Article

Puebla City Water Supply from the Perspective of Urban Water Metabolism

David Pérez-González , Gian Carlo Delgado-Ramos [*] , Lilia Cedillo Ramírez , Rosalva Loreto López , María Elena Ramos Cassellis , José Víctor Rosendo Tamariz Flores , Ricardo Darío Peña Moreno [*]

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Abstract: Urban population growth and the expansion of the built environment, pollution, overexploitation of water, inequality in water distribution, and the impacts of climate change in future availability of water, are all elements that jeopardize urban water security. Due to the complexity of urban water systems and their relevance for urban life, a holistic and integrative perspective is therefore needed to address such challenges. In this paper, Urban Water Metabolism (UWM) has been used for comprehensively understanding water (in)security in the City of Puebla (Mexico) and its metropolitan area. Water inflows and outflows have been estimated using a 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 to service providers and water related business, yet ineffective to guarantee 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 provision of water, economic interests must be reconsidered and therefore adjusted so they can be in line with such aspirational socioecological goals. UWM accounting can therefore inform new water governance arrangements, those based on both the best available knowledge and a vibrant participation of all relevant stakeholders.

Keywords: Urban Water Metabolism; city of Puebla; urban sustainability; Human Right to Water and Sanitation; water governance

1. Introduction

More than half of the world's population currently lives in cities [1]. By 2050 urban population is expected to reach 68.4% of total population due to the addition of 2.43 billion urban inhabitants [2]. By the same year, urban population in Latin America and the Caribbean is projected to reach 90% of total population [3]. Under a tendential scenario, population growth will translate into a higher demand of resources, including water [4]. Water availability is however already compromised as a consequence of overexploitation, pollution and the impacts of climate change such as a reduction of precipitation in mid-latitudes where the City of Puebla is located [5,6].

Part of the Megalopolis Central Region, the City of Puebla and its metropolitan area (which comprise Tlaxcala) is the fourth largest metropolitan area in Mexico after those of Mexico City,

Monterrey and Guadalajara [7]. 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) [8]. 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 [9,10].

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 [11]. Urban Metabolism (UM) is an appropriate approach that has its historical origins in the concept of "social metabolism" of Marx's economic theory [12,13]. This concept regained relevance applied to cities due to Abel Wolman's article "the metabolism of cities" [14]. The UM metaphor implies understand 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 presupposes limited capacities for decision making) and, in some cases, considering mechanisms for "closing cycles" which are at the base of urban circularity [15]. This holistic approach of urban metabolism accounting helps to interweave into a central model urban energy and material inflows, distribution, outflows and the potentiality for circularity, allowing 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 to engineering notions of water management and thus to more traditional industrial ecology approaches, yet a hybridization with other inter and transdisciplinary disciplines and fields of knowledge [16,17]. Studies vary from the assessment of multiscale institutional programs [18], the evaluation of city water (in)efficiency [19–21] or the integration of the urban nexuses approach to UM or UWM studies (e.g., Water-Energy-Carbon Nexus) [22–25], to the analysis of climate change implications and health impacts of pollution into UM and UWM [26–28]. 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 [29–33].

In Latin America, the number of UM studies is noticeable lower compared to Europe, USA or Asia [34], and only a fraction of them specifically deals with water. Some works apply the concept without quantifying flows and stocks [35–39], others partially include quantitative elements [40,41] or information from internal system processes [42–45], while others offer a material balance of inputs and outputs of the entire urban system, including its subprocesses [46,47]. Some of them include returning flows, moving from linear to circular UM approaches [48–51]. Must of UM and UWM case studies revisit large cities, neglecting the analysis of small and medium cities despite that the latter are those expected to growth the most [34]. Fewer than half of the above studies include bottled and tanker truck water flows in their analysis.

In the City of Puebla, an environmental historical accounting of water appropriation framed withing the social metabolism theory [52,53]. 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 or Google Scholar. The nearest type of water accounting studies at the urban scale, besides those related to water availability and water quality [54–69], comprises the assessment of rainwater capture potential which has been evaluated using a system dynamic model [70].

This paper offers the first UWM accounting for the City of Puebla, a medium-sized city struggling with limited water availability, increasing exploitation of the Puebla Valley Aquifer (PVA) [67–69,71], inefficient and inequitable distribution of water [33,70], service cuts to dwellings due to non-payment, excessive charges for users [72], water contamination and prevalence of diseases in communities nearby contaminated water bodies [54,55,57,62,73,74], as well as with water related socio-environmental conflicts [31,75] within a context of privatization of the public water service

(which legally took place in December 2013). All the above, and certainly the latter, has affected guaranteeing the Human Right to Water and Sanitation (HRWS).

The accounting model is based on a Material Flow Analysis (MFA) method to balance the flows, using the Monte Carlo simulation to estimate bottled and tankered water consumption flows for which there are no official records. Rainfall and runoff over the urbanized surface have been estimated in accordance with the standard NOM-011-CONAGUA-2015. The UWM approach described and applied below to the City of Puebla has allowed us to assess the diversity and complexity of urban water issues from a systemic perspective, relating the magnitudes found by the model to the water problems mentioned above and the associated expressions of social contestation, but also recognizing the potential of the model for social empowerment and thus, for ultimately enabling the advancement of a more sustainable, inclusive and just urban water governance.

2. Materials and Methods

MFA method was applied to estimate the UWM of the City of Puebla and its metropolitan area [76], with the support of the software STofflussANalyse (STAN) version 2.6 developed by the Vienna University of Technology (https://www.stan2web.net/). 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 to 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 by two subsystems: a biophysical and a social subsystem. The first one corresponds to the 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 [77]: 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 the 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). Circulation refers to water distribution, either through pipe networks, water trucks or bottled, from its sources to consumption and excretion. Is in 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, being 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, 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.

