and tanker truck flows are respectively equal to 0.67%, 1.52%, and 6.10% of the total water volume extracted by the water utility. The amount paid for these flows compared to the amount collected by prepayment in 2019 was: 8 times higher for big-brand bottled water; between 3 and 4 times higher for LPWC service; and for tanker truck service, it was equivalent (Figure 12). This is without omitting that a water shortage enables the proper conditions for increasing water tanker truck rates [132].

(**a**) (**b**)

Figure 12. (**a**) Flows and their total annual costs in Puebla city. Authors' own elaboration. Note: The blue columns refer to the flow of water (Mm^3/year). An estimated cost (USD) is associated with each flow column, indicated by the red shaded area. (**b**) Details flow rates and costs only for the flow of big brand bottled water.

The above reveals that the cost paid for alternative water acquisition compared to the amount collected by the water utility is several times higher, and it indicates that the service quality directly affects water affordability; therefore, the lack of accessibility and acceptability of the water service in the City of Puebla generates water affordability problems and consequently a lack of compliance by HRWS. At the same time, that situation generates profits for some private parties related to alternative water services, aggravating prevailing income inequalities.

Bottled water consumption in three UWM studies in Mexican cities was inversely proportional to city size. For example, bottled water consumption in Mexico City ranged from 0.65 LPCD [87], for the City of Puebla, 3.85 LPCD, and for Tepic, 7.09 LPCD [51]. The differences between the three magnitudes refer to the lack of precision in the estimates of bottled water consumption. To corroborate any trend, it is necessary that more UWM studies include the estimation of this flow.

3.6. Inconsistencies in the Data That Coincide with Water Related Problems

Absences and inconsistencies in the data collected for the UWM model are common in UWM and UM studies [15]. In the case of the City of Puebla, data limitations coincide with water management challenges, for example: the increase in VPA water availability between 2013 and 2016 is incongruent [12,13,91], but is conducive to the concession of larger volumes of water and consequently aggravating the overexploitation of the VPA; the incongruent data related to wastewater treatment is consistent with water pollution [57,64,123–125] and related socio-environmental conflicts [38,39]; the absence of information on the consumption of bottled water and water transported by tanker truck conceals the negative consequences of their consumption for water affordability (and thus to the compliance of HRWS). Other information and data limitations hide water issues, masking potential water mismanagement, including informality and illegality.

In the era of information and communication technologies, an automatic and transparent water information monitoring system is possible and should be implemented. This will allow all stakeholders to generate knowledge, awareness, and agile decision-making on the city's water issues. At this point, the UWM approach is useful to integrate water variables and reduce the complexity of these magnitudes to make them more understandable to all stakeholders and the general public.

Comments on the Data Collected

The water rights data from REPDA and the survey data simulated via Monte Carlo may involve a certain degree of uncertainty. In the case of REPDA data, its weakness arises from CONAGUA's water management, as their estimates of aquifer water availability are based on water rights rather than empirical measurements. For bottled and transported water, the estimation offered provides an approximation of its flow rate, which lies within a reasonable range in comparison to two Mexican cities (as stated in Section Accessibility, Affordability, and Accessibility of Water in the Central City of Puebla). It still needs to be further validated through a larger data sampling exercise. We consider that having a preliminary approximation of these flows is preferable to having none at all, as they allow us to quantify the effect of the lack of HRW assurance on the city's residents.

In contrast to the aforementioned, the part of the model corresponding to the central city of Puebla was mostly developed with empirical information provided by the water company.

4. Conclusions

Understanding water-related challenges in cities from a holistic perspective is crucial in an environmental and climate-changing context. The quantification of the UWM model for the city of Puebla provided a guide to identifying water problems that go beyond efficiency and performance issues. These include environmental issues with the water supply system, socio-environmental conflicts, challenges complying with the HRWS, and a lack of key information for policy design and decision-making.

Using a UWM model to address the city's water problems can help identify the relationships between social and environmental elements. For example, the lack of compliance with the HRW can lead to a further decrease in water-related energy efficiency in the city because it is a favorable condition for corporations to sell water-related products, particularly big-brand bottled water (but also household filtration systems and alike). Another relationship noted is that the water utility is losing a similar amount of water as it is importing from the surrounding cities, which is incongruous, energy-inefficient, and socio-environmentally unjust. In simpler terms, there is a relationship between socio-environmental justice and the water-energy-carbon nexus.

