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Advancing urban metabolism studies through GIS data: resource flows, open space networks, and vulnerable communities in Mexico City.

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Advancing urban metabolism studies through GIS data: resource flows, open space networks, and vulnerable communities in Mexico City.

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1. INTRODUCTION

1.1 URBAN METABOLISM AND OPEN SPACE NETWORKS

Growing evidence demonstrates that cities with high resource consumption and waste generation are more vulnerable to scenarios of future resource scarcity due to climate change and global population growth (Manna et al., 2018; Parish et al., 2012; Hanjra & Ejaz Qureshi, 2010). Urban planning defines urban forms and the types of infrastructure in a city depending on geographic characteristics and construction material preferences, thus determining an important part of the overall resource efficiency of the urban fabric (Yang et al., 2014; Pincetl et al., 2012; Deilmann, 2009). Urban Metabolism (UM) research has evolved substantially in recent years by adopting an interdisciplinary and multi-scale approach in the analysis of internal resources and social-ecological dynamics in urban systems, encompassing different lines of thinking as in industrial ecology, urban ecology, political ecology, and political-industrial ecology (Newell et al., 2017; Newell and Cousins, 2015; Castán Broto et al., 2012). In industrial ecology, UM is defined as the sum total of all technical and socio-economic processes associated with the production, distribution and consumption of resources that occur in cities, resulting in growth, production of energy, and elimination of waste (Kennedy et al., 2007). UM studies provide valuable insights to inform strategies for more resource-efficient cities by developing holistic frameworks for urban modelling (Kennedy et al., 2011; Barles, 2010), which can advance understanding of the impacts of human activities on the natural environment.

In this article, we argue that integrating spatially explicit UM data into urban planning can leverage the resource-efficient development and management of open space networks (OSN).

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OSN are interconnected systems of natural and semi-natural green-blue infrastructure areas and public space in an urban region (Frazier & Bagchi-Sen, 2015; Linehan et al., 1995). From a UM perspective, OSN planning strategies can help generate or recycle resources as well as reduce resource demand through optimized, multi-scale, and qualitative use of urban space (Kennedy et al., 2011; Agudelo-Vera et al., 2012; Leduc and Van Kann, 2013). In other words, OSN can be used as an asset to minimize resource extraction, energy consumption and waste generation, while preserving urban ecological dynamics.

Previous spatially explicit UM studies have illustrated spatiotemporal dynamics of materials and resource flows and infrastructure at multiple scales (Yeow & Cheah, 2019; Smit et al., 2019; Spierre Clark & Chester, 2017, Guibrunet et al., 2016), building stocks (He et al., 2020; Mao et al. 2020; Lanau & Liu 2020; Miatto et al., 2019), energy and water urban harvesting scenarios (Agudelo-Vera et al., 2012), and integrated the spatial dimension of environmental and socio-economic information (Caputo et al., 2019; Choe & Thorne, 2019; Farzinmoghadan et al., 2019; Juwet & Ryckewaert, 2018; González et al., 2014; Leduc & Van Kahn, 2013). However, these studies mainly focused on the quantification of resource flows/stocks, their circulation and location in urban systems, and the relations of power among stakeholders, without considering the use of space as a means to improve the resource efficiency of the system being studied. A growing number of works highlight the benefits of integrating spatially explicit accounts of UM flows/stocks for informing policy-making and resource management strategies at the city level. For example, mapping the distribution of energy demand by district in Bengaluru, India, allowed Nalini (2016) to understand the local water-energy nexus and the spatial dimension of UM flows and resource infrastructure. By overlapping spatially explicit water and energy datasets, researchers were able to relate the location of inefficient sections of the drinking water distribution network and pumping

facilities with high energy consumption districts and geographic features of the city. Wielemaker et al. (2019) used geographic boundaries, socio-demographic data, and GIS-based information on urine and feces at the neighborhood and building levels in Amsterdam to produce a spatially explicit inventory of nutrient hotspots in several areas of the city. The spatially explicit data at the local level allowed to identify clusters of buildings with a high nutrient load and, through this, to better inform the planning of future sanitary systems. These studies demonstrate the value of spatially explicit UM data on critical flows/stocks (energy, construction materials and nutrients) at different scales (regional, urban and building) and suggest further research to consolidate spatially explicit data harvesting methods. However, they did not focus on applicability of results in practice or the identification of opportunities to enhance the incorporation of UM results into urban planning and design strategies (Perrotti, 2019). Consideration of urban spatial structures (i.e., open spaces) underpinning metabolic flow/stock dynamics can favor the uptake of UM studies by planning practitioners and, consequently, significantly contribute to the development of a systemic approach to resource efficiency in urban systems (Perrotti, 2020).

Reinforcing and preserving existing OSN in urban areas can increase urban populations' exposure to natural environments, enhance biodiversity, increase soil water infiltration and reduce the concentrations of atmospheric pollutants (Tratalos et al., 2007; Cohen et al., 2014), while providing opportunities for recreation and physical activity, promoting community identity and a sense of well-being (Perrotti & Iuorio, 2019), and increasing economic benefits (Zhang et al., 2012), among other social-ecological benefits (Perrotti et al., 2020). Previous research on OSN has, for example, focused on land-use regulations to preserve existing ecological networks (Ahern, 2004; Weber & Wold, 2000), applied landscape ecology models to integrate future vacant lots in shrinking cities (Frazier & Bagchi-Sen, 2015), investigated

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energy and resource requirements for scaling-up urban agriculture (Mohareb et al., 2017), and designed scenarios to reframe circular economy questions through urban and landscape planning strategies (Amenta & Van Timmeren, 2018; Marin & De Meulder, 2018). Another prolific line of research focused on assessing the loss of connectivity among fragmented green patches caused by uncontrolled urban form and urban sprawl (Yacamán Ochoa et al., 2020; Toger et al., 2016). It demonstrated that enhancing connectivity can provide higher social-ecological values in urban environments (Frazier & Bagchi-Sen, 2015).

Despite the increased focus on the social-ecological values of OSN over the last decades, only a limited number of studies have related the spatial configuration of open spaces with resource accessibility; this represents a critical frontier in UM research. Spatially explicit studies on resource consumption and the availability and accessibility of utility networks and infrastructure can help urban and landscape planners identify opportunities in the urban space for mitigating resource-related vulnerabilities (e.g., neighborhoods with high energy demand and/or significant solid waste generation) and enhancing the harvesting of local resources through spatial design strategies. Based on this premise, this article will present a methodological strategy to investigate how the use of GIS-explicit data can improve the applicability of UM studies in the planning and management of OSN. Addressing this question can provide novel insights into using OSN to achieve more efficient distribution and concentration of UM flows and infrastructure in urban systems.

1.2 BACKGROUND: MEXICO CITY

Vulnerable communities, communal lands, and indigenous areas

Mexico City is located on a plateau at 2,240 meters above sea level, surrounded by volcanic mountains in the Valley of Mexico with a total area of 1,480 km² and approximately 8.9 million inhabitants. An estimated 3.4 million live below the poverty line and are in a situation of social and economic vulnerability (CONEVAL, 2018). This population is mainly located in low-income neighborhoods on the urban-rural edge and some areas of the city center; they have deficiencies of access to education, healthcare, basic services, public space, housing quality conditions, and property titling (Ziccardi, 2014; Bayón & Saraví, 2013; Aguilar & Mateos, 2011). The large urbanized region within which Mexico City is located is known as the Metropolitan Zone of the Mexico Valley and has a total population of approximately 21 million, including 60 other municipalities in the states of Hidalgo and Mexico (see Figure 1). Mexico City is managed by a city government (*Gobierno de la Ciudad de México*) and includes 16 independent boroughs (*alcaldías*) with diverse geographic and socio-economic characteristics. The boroughs are subdivided into neighborhoods (*colonias*); for statistical analysis, these are divided into rural and urban “basic geostatistical areas” (AGEB, *Área Geo-Estadística Básica*), which constitute the smallest units of the national census.

(Insert Figure 1 about here)

Approximately 59% of Mexico City’s land area is classified as Conservation Land (*Suelo de Conservación*) due to unique climatic, topographic, and soil characteristics, and includes a variety of agricultural and natural ecosystems such as forests, grasslands and wetlands. About 12% of the Conservation Land is urbanized (SEDEMA, 2016) and 3% is covered by informal

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settlements (*asentamientos humanos irregulares*), i.e. residential areas where inhabitants lack legal ownership of the land and basic services are limited due to irregular land occupation, precarious dwelling construction, or for being located in hazardous areas of high ecological value (Aguilar and López Guerrero, 2012; UN-HABITAT, 2015). Moreover, being built without the support of local authorities, they are not always connected to the municipal utility networks and, in some cases, basic needs (e.g., drinking water) are fulfilled through informal means such as water trucks, public hydrants, natural springs, rivers, and wells (Aguilar and López Guerrero, 2012). In 2010, it was estimated that more than 50,000 families lived in informal settlements in Mexico City and only 30% of all dwellings in the city were connected to all municipal utility networks: drinking water, electricity, and sewage (PAOT, 2010).