It is to be pointed out that due to the complex dynamics of the natural water cycle, the spatial unit of analysis do not correspond or is not limited to the urbanized area, it is rather the local aquifer area as explained further in the following section.
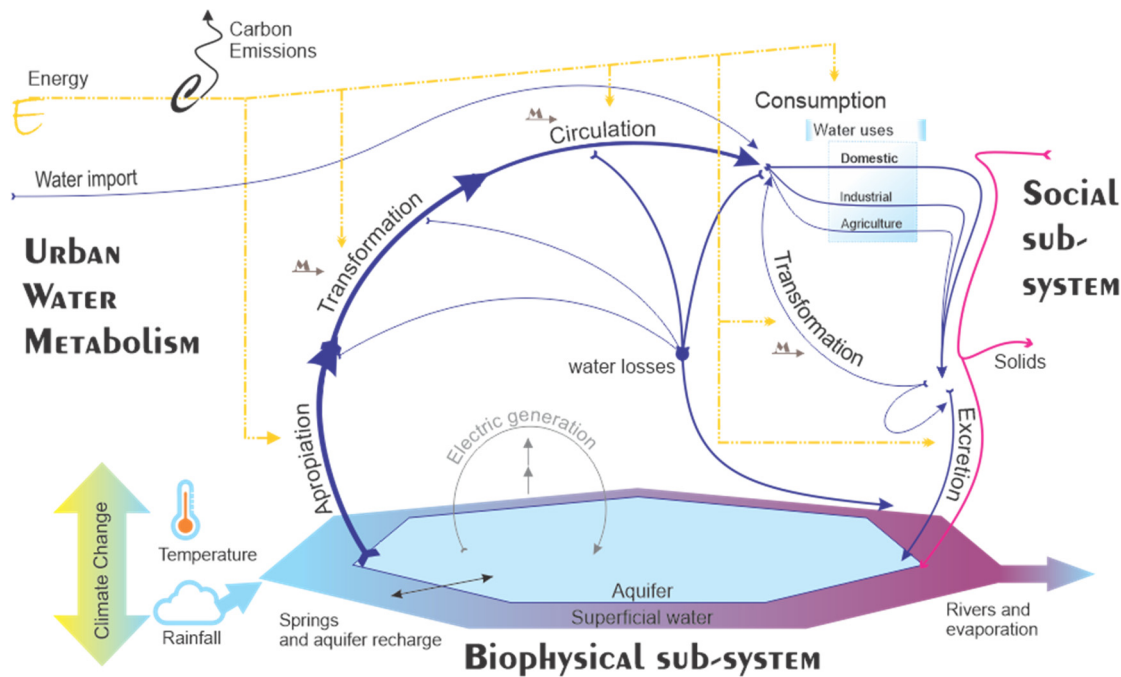
Figure 1. Urban Water Metabolism and its nexus with energy and carbon conceptual model. Authors' own elaboration.

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.
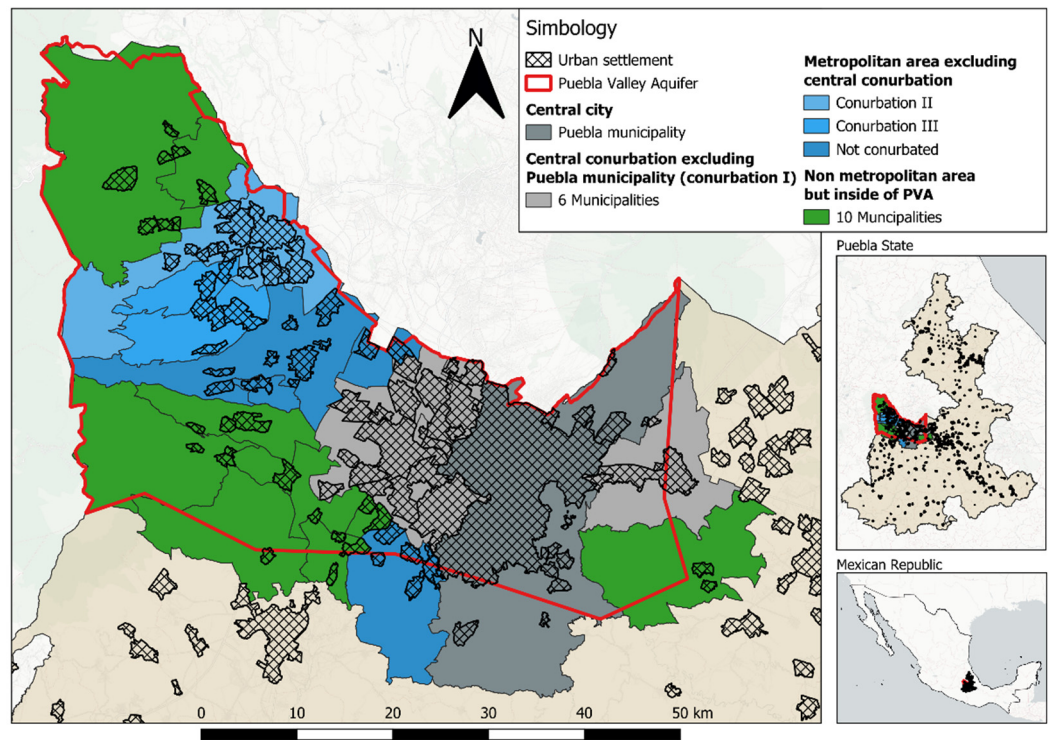

Figure 2. Delimitations of the study area. Authors' own elaboration.

The PVA extends approximately 2,025 km² and intersects with 26 municipalities; 20 of them are within the model's delimitation, and six are partially within [10]. The considered area was subdivided into zones according to their degree of urbanization:

- Non-metropolitan area within PVA
  - o 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, Santa Rita Tlahuapan.
- Metropolitan area outside of the central conurbation
  - o Ten municipalities in the metropolitan area of Puebla that 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, Tlaltenango.
- Central conurbation
  - o Five municipalities contiguous to Puebla central city that comprise our conurbation I: Amozoc, Coronango, Cuautlancingo, Juan C. Bonilla, San Andrés Cholula, and San Pedro Cholula.
- Puebla central city
  - o Puebla "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). 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. [10], and was balanced with precipitation and surface runoff water flows which was calculated according to the Mexican official standard NOM-011-CONAGUA-2015 with precipitation historical data from 14 meteorological stations (21065, 21248, 21120, 21163, 29170, 21101, 21247, 21034, 21249, 21016, 21046, 21167, 21223, 21214) 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.
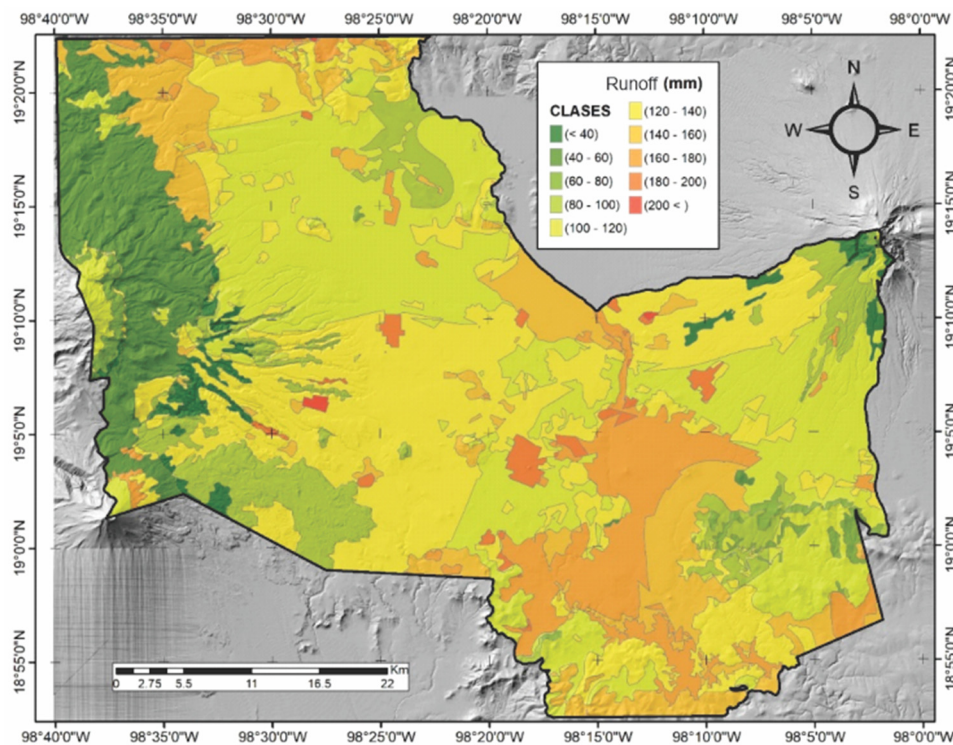
Figure 3. Water runoff in PVA. Authors' own elaboration.