Regarding the latter, one bold assumption is that, in addition to efficiency, guaranteeing the HRW and pursuing water justice could indirectly contribute to the mitigation of climate change, although this scenario may not be economically viable for water-related companies under the model described above. It is necessary to discuss the previous idea since ensuring the HRW under current conditions involves additional energy costs (in addition to economic costs that are partially passed on to water final users). In any case, what was just said demonstrates the inseparable connection between social and physical aspects.

Although we acknowledge the limitations of the snowball sampling method employed in our Monte Carlo simulation, we still consider that our findings are meaningful due to the reduced weight of such flow. Nonetheless, using spatialized probabilistic sampling could certainly improve the reliability of the results, which may be relevant for designing specific intervention mechanisms for improving the HRW, starting with the most critical areas of the city. This possibility suggests that it is feasible to generate valuable estimations for the decision-making of undocumented flows by using data associated with consumer behavior. This approach could help overcome the obstacle of insufficient information, which is a widespread problem in the cities of Mexico and other developing countries.

The UWM model for the city of Puebla was a first approximation. Therefore, it is not currently focused on future scenarios. However, it serves as a baseline model with potential for improvement, either in the quality of information or the level of detail, providing the opportunity to address specific water issues in a context in which spatializing prevailing dynamics and inequalities may be particularly relevant for policy design and decision-making. Our findings can also serve as a basis for developing a dynamic forecasting model that could help identify the potential of different policies and interventions for improving at different scales the efficiency and sustainability of the city's water metabolic flows, all while complying with the HRW. We aim to develop such a study in an upcoming paper.

We conclude that the holistic approach offered by the UWM perspective enables indeed a more robust understanding of the complexity of urban water systems, as shown in the case of the city of Puebla. Besides allowing the generation of specific information and data for technical decision-making, it can also support the generation of "digestible" assessments that can help identify not only current and potential future challenges but also who is or could be affected or benefit the most.

Such digestible assessments for non-specialized stakeholders but also for policymakers are highly relevant for informing, empowering, and finally mobilizing stakeholders and society in general. Informed social awareness of prevailing water challenges can enable behavioral changes, consensus building, partnership and alliance generation, and the co-generation of solutions, all of which we expect to be part of a (new) participatory water governance model for a more sustainable, climate-ready, just, and inclusive UWM profile for the City of Puebla.

We concur with Delgado and Blanco [52], who have pointed out for other water metabolic case studies that current and future urban water challenges will require "hybrid governance", meaning one that manages to integrate, at different scales, three central aspects: (i) *policy* or institutional aspects; (ii) *polity* aspects or power relations in place; and (iii) *politics* or the mechanisms and instruments to achieve certain desirable outcomes. This paper sets out a more robust understanding of the departure point for the city of Puebla, which is certainly needed for stimulating and informing change.

Finally, we believe that UWM studies significantly contribute to, yet do not exhaust, such an endeavor, which is the backbone of putting into practice the right to the city [79]. Building such a paradigm shift therefore demands hybridizing UWM with other perspectives and fields of knowledge, including urban water political ecology, institutional and capacity-building studies, and behavioral studies, among others. With that in mind, we have addressed HRW as a structural component of our UWM approach, allowing us a way to address but, as said, not exhaust the above-mentioned *policy* and political aspects. In a UWM dynamic forecasting model, explicitly incorporating all three hybrid governance aspects will certainly be relevant to elucidate the viability of transformational actions at different scales, and for alternative scenarios, a context in which multicriteria performance indicators—quantitative and qualitative ones—will certainly need to be further developed and tested to robustly inform decision-making processes (as advised by Renouf et al. [21] and Serrao-Neumann et al. [133]).