Vulnerable communities are defined as urban and rural areas with a majority of the population living with precarious access to basic services, public space, and housing quality conditions due to their socio-economic status or irregular land occupation. These areas can play a key role in future natural-system conservation strategies and the management and planning of new infrastructure and OSN in Mexico City (Wigle, 2010), considering that many of them are located on the urban-rural edge, at the intersection of nature reserves, communal lands, and indigenous areas (*pueblos originarios*). Communal lands are properties given to farmers after the Mexican Revolution (1910–1912), and are held by a community for agriculture use, residential settlement, and public use. This period of land reform ended in 1992, with a constitutional amendment that allowed privatization of communal lands (Lerner et al., 2018; Jones & Ward, 1998) and resulted in the conversion of green areas into new urban developments. Due to rapid urban growth over the last 30 years, communal lands were annexed to areas inhabited by indigenous, which were historically rural areas developed independently from Mexico City (Arach et al., 2018; Medina, 2009). These indigenous areas

are territorial units preserving and reproducing totally or partially their own social, economic, cultural, and political institutions, establishing their political status with juridical personality, own patrimony and right to self-determination (SEPI, 2019). All indigenous areas have leaders elected by their community, who have the responsibility to encourage collective works for common benefits, organize community work and social development projects, and establish agreements between neighbors to solve conflicts such as those associated with the distribution of resources and common lands (Ortega Olivares, 2010). Common to both communal lands and indigenous areas is the legal and spatial capacity (i.e. independent governance supported by local authorities and areas with public open spaces) to organize different communities with a local-scale and community-led approach to decentralized resource management while preserving their cultural heritage, identity, and habitat.

Existing UM studies

The use of a UM approach to study Mexico City is still limited to few research projects. Depending on the discipline and focus of the study, these vary with regard to the metabolic flows analyzed and scale of study (Delgado-Ramos, 2021, 2015a, 2015b, 2013; Huerta-Barrientos, 2018; Guibrinet et al., 2016; Kennedy et al., 2015; Hoornweg et al., 2011; Paez, 2010). However, the translation of these studies into spatially explicit accounts (e.g., GIS mapping) of resource flows/stocks and an understanding of the role of OSN in resource management in Mexico City are still limited to date. Researchers have used UM frameworks to study the configuration of waste management systems, drinking water consumption and water infrastructure (distribution system and sewer network) from an urban political ecology perspective (Guibrinet et al., 2016; Delgado-Ramos, 2015a). Other studies have focused on the impact of material flows on GHG emissions (Delgado-Ramos, 2015b; Hoornweg et al.,

2011) and the assessment of a social-ecological metabolism (Huerta-Barrientos, 2018), included Mexico City in a comparative study of 27 megacities worldwide (Kennedy et al., 2015), and examined the potential benefits of urban energy transition (Paez, 2010). Guibrunet et al. (2016) studied the role of the informal sector in the collection and recycling of municipal solid waste (MSW) in areas of Mexico City where municipal waste collection services are not available. They focused on urban waste flows in the Tepito neighborhood (*Cuauhtémoc* borough), where, following the development of a parallel political structure by local leaders (*caciques*), basic services were provided in exchange for an informal tax paid to the local community. MSW flows were mapped to understand the available distribution and disposal infrastructures, to compare the public, private, and informal waste management systems, and study their interdependence. However, the approach proposed by Guibrunet et al. did not encompass a spatially explicit accounting of MSW flows (e.g., GIS map with solid waste generation by borough or AGEb). Delgado-Ramos (2015a) described the environmental and economic challenges arising from the development of the drinking water distribution system. In particular, he studied the inflow of bottled water (the most common solution for consuming drinking water in Mexico City), inequalities in the distribution and access to drinking water across high/low-income boroughs (which can have a difference of 3 to 1 in total per capita consumption), as well as the social movements for environmental justice related to water accessibility.

In conclusion, based on the results of our preliminary context analysis and previous UM studies, Mexico City provides a relevant case study for our research due to: i) its complex and energy-intensity infrastructure for water extraction, distribution and drainage, ii) a large population living in informal settlements and low-income neighborhoods that are more

vulnerable to resource access and public space; iii) the high concentration of common lands, indigenous areas, resource infrastructure, and nature reserves in several areas of the city.

For Review Only

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3 **2. MATERIAL AND METHODS**
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8 We performed a Geographic Information System (GIS)-based assessment of the metabolism
9 of Mexico City at two urban scales: city administrative boundary (including the 16 boroughs)
10 and borough scale. These scales were investigated through the compilation of primary GIS
11 data (see supporting information) and the following available datasets: (1) resource flows,
12 including drinking water consumption and wastewater outflows, electricity consumption,
13 generation of organic and inorganic MSW, and construction solid waste (CSW); (2) location
14 and capacity of utility infrastructure and resource management facilities; (3) geographic
15 features of the city (e.g., topography and land-use cover areas), including OSN; (4) location of
16 vulnerable communities; and (5) location of indigenous areas and communal lands and their
17 administrative limits.
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33 Resource infrastructure datasets include main generation, distribution, and storage facilities
34 within the city administrative boundary (electrical power plants and substations, water
35 distribution system and sewage network, recycling and compost plants). OSN datasets include
36 public and private green spaces (parks and gardens), blue spaces (rivers, streams, channels,
37 and lakes), gray spaces (squares and pedestrian walkways), and nature reserves.
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47 Vulnerable communities' datasets include location data for informal settlements and areas
48 with a high urban marginality index. The urban marginality index was presented in the
49 Mexico City Resilience Strategy report (CDMX Resilience Office, 2016); we used it to assess
50 the overall degree of deprivation for the population in each AGEb based on a set of socio-
51 economic variables. These include percentage of children without access to education,
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population without access to health services and high death rate at birth, as well as population living in houses with dirt floors and not connected to the water and sewage system.

Borough Pattern Scan

After mapping the selected GIS layers, a detailed analysis of per capita data patterns was performed for each borough. The boroughs were classified according to their (high/low) resource efficiency. We intentionally use a broader definition of resource efficiency, which is intended to be an optimal combination of low resource use (UM flows) and high resource access (resource infrastructure and OSN). Boroughs were classified as more resource efficient if they had lower resource use (less resource consumption and waste generation than the city average) and higher resource access than the city average; inversely, boroughs with higher resource use and lower resource access were classified as less resource efficient (see Figure 2).

(Insert Figure 2 about here)

The criterion used to analyze resource use was the total amount of resource consumption (for water and energy flows) or generation (for solid waste flows). For resource access, the criteria used were the location and capacity of resource infrastructure by type of flow, and the location of OSN. Each criterion is characterized by sub-criteria (see supporting information), which were defined using spatially explicit data. The Borough Pattern Scan allowed for the identification and classification of areas with high or low resource efficiency based on resource consumption/infrastructure and urban space availability (i.e., OSN). Spatially explicit socio-economic datasets were used to characterize resource efficiency by identifying communities affected by resource vulnerability (informal settlements and areas with high

urban marginality index), and decentralized resource management structures (communal lands and indigenous areas).

To classify the boroughs, each sub-criterion was evaluated using a value index (see supporting information for details on calculations). A “1” score was assigned to the highest value of each sub-criterion and a “0” score in case of a null value. Then, the scores for the remaining sub-criteria were proportionally calculated based on comparison with the highest score. For example, *Cuauhtémoc* had the highest quantity of MSW generation per capita and was evaluated with a score of 1; *Iztapalapa* had half as much MSW generation per capita and was evaluated with a score of 0.5. The final score of each criterion corresponds to the mean of all scores assigned to its sub-criteria (e.g., the values assigned to solid waste flows of all boroughs were calculated as mean values of the sub-criteria MSW and CSW generation). Finally, to highlight high/low scores for each criterion, criteria with scores above the mean score were marked with a “+” symbol and those under the mean score with a “-” symbol.

3. RESULTS

Table 1 illustrates the quantification and classification of all data used in the GIS analysis by criteria and for each of the 16 boroughs; sub-criteria with values 10% above the average are highlighted in red, while orange is used for average values, and gray for values 10% below the average. All values are on a unit-per-capita basis, except for the vulnerable communities, communal lands, and indigenous areas criteria, in which values are provided based on total square kilometers by borough.

(Insert Table 1 about here)

The first set of maps refers to the spatial distribution of resource flows and utility infrastructure by borough (Figures 3, 4, and 5), including total and per capita resource use, and the location of resource infrastructure, administrative/storage facilities, and main distribution network. The second set of maps includes the distribution of OSN (Figure 6.a), and the location of areas characterized by vulnerable communities, communal lands, and indigenous areas (Figure 6.b). Results of the Borough Pattern Scan are presented in Figure 7, including a set of tables (Figure 7.a) and a synthesis map (Figure 7.b), in which the spatial distribution of resource infrastructure, OSN, and vulnerable communities within communal lands and indigenous areas are overlaid to highlight in-boundary spatial relation dynamics (e.g., location, elevation, overlapping, type of boundaries, closeness). The synthesis map allows for identification of the OSN or their components; it can be used to mitigate context-specific resource-related vulnerabilities and enhance resource-efficient urban and landscape planning strategies.

Resource use

The result of our mapping highlights that boroughs in the city center (*Azcapotzalco, Benito Juárez, Cuauhtémoc, Miguel Hidalgo, and Venustiano Carranza*) have the highest resource use per capita compared to the per capita average for Mexico City as a whole. The lowest resource use is concentrated in two areas of the city: the northeastern boroughs with vulnerable communities (*Gustavo A. Madero, Iztacalco and Iztapalapa*) and the southern rural boroughs with the highest surfaces of informal settlements (*Milpa Alta, Tlalpan, Tláhuac and Xochimilco*). In Mexico City, average water consumption is 350 l/day/capita, and electricity consumption is 1,753 kWh/year/capita. Five out of the 16 boroughs generate more municipal solid waste per capita than the average (1.42 kg/day), of which all except *Xochimilco*, are located in the city center and encompass more than 50% of the illegal dumping sites.