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 Registry of Water Rights (*Registro Público de Derechos de Agua* – REPDA) available at https://app.conagua.gob.mx/ConsultaRepda.aspx. Due to the absence of empirical data, the harvesting and discharge concessions were considered a proxy for actual flows.

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 thru both, direct contact with the institution's personnel and public solicitations of information (www.plataformadetransparencia.org.mx). 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

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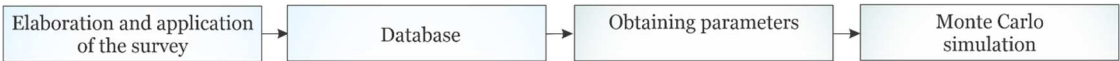
Figure 4. Summary of induction method for tanker truck and bottled water flows. Authors' own elaboration.

2.3.1. 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. The survey was written in

a colloquial language with multiple-choice answers accompanied by images to facilitate understanding by 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. This survey was applied in 2021 to 256 dwelling residents in the city.

- The second survey consisted of 7 questions applied on-site to five LPWCs in 2021 to gather information on their purification process 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 [76]. 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: We add 500 liters of storage capacity to city's dwellings that store extra water in sinks, floor-level water tanks (*tinacos*), barrels, jars or buckets; The average capacity of a tanker truck is 10,000 liters; The capacity of carboys is 20 liters, the average capacity of a carafe is 5 liters, and that of a bottle is 1.5 liters. Sugared and carbonated beverages were not considered; The average price in 2021 of a big brand water carboy (Bonafont, Epura, Ciel, etc.) was USD$1.90 while the one of other carboy brands was USD$1.70. The average price of a bottle of water and that of LPWC carboys was US$ 0.60. In 2021 the exchange rate was around 20 Mexican pesos for every 1 USD.

The Monte Carlo simulated operations 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 1b. Two probability distributions were used, where 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, it is considered 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 (3)).

$$C_{dwelling} = C_{wt+cis} + C_{extra} \tag{3}$$

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 (4)–(6) were then operated with Monte Carlo simulation (Table 1a).

$$Q_{tanker-t,\text{wt}} = Ac * Pa * Rc * Mcp * V/10^9 \tag{4}$$

$$Q_{tanker-t,cis} = At * Pt * Rt * Mtp * V/10^9 \tag{5}$$

$$Q_{tanker-t} = Q_{tanker-t,\text{wt}} + Q_{tanker-t,cis} \tag{6}$$

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 with- a cistern (A_{cis}), we suppressed the terms for the number of tankers (Pa, Pt) from the Equations (4) and (5), resulting in Equations (7) and (9).

$$A_{wt} = Ac * Rc * Mcp * V / 10^9 \qquad (7)$$

$$A_{cis} = At * Rt * Mtp * V / 10^9 \qquad (8)$$

$$A_v = A_{wt} + A_{cis} \qquad (9)$$

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 to carboys from LPWCs (Equations (10)–(13)). A distinction was made between the magnitudes of big brands and LPWC bottled water to estimate and compare their costs.

$$l_{v1} = E_1 * cap_1 \qquad (10)$$

$$l_{v2} = E_2 * cap_2 \qquad (11)$$

$$l_{v3} = E_3 * cap_3 \qquad (12)$$

$$l_{v4} = E_4 * cap_4 \qquad (13)$$

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 (14) a (17)). The total flow of bottled water supplied in the city is equal to big brand bottled water plus bottled water from LPWCs (Equations (18) and (19), and Table 2a).

$$Q_{em1} = L_{v1} * Rba * V * 365 / 10^9 \qquad (14)$$

$$Q_{em2} = L_{v2} * Rba * V * 365 / 10^9 \qquad (15)$$

$$Q_{em3} = L_{v3} * Rba * V * 365 / 10^9 \qquad (16)$$

$$Q_{er} = L_{v4} * Rba * V * 365 / 10^9 \qquad (17)$$

$$Q_{em} = Q_{em1} + Q_{em2} + Q_{em3} \qquad (18)$$

$$Q_e = Q_{em} + Q_{er} \qquad (19)$$

2.3.6. Approximation to the costs of water flows distributed in tanker trucks and bottled water

Under the assumption that tanker and bottled water is distributed in containers of known capacities (C), then it is possible to approximate the number of containers needed (R) to move the water flow (Q) (Equations (20)–(24)). Monte Carlo simulation was not applied in this procedure.

$$R_{tanker-t} = Q_{tanker-t} / C_{tanker-t} \qquad (20)$$

$$R_{em1} = Q_{em1} / C_{em1} \qquad (21)$$

$$R_{em2} = Q_{em2} / C_{em2} \qquad (22)$$

$$R_{em3} = Q_{em3} / C_{em3} \qquad (23)$$

$$R_{er} = Q_{e4} / C_{em4} \qquad (24)$$

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 (25)–(31), and Table 3a).

$$Pt_{tanker-t} = Pu_{tanker-t} * R_{tanker-t} \tag{25}$$

$$Pt_{em1} = Pu_{em1} * R_{em1} \tag{26}$$

$$Pt_{em2} = Pu_{em2} * R_{em2} \tag{27}$$

$$Pt_{em3} = Pu_{em3} * R_{em3} \tag{28}$$

$$Pt_{er} = Pu_{er} * R_{er} \tag{29}$$

$$Pt_{em} = Pt_{em1} + Pt_{em2} + Pt_{em3} \tag{30}$$

$$Pt_e = Pu_{em} + Pu_{er} \tag{31}$$

2.4. Consumo energético y emisiones de carbono de la empresa de agua

Energy intensity data for each process was obtained from SOAPAP's energy consumption and flow rates [78]. Carbon emissions were estimated by multiplying the amount of water consumed by the coefficient of CO_2e emissions per unit of energy [79]. Due to a lack of information, energy consumption beyond SOAPAP processes was not estimated.

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 subsistem

UWM of the City of Puebla and its metropolitan area operates within the hydrological cycle of the PVA region. This region receives 2,011.21 Mm^3/yr of precipitation, which feeds the surface runoff of the region with 305.95 Mm^3/yr, while 1,588.75 Mm^3/yr is evapotranspired.