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su151914549/s1. Figure S1. Number of surveys applied per neighborhood in the city of Puebla. Figure S2. Probability density plot of water storage capacity in dwelling with cistern. Figure S3. Proposed probability distribution for water storage capacity in dwelling with cistern. Figure S4. Probability density plot of water accumulation in dwellings without a cistern, with a water storage tank. Figure S5. Beta PERT probability distribution for similar water storage capacity in dwellings with water tank. Figure S6. Probability density plot of the number of tanker trucks supplying water to the dwellings with water tank. Figure S7. Beta PERT probability distribution simulating the number of tanker trucks supplying water to the dwellings with water tanks. Figure S8. Probability density plot of the number of tanker trucks supplying water to dwellings with cistern. Figure S9. Proposed Beta Pert probability distribution for the simulation of the number of tanker trucks supplying water to dwellings with a water tank. Figure S10. Proposed "Yes-No" probability distribution for similar the ratio of dwellings that have a cistern (Rc). Figure S11. Proposed "Yes-No" probability distribution for the ratio of dwellings that have a water tank (Rt). Figure S12. "Yes-No" probability distribution simulating the ratio of dwellings with tankers receiving water service from tanker trucks (Mcp). Figure S13. Yes-No probability distribution that simulates the ratio of dwellings with water tanks that are supplied with water by tanker trucks (Mtp). Figure S14. Forecast of the flow transported by tanker trucks to supply the dwellings (Units in Mm^3/yr). Table S1. Statistical data related to the prediction graph of the flow rate transported by tanker truck. Table S2. Percentiles related to the forecast graph of the flow rate transported by tanker truck. Figure S15. Sensitivity graph of the prediction of the flow rate transported in tanker trucks. Figure S16. Graph forecasting water storage capacity in the city's dwelling units. Units (Mm^3/yr). Table S3. Statistical summary of the forecast graph for the water storage capacity in households. Table S4. Percentiles of the forecasted graph for the accumulation capacity in residential units. Figure S17. Sensitivity plot of forecast water storage capacity in dwelling units. Figure S18. Probability density plot of daily consumption of bottled water in 20-L Big-brand carboys. Figure S19. Beta PERT probability distribution for similar consumption of bottled water in 20-L carboys (Big brand). Figure S20. Probability density plot of daily consumption of bottled water in 5-L carafes (Big brand). Figure S21. Proposed probability distribution for the simulation of the flow rate of bottled water in 5 L carafes (Big brand). Figure S22. Probability density of daily consumption of bottled water in 1.5 L bottles (Big brand). Figure S23. Beta PERT probability distribution for similar consumption of bottled water in 1.5 L bottles (Big Brand). Figure S24. Probability density of daily consumption of refillable bottled water in 20-L carboys (LPWC's). Figure S25. Triangular probability distribution for the simulation of water flow rate in 20-L refill carboys. Figure S26. "Yes-No" probability distribution for simulating the ratio of dwellings where bottled water is consumed. Figure S27. Graph of bottled water flow forecast in 20 L jugs (large brand), units (Mm^3/year). Table S5. Statistical summary of the forecast graph of the flow rate of bottled water in 20-L carboys (Big brand). Table S6. Percentiles of the forecast graph of the flow rate of bottled water in 20-L carboys (Big brand). Figure S28. Sensitivity chart of the forecast flow rate of bottled water in 20-L carboys consumed in dwellings (Big brand). Figure S29. Graph of bottled water flow forecast in 5-L carafes (Big brand). Units (Mm^3/year). Table S7. Statistical information of the forecast graph of the flow of bottled water in 5-L carafes (Big brand). Table S8. Percentiles of the forecast graph of the flow rate of bottled water in 5-L carafes (Big brand). Figure S30. Sensitivity analysis graph for forecasting the flow of bottled water in 5-L carafes (Big brand). Figure S31. 1.5 L bottled water flow rate forecast graph (Big brand), units (Mm^3/year). Table S9. Statistical data of the forecast graph of the flow rate of bottled water in 5-L bottles (Big brand). Table S10. Percentiles of the flow rate forecast graph of bottled water in 1.5-L bottles (Big brand). Figure S32. Sensitivity plot of the forecast flow rate of bottled water in 1.5 L bottles (large brand). Figure S33. Forecast graph of bottled water flow in 20-L carboys (refill). Units (Mm^3/year). Table S11. Statistical summary of the forecast graph of the flow of bottled water in 20-L carboys (refill). Table S12. Percentiles of the forecast graph of bottled water in 20-L carboys (refill). Figure S34. Sensitivity plot of bottled water flow forecasting in 20-L carboys (refill). Figure S35. Graph of forecast number of inhabitants per dwelling, units (dwelling inhabitants). Table S13. Statistical summary of the forecast of the number of inhabitants per dwelling. Table S14. Percentiles of the forecast number of inhabitants per Dwelling. Figure S36. Total population in the central city (dwellings in the water company's coverage area). Table S15. Statistical summary of the total population forecast in the water utility's coverage area. Table S16. Percentiles of total population forecast in water utility coverage.

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Appendix A

Table A1. Description of the terms of the equations for calculating the water flow supplied by tanker truck.