Resource infrastructure

Southern boroughs with rural areas are best equipped with water supply infrastructure compared to all other boroughs, while northern boroughs concentrate most solid waste infrastructure in the city and a borough in the city center has the most energy infrastructure. Even though almost every borough has a MSW transfer station, the average pickup radius distance to the transfer station is between 5 km and 12 km, which increases transport distance and, therefore, the associated fossil fuel consumption. Southern rural areas are crossed by 90 km of the Cutzamala-Lerma aqueduct and the electrical power main distribution system. Almost 50% of all rural areas are not equipped with any MSW treatment facility, and the only compost plant in the city is located in the northern urban area of *Venustiano Carranza*, more than 30 km away from the agricultural areas.

In *Iztapalapa*, the Cerro La Estrella natural reserve areas concentrate 50% of all informal settlements. These areas are less than 9 km away from the Bordo Poniente compost plant and 4 km away from the Central de Abastos food-supply complex, which encompasses the two MSW treatment plants. *Gustavo A. Madero* contains the highest number of MSW facilities (including the only recycling plant in the city). The recycling plant is located at the eastern side of the borough and centralizes all such facilities, increasing the distance for transportation of MSW from other areas. The location and proximity of vulnerable communities to the MSW infrastructure and OSN is similar in the two boroughs. As we will see in the Discussion, this points to a potential use of existing open spaces to enhance resource harvesting while improving its accessibility.

Open space networks

The OSN map (Figure 6.a) shows the existing typologies of open spaces and highlights how urban areas contain almost 90% of all the public green-gray spaces. In comparison, rural areas contain more than 92% of the nature reserves, agricultural fields, and blue spaces. Results show that the average quantity of green-gray-blue open spaces available in Mexico City is 3.14 m²/inhab. This is significantly lower than in other cities with similar population density, as for example Madrid, Spain, where it reaches 14 m²/inhab. (ADB-IDB, 2014). The highest quantities of public green spaces per capita in urban areas are found in central boroughs that concentrate low amounts of areas with high urban marginality index and informal settlements, such as *Miguel Hidalgo* and *Coyoacán*, where they reach 14 m²/inhab. and 7 m²/inhab., respectively. Three of the five boroughs with the lowest quantities of public green spaces (less than 1m²/inhab.), *Iztapalapa*, *Gustavo A. Madero*, and *Xochimilco*, concentrate 38% of the total population of Mexico City and the largest amount of areas with informal settlements and a high urban marginality index (44 km² and 30 km² respectively), revealing the inequalities

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in the distribution of OSN between vulnerable communities and other neighborhoods. *Milpa Alta* has the largest land area, with 269 km², the lowest population (137,000 inhabitants), and the lowest electricity consumption (371 kWh/year/capita) in the city. Nature reserves extend over three quarters of the borough's total land area, and the only waste-to-energy plant is located in the northern zone, more than 20 km away from the southern agriculture areas.

(Insert Figure 3 about here)
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4. DISCUSSION

4.1 OSN as a medium to increase resource efficiency

The table and maps presented in the Results section highlight the location and proximity of areas in which urban flows and infrastructure are concentrated, both at the city and the borough scale. Our aim is to present a methodological strategy to investigate how spatially explicit information and data on resource use, resource infrastructure, and OSN can improve the applicability of UM assessments in the planning and management of green-blue-gray public spaces. We focused on OSN as a medium to increase resource efficiency while considering the specific socio-economic conditions of vulnerable communities as well as the assets of the local natural capital.

While Mexico City counts 67 m² of public green areas per inhabitant, these areas are not equally distributed across all parts of the city; they can vary depending on the type of spaces

included (e.g., squares, parks, nature reserves) or type of calculation (e.g., based on ground cover or tree coverage) as shown in previous research (PAOT, 2018; Maldonado-Bernabé, 2019). In rural areas, our results show that the available public green area is limited to 3.44 m²/inhab.; this does not include nature reserves within the Conservation Land, which are not considered to be accessible (lack of pathways and benches for elderly and disabled people), nor safe (lack of illumination increasing the feeling of insecurity), nor functional (lack of facilities such as public toilets) to all inhabitants (WHO, 2010). Previous research demonstrated that the distribution of public green areas per inhabitant in Mexico City is directly related to each borough's socio-economic characteristics, with lower quantities of green areas in lower-income neighborhoods (Fernandez-Alvarez, 2017; Checa Artasu, 2016). We identified seven boroughs that have lower quantities of public green areas (less than 9 m²/inhab.), including four boroughs with high resource use: *Azcapotzalco*, *Benito Juárez*, *Cuauhtémoc*, and *Venustiano Carranza*. Future plans to increase available green space in these boroughs could provide opportunities for integrating new utility infrastructure to improve resource access and enhance the transition from a linear to a circular metabolism.

Xochimilco has the second-highest MSW generation rate in the city (2.24 kg/day/capita). The borough could benefit from its productive agricultural land to reinforce the existing local composting systems, create new organic waste treatment plants, produce energy from waste (e.g., composting, anaerobic digestion), increase energy access for the local population, and provide compost and digestate for future agriculture production. Synergies among different urban functions could lead to mutual benefit in terms of resource cycling, especially for fertilizers and energy production (Wielemaker et al., 2018). Previous research in other contexts studied the energy potential from composting and incinerating all organic MSW; for example, in Denmark, this would be equivalent to 5% of the country's total energy

consumption, including transport (Lehmann, 2011). The use of under- or unused surfaces in and around infrastructure facilities could be used to install renewable energy systems (e.g., photovoltaic panels). Previous studies suggest that, depending on the total amount of available area and local climatic characteristics, this energy could be used for private or public transport (Neumann et al., 2012), reducing fossil fuel consumption and associated GHG emissions while promoting the use of underexploited surfaces in the city to produce energy (among other benefits).

4.2 Decentralized and multifunctional planning of OSN

A long-term overexploitation of the city’s underground aquifers and its complex drainage system has resulted in the depletion of the aquifers, causing shortages in the water supply system and subsidence in some areas of the city (Legorreta, 2006). To meet 42% of total urban water demand (SACMEX, 2018), the Cutzamala-Lerma system, an energy-intensive and expensive drinking water system (Tortajada, 2006), pumps water to Mexico City from rivers more than 1,000 km away. About 2.280 million kWh are required to pump all this water, equivalent to the total electricity consumption of the 6.5 million inhabitants of the neighboring city of Puebla (SACMEX, 2012).

Building on the assessment of resource use and available areas of OSN at the borough scale as summarized in the Borough Pattern Scan, planning strategies can be proposed to increase the accessibility and efficient use of these resources. Highly urbanized boroughs with high drinking water consumption per capita (e.g. can expand their water supply system by adding decentralized infrastructures. Since 2019, the Mexico City SCALL (*Sistema de Captación de Aguas de Lluvias*) program has developed rainwater harvesting (RWH) solutions for individual homes in boroughs with water accessibility issues. Although the number of

beneficiaries increases every year, a considerable part of the city's vulnerable population is unable to benefit from the program, due to a lack of required official documentation such as residence certificates and planning permits (SEDEMA, 2019). Planning communal RWH systems in public spaces and in available, underused resource facilities (e.g., roofs and parking lots of water/electricity plants) can contribute to mutualizing efforts, reducing material costs, improving water accessibility for vulnerable communities, and reducing pressure on the current energy-intensive drinking water system through local and decentralized solutions (Valdez et al., 2016; Agudelo-Vera et al., 2012). Boroughs with high water consumption, in which utility infrastructures are mostly located in agricultural areas (e.g., *Milpa Alta*), could benefit from state-of-the-art design solutions for linear water catchment parks (Ibrahim et al., 2020). These could be constructed alongside existing aqueducts or below electric lines for use in agriculture irrigation, which could create an alternative or supplementary irrigation system and increase water storage capacity through wetland planning and landscaping. Moreover, the planning of a mixed RWH system on rooftops and publicly open green infrastructure could increase water accessibility for households not connected to the primary water drinking system while contributing to improving the connectivity of the whole OSN. As demonstrated in previous research, RWH systems can reduce household water and energy consumption as well as the overexploitation of groundwater consumption by providing an alternative water source, while preventing flooding by reducing stormwater flows in the rainy season (Jalife Acosta et al., 2018; Valdez et al., 2016; Nanninga et al. 2012; Legorreta, 2006).

Previous studies have demonstrated that informal settlements, together with other public and private infrastructure (e.g. highways and housing developments), contribute to the erosion of green areas in boroughs within the Conservation Land due to housing shortage and limited

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land accessibility (Aguilar & Santos, 2010). GIS mapping and spatial calculation are affecting the social construction, environmental impact, and regulation processes of informal settlements in the Conservation Land, as they are now mapped and subject to urban planning regulations (Connolly & Wagle, 2017). Southern boroughs could reinforce existing urban development plans (*Programas Delegacionales de Desarrollo Urbano*), integrating individuals and organized groups within the communities involved to preserve and enhance local resources (e.g., forests, grasslands, and agriculture fields). Moreover, involving community leaders in participatory design processes and GIS data collection, would strengthen local socio-environmental organizations and favor the decentralization of resource management (Santos et al., 2015; Silva, 2013).