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 sum 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 meters. In some areas in the south of Puebla central city, the static water level has decreased by up to 80m between 1973 and 2002 or an average annual decrease of 2.75 meters [10,68]. Current decline in water levels should be more severe, compromising regional water security. [65,66]. 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 [80].

It is to highlight that University Center for the Prevention for Natural Disasters (Cupreder) found inconsistent data in the PVA official information update documents. Such document, which informs policy officials if new water permits can be release, reported an increment in the PVA recharge by 20 Mm^3/yr between 2013 and 2016 (from 339 Mm^3/yr to 360 Mm^3/yr) [81–84]. Such increment has once again been reported in CONAGUA's 2020 update [10], which concludes that 20.6 Mm^3/yr are available for new concessions, yet no details on the estimation model are given. 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 dynamism, mostly residential housing and industrial parks [85–89].

The total surface water and groundwater inflows to the PVA region is 662.88 Mm³/yr.

3.2. Urban Water Metabolism in the PVA Region

As shown in Figure 5, water extracted from the environment totalize 671.83 Mm³/yr, comprising 300.16 Mm³/yr of surface water and 334.01 Mm³/yr of groundwater. Of 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 Mm³/yr and 36.156 Mm³/yr correspond respectively to imported water from outside the aquifer, plus the aboveground rainfall runoff estimated for the central city.
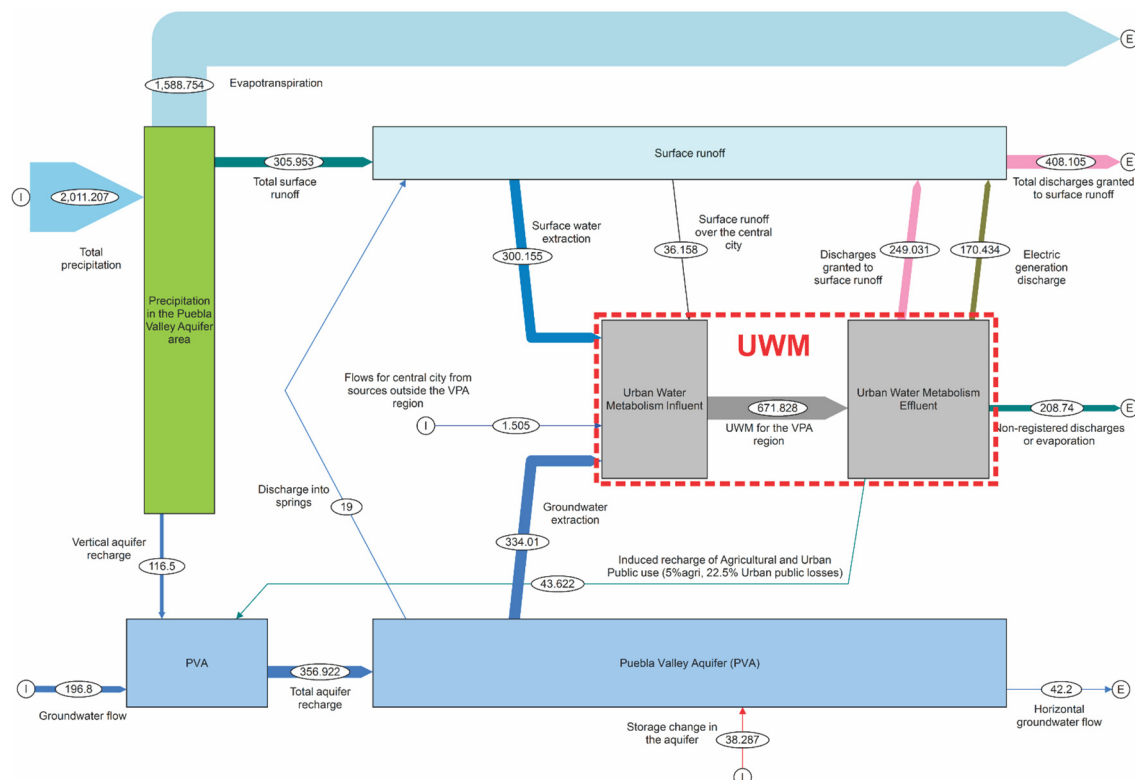

Figure 5. UWM of the City of Puebla and its metropolitan area. Authors' own elaboration.

3.2.1. UWM outside the central city of Puebla

Total appropriated water in settlements outside the central city was 352.56 Mm³/yr of water, composed of 110.37 Mm³/yr of surface water, 185.76 Mm³/yr of groundwater, and 56.43 Mm³/yr of surface water for power generation. Of the total water withdrawn, an then used, is discharged as follows: 33% of the discharges are concessioned (discharged 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 (which can vary between evaporated water, water that makes up the food harvested in the area, or informal discharges). See Figure 6.
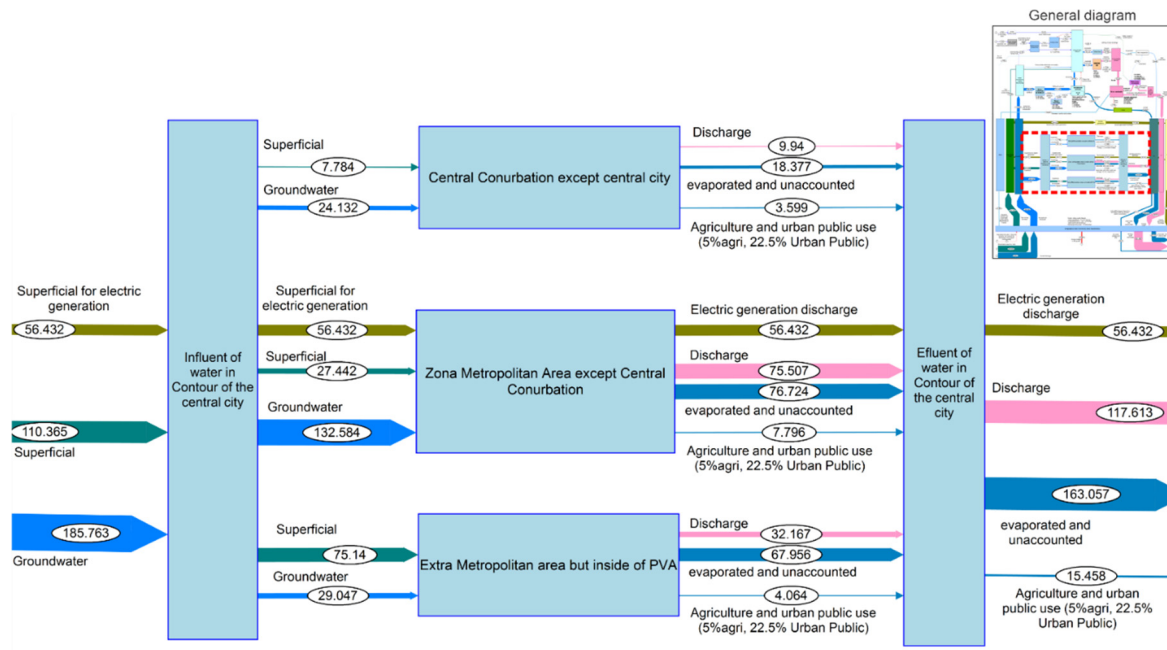
Figure 6. Urban Water Metabolism in the outskirts of the central city of Puebla. Authors' own elaboration.