Symbol	Variable	Unit	Source
$Q_{tanker\text{-}t}$	Flow distributed by tanker truck.	Mm^3/yr	Result
$Q_{tanker\text{-}t,wt}$	Flow distributed by tanker trucks in households with water tank.	Mm^3/yr	Result
$Q_{tanker\text{-}t,cis}$	Flow distributed by tanker trucks in households with cisterns.	Mm^3/yr	Result
A_{wt}	Total accumulation capacity in dwellings with water tank.	Mm^3	Result
A_{cis}	Total accumulation capacity in dwellings with cistern.	Mm^3	Result
A_v	Total accumulation capacity in all dwellings.	Mm^3	Result
Ac	Accumulation capacity in individual homes with cisterns.	(Lt/hh)	Survey *
Pc	Number of tanker trucks per year supplied to dwellings with cistern.	(tt/yr)	Survey *
Rc	The ratio of households with a cistern to total households.	(adimensional)	2020 census
Mcp	The ratio of households with cisterns using tanker trucks to total number of households with cisterns.	(adimensional)	Survey
At	Accumulation capacity in individual homes without a cistern.	(Lt/hh)	Survey
Pt	The number of annual tanker trucks that supplied homes without a cistern.	(tt/yr)	Survey *
Rt	The ratio of households without a cistern to total households.	(adimensional)	2020 census
Mtp	The ratio of households without a cistern using a tanker truck to the total number of households without a cistern.	(adimensional)	Survey
V	Total housing in SOAPAP coverage.	(dwellings)	SOAPAP

* Random values based on probability distribution derived from survey data. Note: tanker truck (tt), household (hh), liters (Lt).

Table A2. Description of the terms of the equations for calculating the flow of water supplied by tanker trucks.

Symbol	Variable	Unit	Source
Q_e	Bottled water flow rate.	Mm^3/yr	Result
Q_{em}	The flow rate of gran-de brand bottled water	Mm^3/yr	Result
Q_{er}	The flow rate of bottled water at LPWCs	Mm^3/yr	Result
Q_{em1}	Big Brand bottled water in carboy's	Mm^3/yr	Result
Q_{em2}	Big Brand bottled water in 5 L carafes	Mm^3/yr	Result
Q_{em3}	Big Brand bottled water in 1.5 bottles	Mm^3/yr	Result
L_{v1}	Liters of water distributed in Big Brand carboys	(Lt/d/hh)	Survey *
L_{v2}	Liters of water distributed in Big Brand 5 L carafes	(Lt/d/hh)	Survey *
L_{v3}	Liters of water distributed in Big Brand 1.5 L bottles	(Lt/d/hh)	Survey *
L_{v4}	Liters of water distributed in LPWC carboys.	(Lt/d/hh)	Survey *
Rba	The ratio of households consuming bottled water to total households.	(adimensional)	Survey *

* Random values based on probability distribution derived from survey data. Note: tanker truck (tt), household (hh), liters (Lt).

Table A3. Description of the equations for calculating the water cost distributed by tanker trucks and bottled water.

Symbols	Variable	Unit	Source of Information
$C_{tanker\text{-}t}$, C_{em1}, C_{em2}, C_{em3}, C_{em4}	Capacity of each type of container	Mm^3/yr	Market
$R_{tanker\text{-}t}$, R_{em1}, R_{em2}, R_{em3}, R_{er}	Number of each type of container	Container's	Equation result
$Pu_{tanker\text{-}t}$, Pu_{em1}, Pu_{em2}, Pu_{em3}, Pu_{er}	The unit price of each type of container	$/container	Price (2021) *
$Pt_{tanker\text{-}t}$, Pt_{em1}, Pt_{em2}, Pt_{em3}, Pt_{er}	The total cost of each type of container	(Lt/day/hh)	Equation result

Note: AE for bottled water. Tanker truck (tt), household (hh), liters (Lt). * Price information was collected in supermarkets in 2021. Prices tend to be higher in private stores.

Appendix B

A survey was conducted to 264 inhabitants of the City of Puebla, excluding 8 that did not correspond to the proposed delimitation. 256 valid responses were processed obtaining the statistical data presented in Table A4. Those parameters simulated with the Monte Carlo method applied to Equations (2), (3) and (12)–(15).

Table A4. Parameters to estimate water supplied by tanker truck and bottled water with Monte Carlo simulation.

Symbol	Minimum	Mode	Maximum	Single Value	Correlation	With the Variable	Assumed Distribution
Water supplied by tanker truck							
Ac	3100	7203	11,600	-	0.95	*Atm*	*Beta PERT*
Pc	1	2.836	24	-	-	-	*Beta PERT*
Rc	-	-	-	0.590	−1	*Rc*	*Yes-No*
Mcp	-	-	-	0.307	-	-	*Yes-No*
At	450	1346	1600	-	0.95	*Acm*	*Beta PERT*
Pt	1	3.322	24	-	-	-	*Beta PERT*
Rt	-	-	-	0.410	−1	*Rt*	*Yes-No*
Mtp	-	-	-	0.230	-	-	*Yes-No*
Vt	-	-	-	506,019	-	-	*Unique value*
Bottled water supply							
Lad_r	0	2.389	31.429	-	−0.562	Q_{em}	*Triangular*
Lad_1	0	0.570	20	-	0.106	Lad_3	*Beta PERT*
Lad_2	0	0.008	2.143	-	−0.000	Lad_1	*Beta PERT*
Lad_3	0	0.059	2.357	-	0.290	Lad_2	*Beta PERT*
Rba	-	-	-	0.902	-	-	*Yes-No*