4.3 OSN and the multi-scale UM approach – Limitations

The selection of system boundaries and resource datasets used in UM studies depend on the research objectives and the level of disaggregation of available data at different urban scales (e.g., region, borough, street, building). The use of resource flows datasets, based within an industrial ecology framework, and the use of socio-economic and open space location datasets provided a hybrid analytical framework that allowed us to assess impacts on vulnerable communities to achieve our research objectives. Moreover, integrating available fine-grain data at borough scale allowed identifying specific areas with disadvantaged socio-economic characteristics at the AGEb level, which favored a more detailed multi-scale approach. For example, our results showed that approximately half of the total areas with vulnerable communities are located within indigenous areas and one third of the total areas with informal settlements are located in communal lands and indigenous areas. However, limiting our study to Mexico City excluded the possibility of studying the spatial relationship between resource use and infrastructure within the entire urban system of the Metropolitan Zone of the Valley

of Mexico, which is home to a growing population vulnerable to OSN availability and resource accessibility (OECD, 2015).

The use of the Borough Pattern Scan allowed us to classify spatially explicit data by resource type; through this, we were able to study their location, overlapping, and proximity in relation to the geographic and socioeconomic characteristics of Mexico City. However, this approach is limited in scope as it was focused on an analysis of per capita values at the borough scale, without allowing us to disaggregate values into areas of interest at the neighborhood scale. In addition, data on informal resource flows (e.g., solid waste collection and recycling by organized groups in communities) were not included in our study due to their limited availability. For the OSN datasets, information about land ownership was essential to pursue our research objectives based on publicly owned OSN. However, it is worth noting that the quantities of per capita private green areas (8.69 m^2) is almost triple that of public green areas (2.84 m^2 per capita). On the basis of current limitations, the Borough Pattern Scan could be calculated using different boundaries (e.g., AGEb, water catchments) in a specific urban area, adapting it to specific resource flows, its infrastructure, and internal diversity of OSN, to address future research objectives.

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4 **5. CONCLUSIONS AND FURTHER RESEARCH**
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9 Our research has provided a spatially explicit account of UM flows and infrastructure in
10 Mexico City, integrating the mapping and assessment of OSN, and supported by datasets on
11 vulnerable communities, communal lands, and indigenous areas. By presenting the Borough
12 Pattern Scan and the spatialization of UM data on maps, we identified opportunities to
13 increase resource efficiency by using OSN and their spatial configuration as a lever to
14 sustainable urban and landscape planning. This research also contributed to a deeper
15 understanding of the location and proximity of resource infrastructure and pointed to
16 development opportunities for vulnerable communities in Mexico City. As shown in a
17 previous study of the MSW system of Mexico City (Guibrunet et al. 2016), informal social
18 organizations and alternative land/resource governance systems can engage different actors in
19 the process of producing or transforming resource flows/stocks. The integration of socio-
20 economic data in the UM study allowed us to identify spatial relations (and co-existence)
21 between vulnerable communities, indigenous areas, and communal lands, which can enhance
22 more resource-efficient urban and landscape planning strategies to mitigate vulnerabilities to
23 resource access and enhance resource efficiency.
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46 Despite limited access to spatially explicit datasets for Mexico City, we were able to compile
47 spatially explicit UM datasets intended for use by planners and practitioners in planning and
48 of OSN. This was possible by performing an integrated quantitative and qualitative spatial
49 UM analysis based on classification of available GIS datasets as well as the plotting of
50 existing quantitative data on maps. Then, through the use of Borough Pattern Scan, we could
51 classify the type of spatial data needed to understand the dynamics of resource use and
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resource access and introduced the planning of OSN as a new strategy to leverage resource efficiency.

Based on the outcomes of our work, further research can focus on using finer-scale analysis for integrated UM and GIS analysis as a way to improve UM application in urban and landscape planning across different contexts. Such analyses can refine research results and provide a context- and community-specific understanding of metabolic dynamics, resource accessibility, resource governance and management, urban structure, economic and productive dynamics, and planning strategies for nature conservation. Spatially explicit data on informal resource extraction, distribution and consumption (e.g., illegal water wells) should be systematically integrated into future UM assessments to better express relations among resource intensity/availability and the configuration of OSN in vulnerable communities. This can enable researchers, practitioners and planners to jointly work toward decision-making and design strategies that could better respond to communities' ambitions toward more resilient and sustainable cities.

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SUPPORTING INFORMATION

This supporting information provides supplementary material that complements the methods and findings included in the main research article, including the compiled GIS datasets used in the study, the criteria and sub-criteria used to classify the boroughs, the Borough Pattern Scan detailed calculation by criteria, and a set of maps and tables including details of the selected boroughs analysis by resource flow type.

DATA AVAILABILITY STATEMENT

The authors confirm that the data supporting the findings of this study are available within the article and its supporting information.

FIGURE AND TABLE LEGENDS

Table 1: Evaluation and classification of all criteria and sub-criteria used in the analysis by borough. Highlighted in red are values 10% above the average, in orange the average values, and in gray the values 10% below the average.

Figure 1. The geographic location of Mexico City and its 16 boroughs subdivision. The Metropolitan Zone of the Mexico Valley including the states of Mexico and Hidalgo. Mexico City including topography, administrative boundaries, informal settlement areas (red contour lines), indigenous areas (white contour lines) and communal lands (blue contour lines). The Conservation Land (with green contour lines) delimits the urban and rural areas in the city.

Figure 2: Resource efficiency framework diagram.

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Figure 3: Spatial distribution of drinking water and sewage system flows and infrastructure. Water consumption and wastewater outflows are quantified by borough. The location of infrastructure, resource management facilities and main networks for drinking water and sewage system are highlighted with specific symbols and colors by type.

Figure 4: Spatial distribution of electrical energy flows and infrastructure. Electricity consumption is quantified by borough. The locations of the infrastructure, resource management facilities and main distribution network are highlighted with specific symbols and colors by type.

Figure 5: Spatial distribution of solid waste flows and infrastructure. Municipal solid waste (MSW) and construction solid waste (CSW) are quantified by borough. Locations of the infrastructure and resource management facilities are highlighted with specific symbols and colors by type.

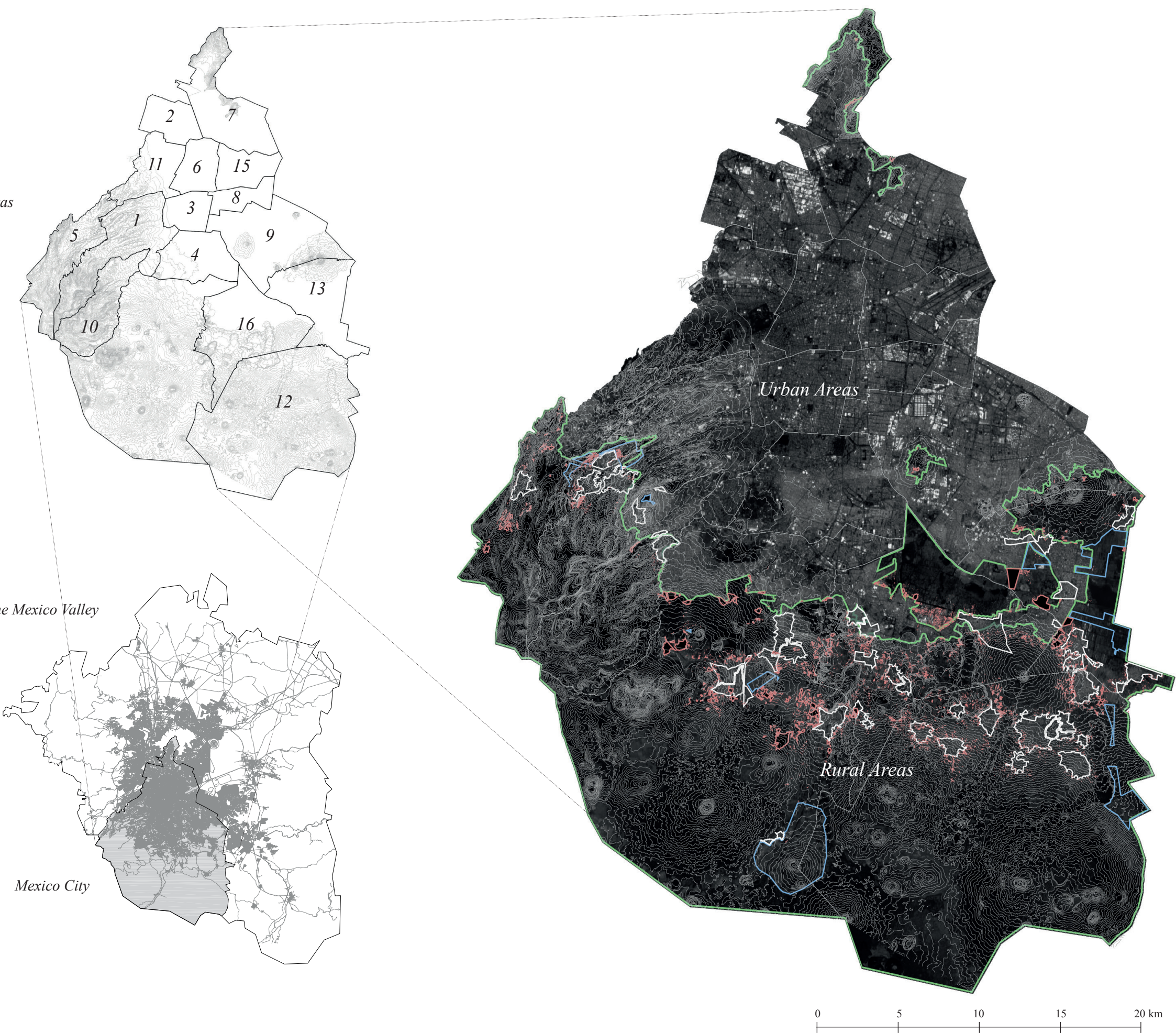
Figure 6: Spatial distribution of the OSN (Figure 6.a) and the vulnerable communities, communal lands, and indigenous areas (Figure 6.b).