The use of surface water gradually decreases as settlements become more urbanized, because of its progressive contamination due to lack of sanitation [90]. The Atoyac River is the primary runoff in the basin, concentrating the water region's pollution. It is considered an "environmental hell" by the Environment and Natural Resources Secretariat of the federal government (SEMARNAT) [91] as it has markedly affected the health of population living nearby, including a greater prevalence of leukemia and cancer [54,55,62].

3.2.2. Water appropriation for the central city of Puebla

A total of 167.74 Mm³/yr of water is extracted from the environment, distributed as follows: 148.33 Mm³/yr of groundwater; 19.36 Mm³/yr of surface water; 0.052 Mm³/yr of rainwater harvested in dwellings; and 33.85 Mm³/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 of big-brand bottled water totalizing 0.75 Mm³/yr. In the same way, groundwater extracted outside the PVA and distributed by tanker trucks within the PVA, was estimated in 1.50 Mm³/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 that contrasts with the high hardness of the groundwater of the City of Puebla [65,68]. Using low hardness water helps them to reduce maintenance 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 say higher LPWCs water prices.

In 2019 the local water utility extracted 124.06 Mm³/yr from the PVA, of which 63% came from the jurisdiction of the Municipality of Puebla and 37% was extracted in the surrounding municipalities (Table 4). Alternative flows to the water utility, add a flow of 8.31 Mm³/yr of groundwater, for the most part privately distributed by tanker trucks. Of this flow 7.57 Mm³/yr was for domestic consumption and 0.66 Mm³/yr distributed to LPWCs. Finally, another flow of 15.96 Mm³/yr was extracted in private wells.

Table 4. 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 (Mm³/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 [62,67]. Hardness is another water quality problem in the PVA, ranging from 286 mg/L to 1,894 mg/L [71].

The water treatment applied by the water utility are chlorination and water softening. The first is applied to all the water extracted 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 Mm³/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 [92]. Inconsistencies were found in the water softening information, such as consuming chemicals without reporting water softening and vice versa (Table 5).

Table 5. Flows softened by the water company in Puebla central city.

Water softener plant	Annual softened flow (Mm³/a)	Percentage (%)	Amount of chemicals (Kton/a)	Consumption of chemicals (Kg/m³)
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 informed they consume bottled water due to mistrust of tap water quality. Of such consumption, 70% corresponded to water supplied by LPWCs who argue to apply ultrafiltration processes. LPWCs 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 result of its price versus the households' income, a situation that unevenly affects guaranteeing the human right to water.

LPWCs are supplied with 2.25 Mm³/yr of water transported by tanker trucks of which 1.88 Mm³/yr is bottled for sale and 0.38 Mm³/yr is used for purification process such as washing of containers, filters, etcetera. LPWCs respondents consider that more than half of these businesses are

clandestine, whose product is even more affordable than the regularized ones because they do not perform the entire purification process, neither 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 distribution network 40.66% of water withdrawn, or 49.476 Mm^3/yr, is lost due to leakages. Only 74.59 Mm^3/yr is thus actually delivered to final consumers. The amount of leaked water in the distribution process is equivalent to that imported from neighboring municipalities (37%). This suggests that improving physical efficiency would reduce the dispossession of water in settlements surrounding the city of Puebla, which in turn would avoid socio-environmental conflicts such as those that occurred in Nealtican or Coronango [31,33]. On the other hand, losses in the distribution network are 4.8 times greater than water distributed in tanker trucks, therefore, if losses were reduced to 20% and distributed equitably to users, the need for tanker truck service could be minimized.

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 1b. 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 6).

Table 6. 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
20L carboys	0.687 Mm^3/yr	
5L carafes	0.066 Mm^3/yr	
1.5L bottle	0.072 Mm^3/yr	
LPWC bottled water		1.879 Mm^3/yr

Source: Authors' own elaboration.

The water flow distributed by tanker truck has been estimated in 7.56 Mm^3/yr. This consumption is due to: i) water inaccessibility of 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) [93]; 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 informed the purchase of tankered water collectively to divide the costs among their neighbors. This situation affects guaranteeing human right to water.

3.2.7. Water consumption in the central City of Puebla

After the distribution water losses, the sum of all flows consumed in the city is 121.17 Mm^3/yr (Table 7), of which only 0.85% is treated water which is mostly reused for irrigating green public areas by the Municipality of Puebla, i.e., the circularity of the UWM is practically nil. Besides that, rainwater harvesting in dwellings corresponds to 0.04% of the total amount of water appropriated from the environment, which according to Martínez Austria's proposal, it would increase up to 0.6 Mm^3/yr [70], representing 0.5% of the total water consumed in Puebla city, so this alternative would not compensate city's water deficit.

Table 7. Influent disaggregated for consumption process in the UWM of the central city of Puebla.

Influent source	Flow Mm³/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	
Discharges to sewers or water bodies	97.24	0.25
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. * Negative sign because it is wastewater that does not enter the uses.

Licensed surface water flow for electricity generation in the Municipality of Puebla is 114.00 Mm³/yr. This flow was included in the UWM model but was not included in Table 7 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) in the municipality of Puebla is *San Lorenzo Potencia* plant, and consumes 0.021 Mm³/yr of water, because 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 the use of 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 8 and Figure 7.

Table 8. Water Flow consumed in the central city of Puebla by uses.

Consumption	Annual flow (Mm³/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: 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.