Appendix C

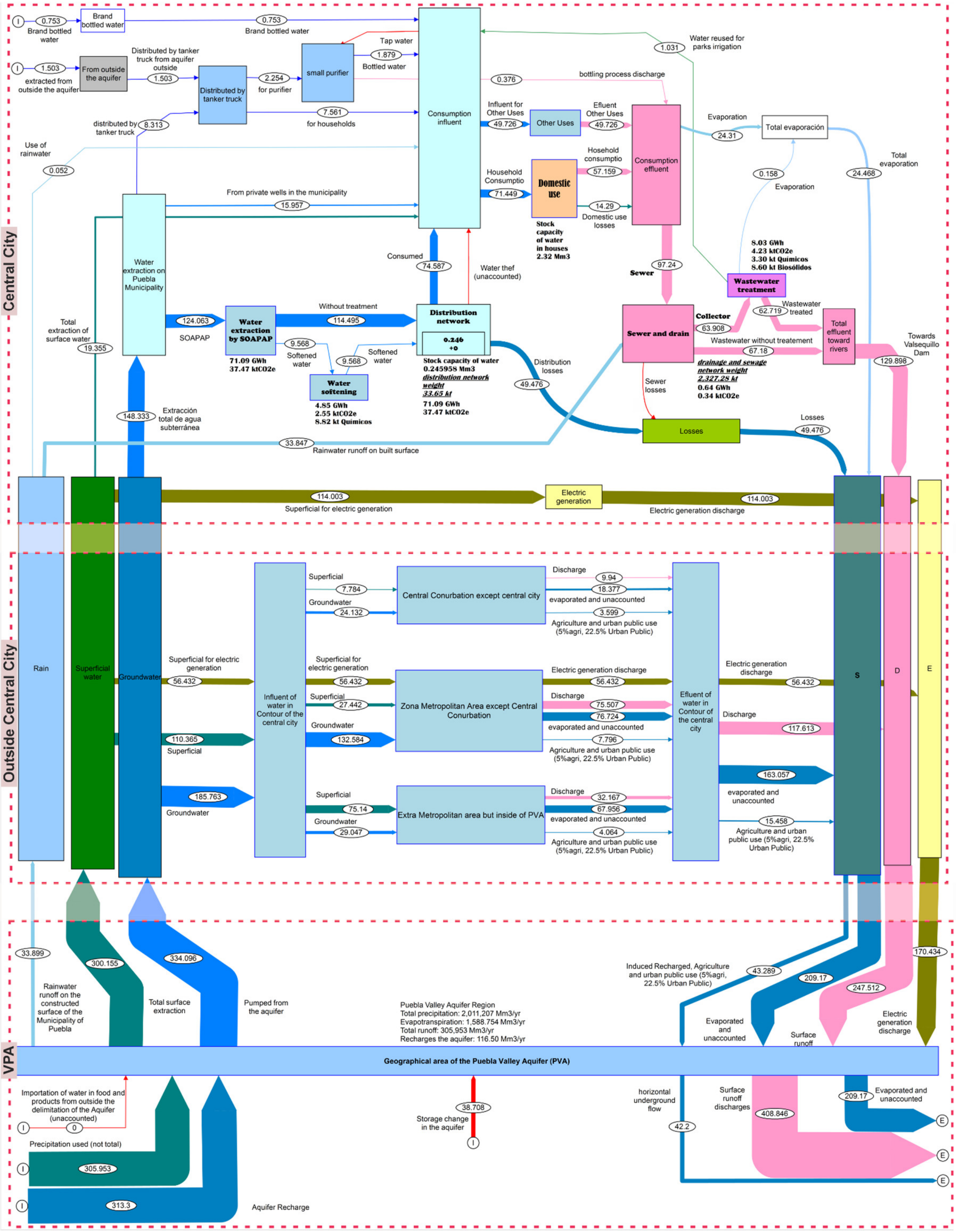

Figure A1. General diagram of the UWM model for the City of Puebla and its metropolitan area. Note: The letters "I" and "E", indicated in the diagram, represent import and export flows. These two flows connect the environment outside of the system boundaries with the processes inside.

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