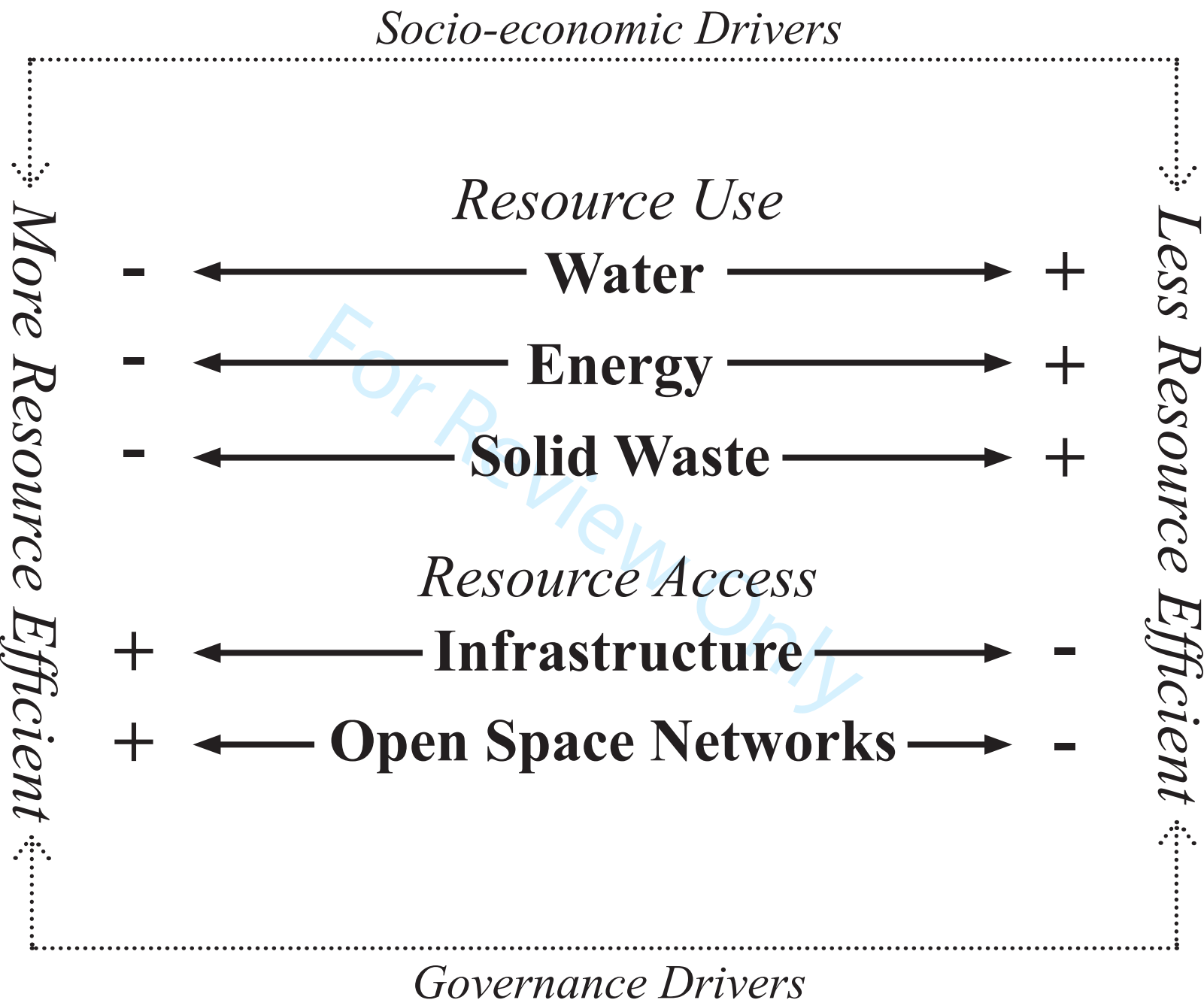
Figure 7: Borough Pattern Scan results by type of resource flow. Synthesis map overlapping resource infrastructures, public OSN, productive landscapes, and vulnerable communities within communal lands and indigenous areas.

Mexico City Boroughs

- 1. Álvaro Obregón
- 2. Azcapotzalco
- 3. Benito Juárez
- 4. Coyoacán
- 5. Cuajimalpa de Morelos
- 6. Cuauhtémoc
- 7. Gustavo A. Madero
- 8. Iztacalco
- 9. Iztapalapa
- 10. La Magdalena Contreras
- 11. Miguel Hidalgo
- 12. Milpa Alta
- 13. Tláhuac
- 14. Tlalpan
- 15. Venustiano Carranza
- 16. Xochimilco

Metropolitan Zone of the Mexico Valley





Water (W)

Administrative limit

Boroughs

W flows

Water consumption (l/day/cap)

Waste water discharge (l/day/cap)

Aqueducts capacity (l/day/cap)

Extraction wells (l/day/cap)

Treatment plants (l/day/cap)

Water pump facilities (l/day/cap)

Water tanks (l/day/cap)

Sewage treatment plants (l/day/cap)

Dams (l/day/cap)

Álvaro Obregón

Azcapotzalco

Benito Juárez

Coyoacán

Cuajimalpa de Morelos

Cuauhtémoc

Gustavo A. Madero

Iztacalco

Iztapalapa

Magdalena Contreras

Miguel Hidalgo

Milpa Alta

Tláhuac

Tlalpan

Venustiano Carranza

Xochimilco

Total

Average

321

6

122

114 (33)

0 (0)

537 (14)

454 (31)

32 (1)

3,994.76 (15)

404

16

0

220 (34)

24 (2)

0 (0)

0 (0)

0 (0)

5

0 (0)

406

14

0

143 (23)

0 (0)

0 (0)

0 (0)

0

0 (0)

355

7

0

324 (76)

0 (0)

236 (5)

0 (0)

114 (1)

0 (0)

293

7

655

26 (2)

0 (0)

1,011 (7)

773 (14)

0 (0)

0.10 (1)

332

25

0

34 (7)

0 (0)

0 (0)

0 (0)

4 (1)

0 (0)

237

4

0

7 (3)

20 (5)

49 (2)

160 (17)

45 (2)

0 (0)

219

5

0

66 (10)

49 (3)

74 (1)

0 (0)

54 (2)

0 (0)

235

4

0

87 (61)

156 (29)

236 (15)

138 (23)

142 (2)

0 (0)

554

3

563

21 (2)

145 (2)

1,062 (9)

1,262 (28)

18 (1)

0 (0)

502

37

0

228 (32)

0 (0)

237 (3)

211 (7)

44 (2)

0.77 (2)

410

1

2,082

169 (9)

0 (0)

0 (0)

2,471 (31)

38 (1)

0 (0)

210

2

0

79 (11)

143 (3)

398 (5)

61 (2)

128 (5)

0 (0)

560

7

648

272 (71)

0 (0)

1,062 (25)

1,153 (71)

5 (4)

0 (0)

203

5

0

30 (5)

16 (2)

135 (2)

26 (1)

0 (0)

0 (0)

374

3

150

505 (81)

54 (6)

415 (6)

555 (21)

37 (2)

1.54 (1)

-

-

-

- (460)

- (52)

- (94)

- (246)

- (25)

- (19)

351

9

263

145 (29)

38 (3)

341 (6)

454 (15)

42 (1)

250 (1)

Energy (E)

Solid Waste (SW)

Administrative limit

Boroughs

E flows

E infrastructure capacity and total number of facilities

SW flows

SW infrastructure capacity and total number of facilities

Electricity consumption (kWh/day/cap)

Electrical power plant (kWh/day/cap)

Waste-to-energy electrical plant (kWh/day/cap)

Electrical substations (kVA/cap)

Municipal SW generation (kg/day/cap)

Construction SW generation (l/day/cap)

Transfer stations (kg/day/cap)

Compaction plants (kg/day/cap)

Recycling plants (kg/day/cap)

Compost plants (kg/day/cap)

Álvaro Obregón

Azcapotzalco

Benito Juárez

Coyoacán

Cuajimalpa de Morelos

Cuauhtémoc

Gustavo A. Madero

Iztacalco

Iztapalapa

Magdalena Contreras

Miguel Hidalgo

Milpa Alta

Tláhuac

Tlalpan

Venustiano Carranza

Xochimilco

Total

Average

1,404

0 (0)