The imbalance between the inputs and discharge, as presented in Figure 7, was compensated with a flow called balance (data from REPDA). For example, industrial discharges corresponded to 34.46% of the water consumed for such use. 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.
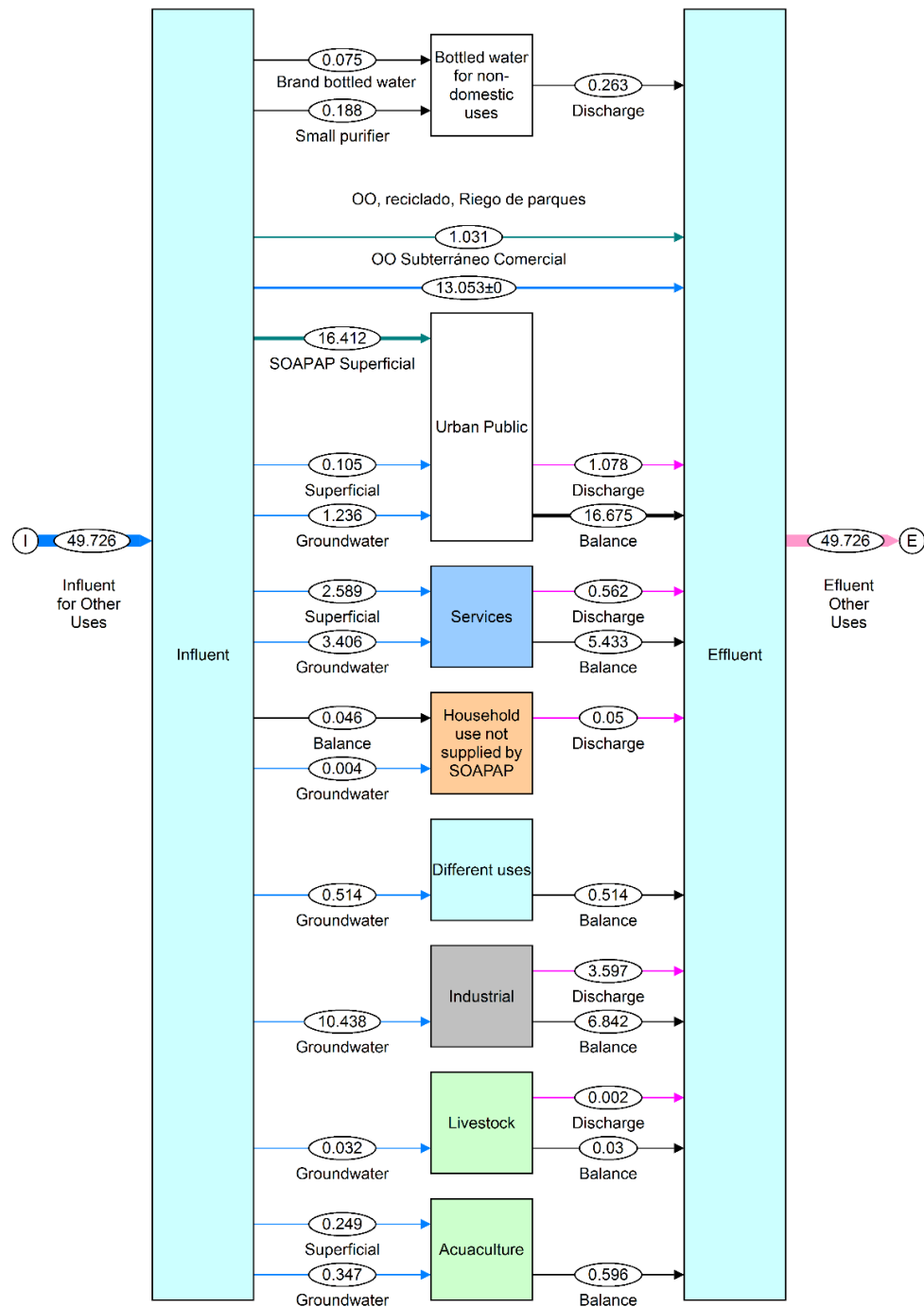

Figure 7. Water uses in the central city. Authors' own elaboration.

The micrometering percentage reported by the water utility is 19.18%of the total users in the central city [94], 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-meters installation due to the associated costs and the distrust towards the water utility which is related to current

excessive rates of water. Measurement is thus seen as a mechanism that will turn the water service even more expensive than what it already is [95–97].

Excessive water bills have caused non-payment of service leading to water cut-offs for delinquent users [98–100]. Water cut-offs causes social conflicts as it challenges guaranteeing HRWS as it 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 [101–106].

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 (Figure 8). The sum of the water storage capacity of the water utility plus the total dwelling's storage capacity totalize 2.57 Mm^3. Figure 8 shows two probability distributions, the first on the left refers to the dwellings without a cistern that stores water in tanks plus barrels or buckets, and the distribution on the right relates to the dwellings with a cistern.
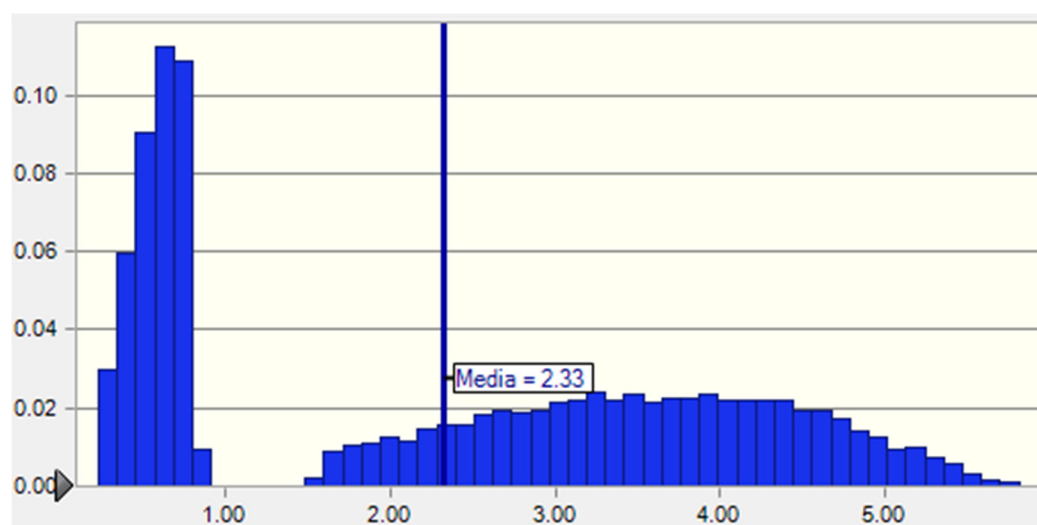

Figure 8. Probability of water accumulation capacity in city dwellings. Authors' own elaboration. Note: Units on the abscissa axis are Mm^3, and the ordinate axis refers to probability.

3.2.9. Water excretion in the central City of Puebla

In Puebla city, drainage and sewerage share the same infrastructure, where rainwater runoff, domestic and industrial discharges confluence. In that water, pollutants found include pharmaceuticals [107], microplastics [60,108], other emerging contaminants [108], and heavy metals [55]. Their confluence allows them to mix and produce chemical reactions that might result in new pollutants mixtures, which may not be treated by WWTPs [109].

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's treated 63.91 Mm3/yr and 67.18 Mm3/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 [110], 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 water sustainability.

3.2.10. Wastewater treatment in the central City of Puebla

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 to 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 9).

Despite the above, it can be argued that UWM in the City of Puebla city 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 spaces irrigation, which represents a circularity of 4.37% (78.52 Mm3/yr) of the total water discharged in the city [46].
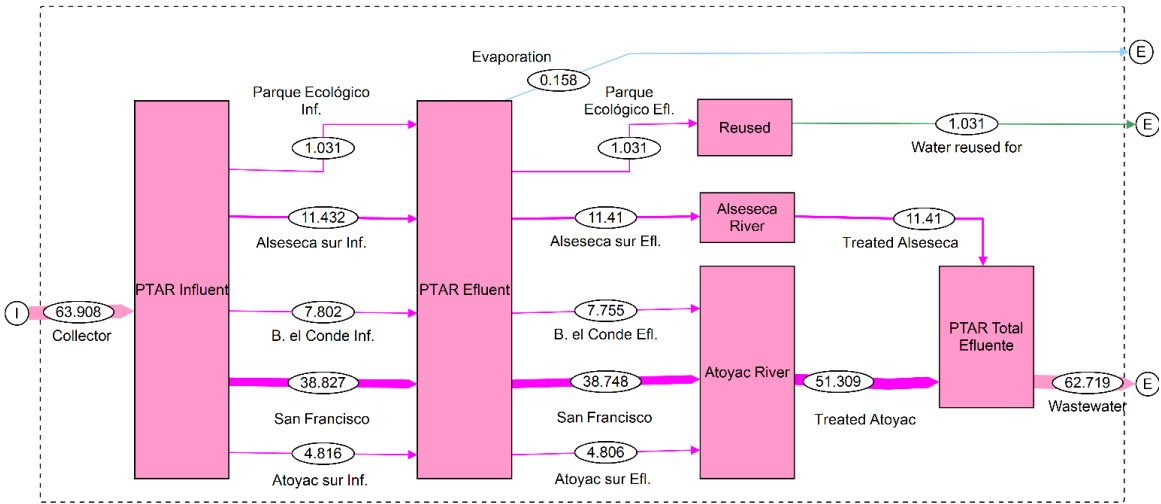

Figure 9. The wastewater treatment process at the water utility. Authors' own elaboration.

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 [73,111]. The dam acts as a sedimentation vessel, a metal scrubber due to the decrease in flow velocity and as a biofilter due the effect of water lily [63]. The dam's water is used for irrigation to produce food consumed in the City of Puebla, its metropolitan area, and other places[112,113].

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 them potentially carcinogenic and linked to diseases such as leukemia or cancer in children and young people in the metropolitan area [56,114].

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$_2$e of which 47.45 KtCO$_2$ are related to water pumping, and 6.79 KtCO$_2$e 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$_2$e/p/yr (Table 9).

Table 9. Urban Water Metabolism energy consumption and carbon emissions in the water utility.

Processes	Percentage	Consumption of energy GWh	Mm³/a (hm³/yr)	KWh/m³	KtCO₂e	KgCO₂e/m³
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.

The estimated energy intensity to treat wastewater flows was 0.1257 KWh/m³, which is lower than the average energy intensity verified fort sanitation in the state of Puebla (0.60 KWh/m³) [78]. It is also lower than the energy consumed in the city of San Purisima del Rincón (0.38 KWh/m³) [27], and lower than of that of other foreign cities such as Oslo (1.32 KWh/m³), Nantes (0.87 KWh/m³), Toronto (1.44 KWh/m³) and Turin (0.94 KWh/m³) [25].

Assuming that energy intensity to treat wastewater is the same as the average intensity of Puebla state (0.60 kWh/m³), a recalculation of the treated wastewater flow would result in 13.39 Mm³/yr, which is equivalent to 10% of the total excreted water of the central city. This differs from data reported by the water utility (63.91 Mm³/yr). It is therefore possible that 90% of the excreted wastewater is actually discharged untreated. This anomaly in data resonates in the face of complaints expressed by social activists who accuse the water utility of fraud, because they assure that sanitation is not performed while users are charged for it [115]. The above is a social problem on top of the environmental one derived from discharging untreated water into Alseseca and Atoyac rivers [116]. The Ministry of the Environment and Natural Resources (SEMARNAT) has even described the current condition of the Atoyac river as an "environmental inferno"; second most polluted river in the country [117].

Water losses in the network imply the waste of 42.09 GWh of energy, contributing to climate change due to the emission of 22.18 Kt of CO_2e. This generates operating costs that the water utility at the end transfer to users through tariffs, affecting water affordability [118].

3.4. Other material flows related to Urban Water Metabolism in the central city of Puebla

The UWM is linked to other flows, 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.

3.4.2. Water treatment chemicals in the central city of Puebla water utility

Water softening required 8,824.7 kg/yr of chemicals comprising sodium chloride, sulfuric acid, calcium hydroxide, anionic polymer, cationic polymer, sodium hypochlorite, antifouling, genefloc, sodium hydroxide, metabisulfite. Wastewater treatment required 3,298.06 kg/yr of chemicals including ferric chloride, anionic polymer, and cationic polymer. The increasing need for drinking 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 in 2019, the water utility supplied 506,024 dwellings, housing approximately 1,874,084 inhabitants. The amount of water withdrawn was estimated at 181.37 liters *per capita* per day (LPCD), a data usually published in official reports; however, it implies the inexistence of 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 water equitably among the population, an extra 72.33 LPCD could be available for distribution. It is to notice that 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, andSenegal [119,120].

3.5.1. Accessibility, affordability, and accessibility of water in the central city of Puebla

The annual costs paid by users for water distributed by tanker and bottled water was estimated at USD 200.31 million, which is 1,285% higher than what the water utility collected by annual prepayment in 2019 which reached USD$15.41 million (payment collection efficiency was reported to be at around 30% of the total collectable income).

The big brand bottled water, LPWCs, and tanker trucks 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 to 4 times higher for LPWC service; and for tanker truck service it was equivalent (Figure 10). This is without omitting that water shortage enables the proper conditions for increasing water tanker truck rates [121].

Figure 10. Flows and their total annual costs in Puebla city. Authors' own elaboration

The above reveals that the cost paid for alternative water acquisition compared to the 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 of 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 [46], for the City of Puebla 3.85 LPCD, and for Tepic 7.09 LPCD [47]. 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. Data collection

Absences and inconsistencies in the data collected for the UWM model are common in UWM and UM studies [12]. 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 [10,81,82], 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 [56,63,112–114] and related socio-environmental conflicts [31,32]; 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 to the general public.

5. Conclusions

UWM accounting and helped us to assess the Puebla of City's main water issues holistically, revealing challenges and opportunities for improving the sustainability of the city's water metabolism while addressing the HRWS.

The UWM model allowed us to relate the macro processes of the hydrological cycle in the Puebla city with others small-scale sub-processes such as domestic consumption of bottled water, among others. The static model can help us as a basis for future predictive models where effects at different scales can be simulated. And the refinement of the data would help us to disaggregate flows in geographic space to observe asymmetries related to HRWS in the city.

The coincidence between the inconsistencies with the official water data and the water problems, leads us to think that there is a relationship between the quality of the information and unsustainable water management. Therefore, the generation of better quality and transparent information could help to improve the management of water processes, and thus improve the sustainability of the UWM.

Although the accounting of bottled and tankered water flows require further validation, approaching water flows from information taken from consumers offers the opportunity to estimate urban water flows that are not officially recorded, and thus highlight hidden flows and their related implications for complying with HRWS. Furthermore, our findings suggest that the lack of compliance of HRWS goes hand in hand with private profit generation, a plausible reason that may explain why most contestation movements in defense of HWRS are against any water privatization model.