0 (0)

0.93 (4)

0.91

0

12.93 (1)

0 (0)

0 (0)

0.08 (1)

2,329

0 (0)

0 (0)

0.51 (1)

1.30

0

20.32 (1)

0 (0)

0 (0)

0 (0)

2,767

0 (0)

0 (0)

0.82 (2)

1.72

0.29

8.48 (1)

0 (0)

0 (0)

0 (0)

1,726

0 (0)

0 (0)

1.47 (3)

1.34

0.04

16.52 (1)

0 (0)

0 (0)

0 (0)

2,442

0 (0)

0 (0)

6.97 (3)

0.94

0

0 (0)

0 (0)

0.21 (1)

3,740

1,070 (1)

0 (0)

2.70 (4)

2.49

0

12.94 (1)

0 (0)

0 (0)

0 (0)

1,088

0 (0)

0 (0)

0.44 (2)

1.50

0

1.37 (1)

2.04 (1)

21.10 (1)

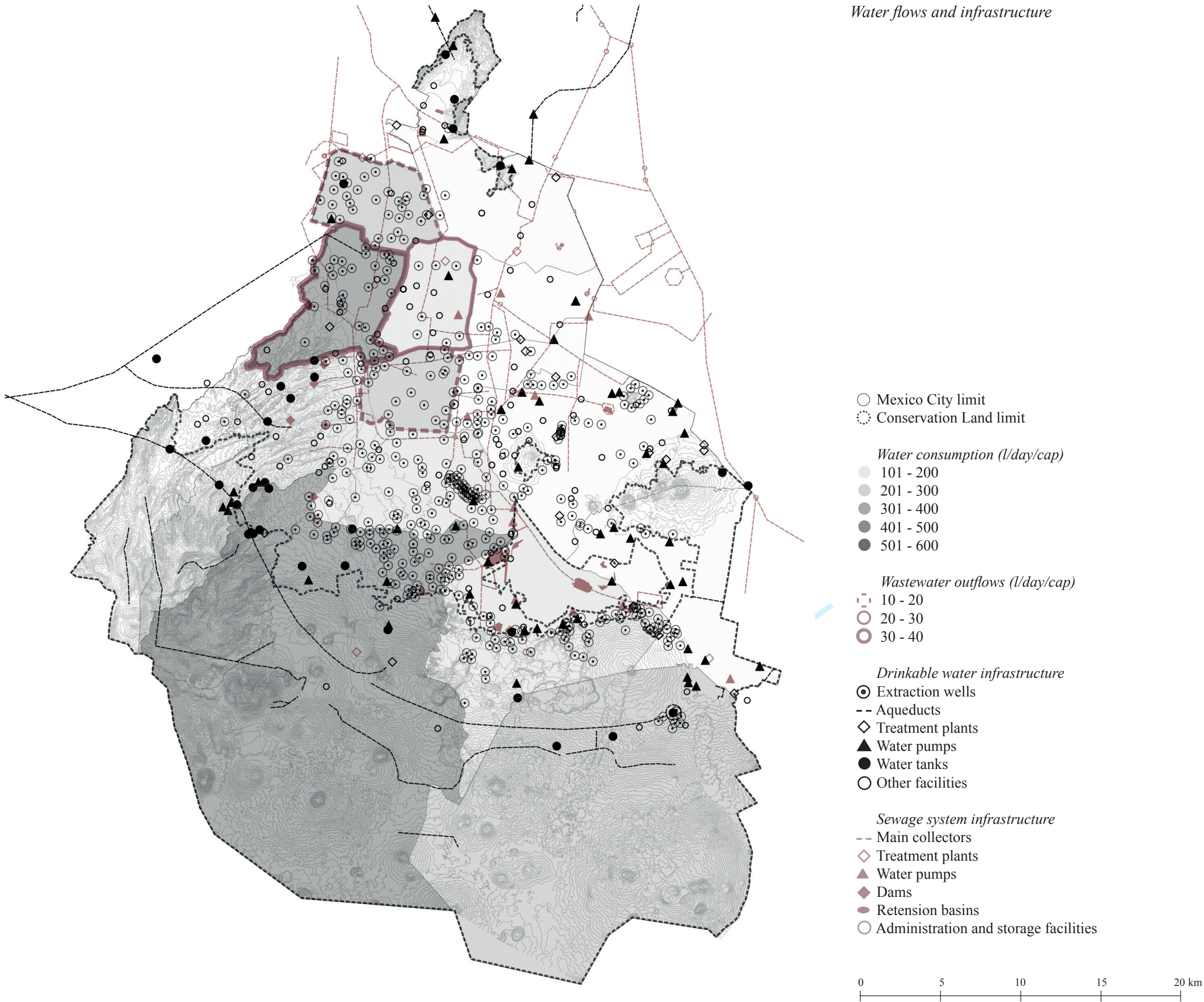
0.05 (1)

1,215

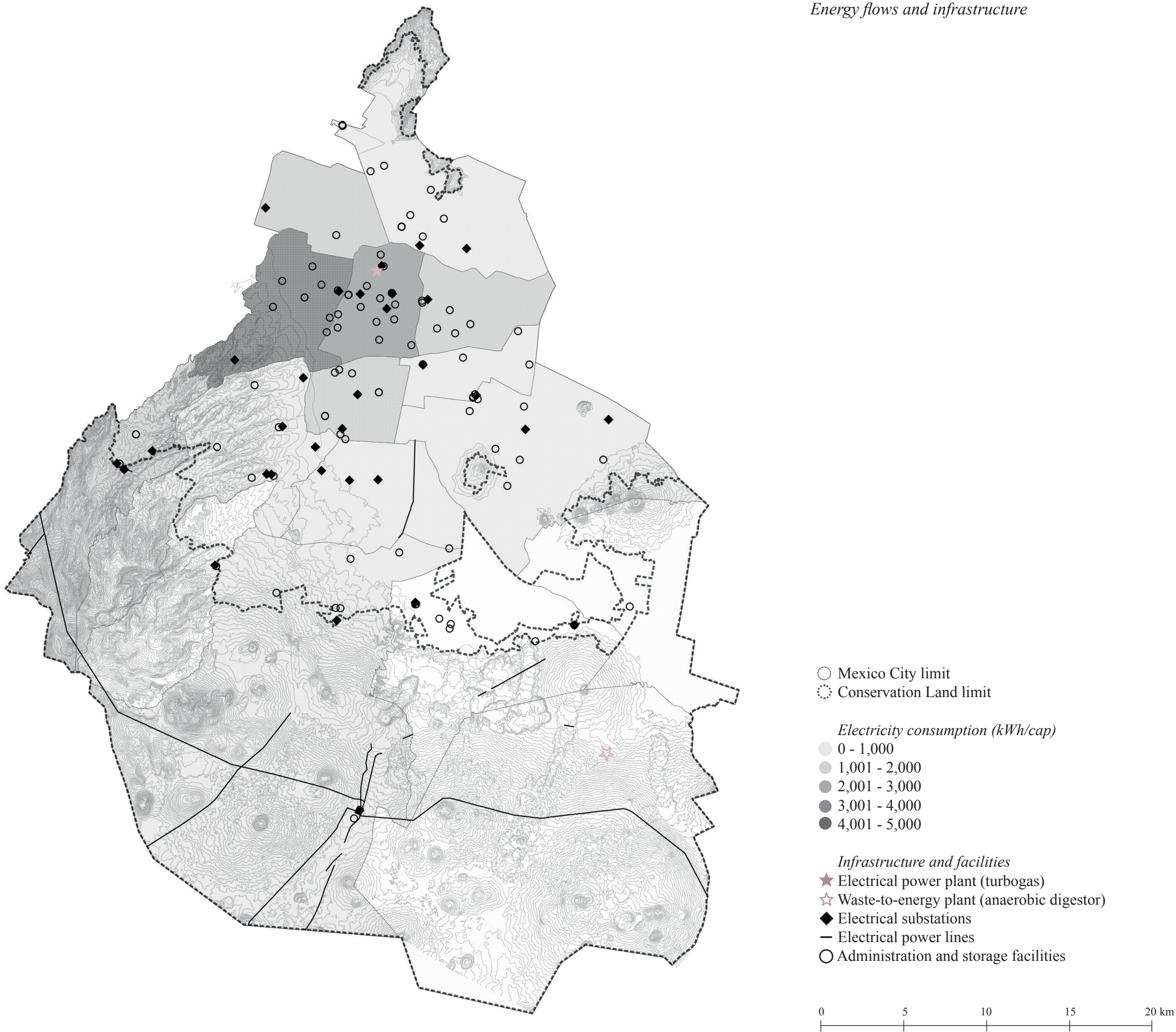
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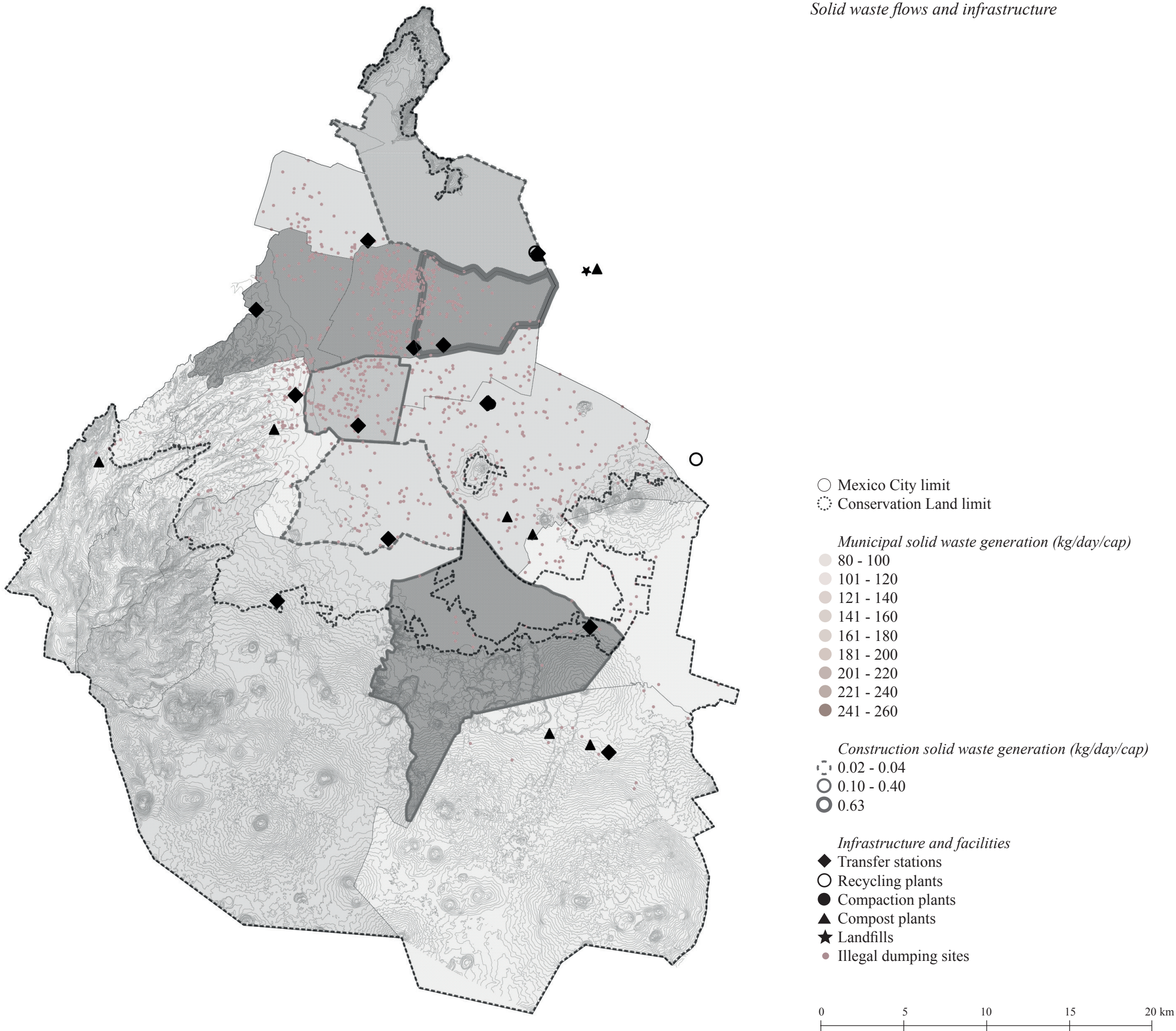
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Energy flows and infrastructure