We recognize that UWM accounting for holistically addressing the complexity of urban water systems is a valuable decision-making tool. Moreover, we consider that data generated by UWM accounting exercises and the analyses they enable, can play a key role informing but also empowering non-specialized stakeholders and inhabitants in general. Informed social awareness of prevailing water challenges may in turn generate the adequate environment for further mobilizing key stakeholders, building consensuses and alliances, and promoting the cogeneration of solutions, all of which we expect to be part of normative participatory governance model for a more sustainable, just and inclusive UWM profile for the City of Puebla.

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.	Mm³/yr	Result
$Q_{tanker\text{-}t,wt}$	Flow distributed by tanker trucks in households with water tank.	Mm³/yr	Result
$Q_{tanker\text{-}t,cis}$	Flow distributed by tanker trucks in households with cisterns.	Mm³/yr	Result
A_{wt}	Total accumulation capacity in dwellings with water tank	Mm³	Result
A_{cis}	Total accumulation capacity in dwellings with cistern	Mm³	Result
A_v	Total accumulation capacity in all dwellings	Mm³	Result
Ac	Accumulation capacity in individual homes with cistern.	(Lt/hh)	Survey*
Pa	The number of tanker trucks per year supplied to tanker homes.	(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 pipelines supplied to 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.	Mm³/yr	Result
Q_{em}	The flow rate of gran-de brand bottled water	Mm³/yr	Result
Q_{er}	The flow rate of bottled water at LPWCs	Mm³/yr	Result
Q_{em1}	Big Brand bottled water in carboy's	Mm³/yr	Result
Q_{em2}	Big Brand bottled water in 5L carafes	Mm³/yr	Result
Q_{em3}	Big Brand bottled water in 1.5 bottles	Mm³/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 5L carafes	(Lt/d/hh)	Survey *
L_{v3}	Liters of water distributed in Big Brand 1.5L 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
$C_{tanker-t}$, C_{em1}, C_{em2}, C_{em3}, C_{em4}	Capacity of each type of container	Mm³/yr	Market
$R_{tanker-t}$, R_{em1}, R_{em2}, R_{em3}, R_{er}	Number of each type of container	Container's	Equation result
$Pu_{tanker-t}$, Pu_{em1}, Pu_{em2}, Pu_{em3}, Pu_{er}	The unit price of each type of container	$/container	Price (2021)
$Pt_{tanker-t}$, 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). *Tomado de tiendas comerciales en 2021. El costo suele ser más elevado en tiendas particulares.

Appendix B

A survey was applied 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 9. Those parameters simulated with the Monte Carlo method applied to Equations (4), (5) and (14)–(17).

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	3,100	7,203	11,600	-	0.95	Atm	Beta PERT
Pa	1	2.537	24	-	-		Beta PERT
Rc	-	-	-	0.590	-1	Rc	Yes-No
$Mcp\ Carboy$	-	-	-	0.307	-		Yes-No
At	450	1,346	1600	-	0.95	Acm	Beta PERT
Ptm	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
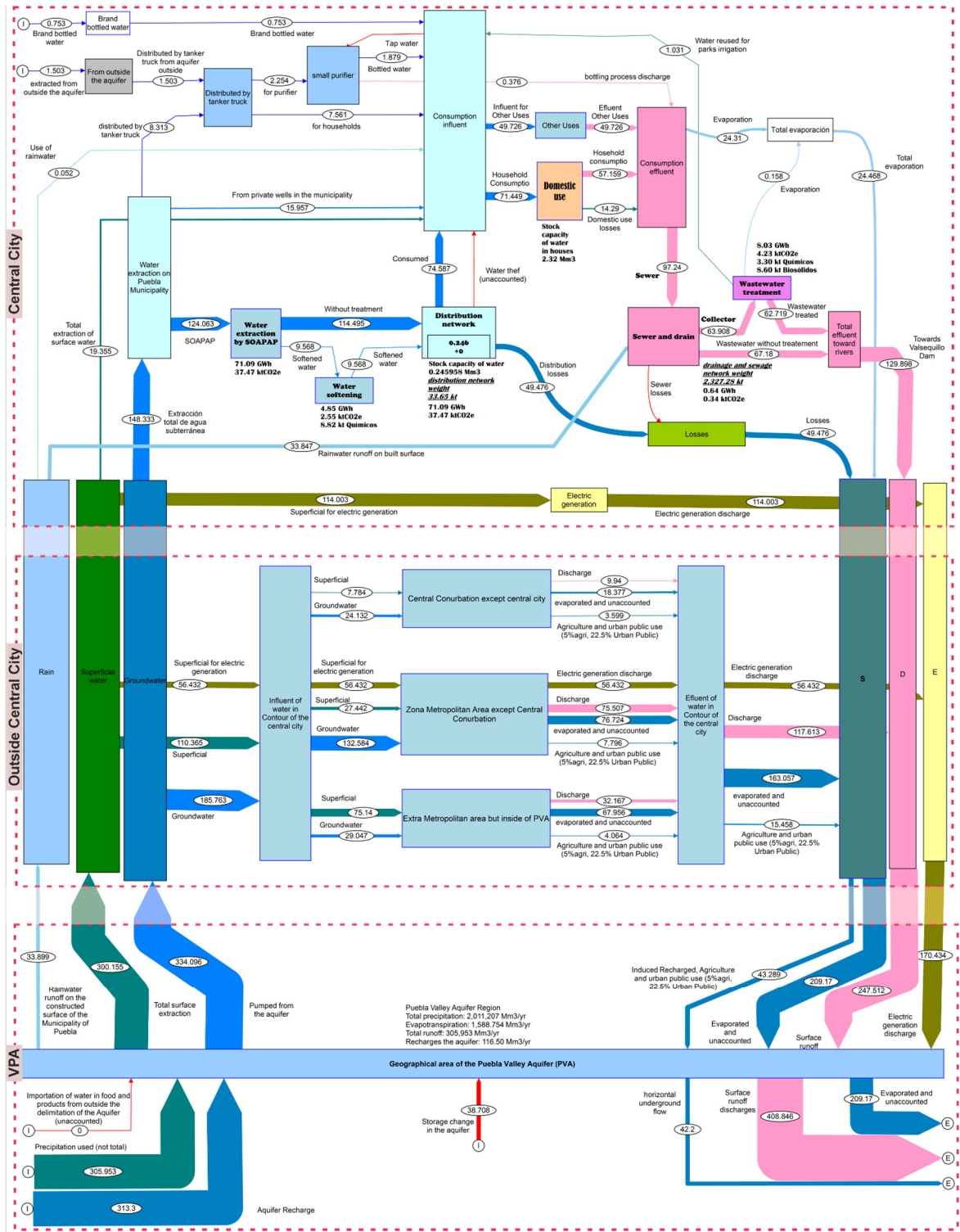
Figure A1. General diagram of the UWM model for the City of Puebla and its metropolitan area.

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