Solid waste flows and infrastructure



a. Open space networks

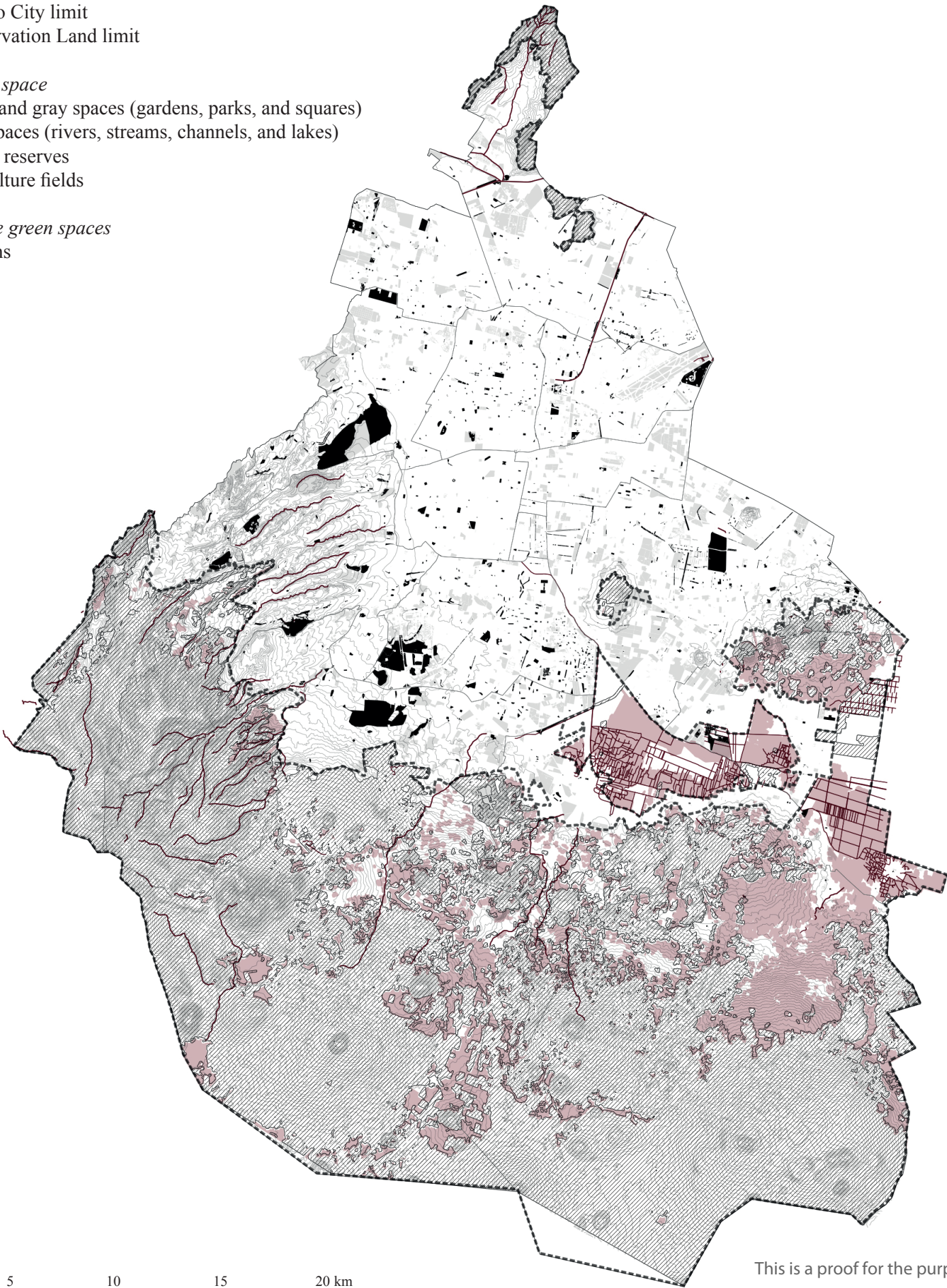
- Mexico City limit
- ⦿ Conservation Land limit

Public space

- Green and gray spaces (gardens, parks, and squares)
- Blue spaces (rivers, streams, channels, and lakes)
- ▨ Nature reserves
- Agriculture fields

Private green spaces

- Gardens



b. Vulnerable communities, communal lands, and indigenous areas

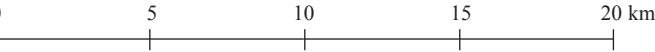
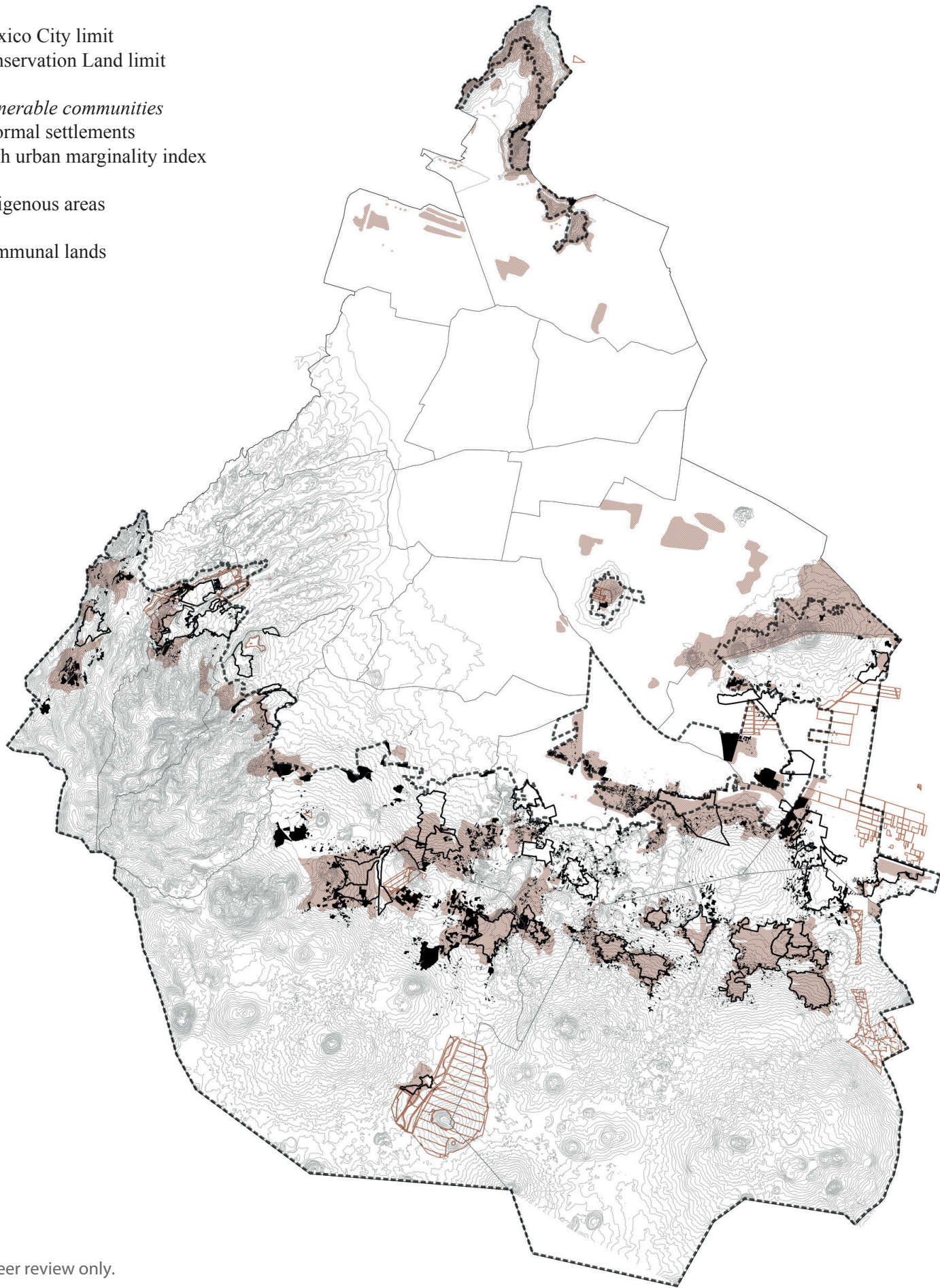
- Mexico City limit
- ⦿ Conservation Land limit

Vulnerable communities

- Informal settlements
- High urban marginality index

Indigenous areas

- Communal lands



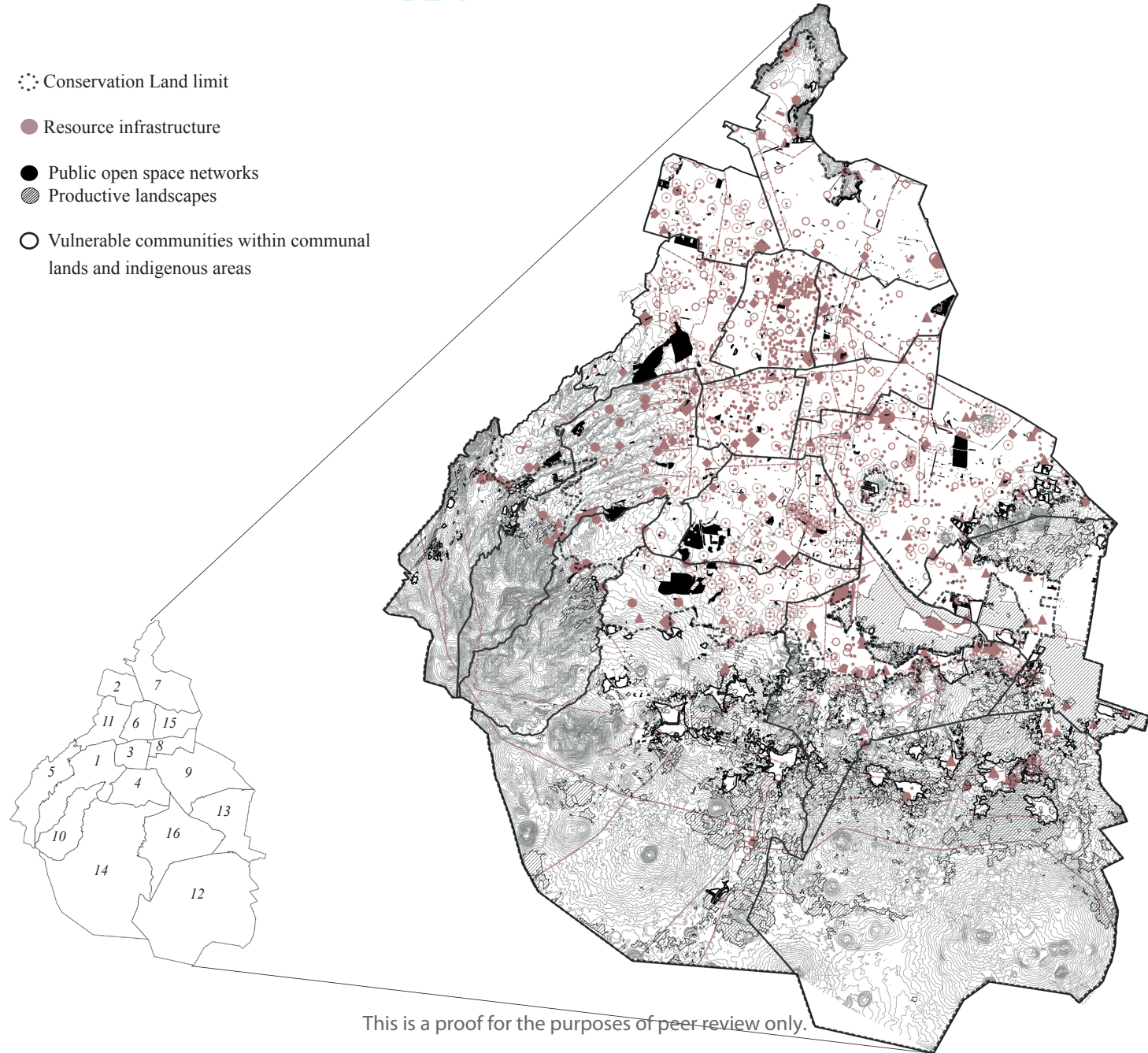
a. Resource Efficiency Classification

1 W: Water, E: Energy, SW: Solid Waste, Infra: Infrastructure, OSN: Open Space Networks.

Boroughs	Resource Use (RU)			Resource access (RA)				Resource Efficiency (RE)	
	UM flows			Resource infrastructure / Open Space Networks				Classification based on RU and RA values	
	W flows index	E flows index	SW flows index	W infra index	E infra index	SW infra index	OSN index	RE Rating	Less-efficient criteria
1. Álvaro Obregón	- 0.37	- 0.30	- 0.18	+ 0.27	- 0.04	+ 0.20	- 0.16	High	E infrastructure, and OSN
2. Azcapotzalco	+ 0.57	+ 0.50	- 0.26	- 0.08	- 0.02	+ 0.31	- 0.20	Low	W and E efficiency, and OSN
3. Benito Juárez	+ 0.56	+ 0.59	+ 0.57	- 0.04	- 0.04	- 0.13	- 0.04	Very Low	All resources efficiency, and OSN
4. Coyoacán	- 0.41	- 0.37	- 0.30	- 0.21	- 0.07	+ 0.25	+ 0.37	High	SW infrastructure
5. Cuajimalpa de Morelos	- 0.36	+ 0.52	- 0.19	- 0.20	+ 0.33	- 0.00	+ 0.31	Medium high	E flows, W and SW infrastructure
6. Cuauhtémoc	+ 0.63	+ 0.80	+ 0.50	- 0.01	+ 0.46	+ 0.20	+ 0.25	Medium low	All resources flows and W infrastructure
7. Gustavo A. Madero	- 0.26	- 0.23	- 0.32	- 0.10	- 0.02	+ 0.41	- 0.11	Medium high	SW infrastructure and OSN
8. Iztacalco	- 0.26	- 0.26	- 0.34	- 0.11	- 0.08	- 0.00	- 0.11	Medium low	All resources infrastructure and OSN
9. Iztapalapa	- 0.26	- 0.23	- 0.25	+ 0.43	- 0.05	+ 0.35	- 0.12	High	E infrastructure and OSN
10. Magdalena Contreras	+ 0.54	- 0.14	- 0.22	+ 0.36	- 0.04	- 0.00	- 0.06	Medium low	W efficiency and OSN
11. Miguel Hidalgo	+ 0.95	+ 1.00	+ 0.46	- 0.13	- 0.05	- 0.15	+ 0.23	Low	All resources efficiency
12. Milpa Alta	- 0.38	- 0.08	- 0.18	+ 0.32	+ 0.33	- 0.06	+ 0.25	High	SW infrastructure
13. Tláhuac	- 0.22	- 0.12	- 0.20	+ 0.32	- 0.00	- 0.00	+ 0.36	High	E and SW infrastructure
14. Tlalpan	+ 0.59	- 0.27	- 0.26	+ 0.29	- 0.01	- 0.08	+ 0.37	Medium high	W flows, E and SW infrastructure
15. Venustiano Carranza	- 0.25	+ 0.44	+ 0.91	- 0.06	- 0.02	+ 0.42	+ 0.29	Medium low	W and E infrastructure
16. Xochimilco	- 0.38	- 0.15	+ 0.70	+ 0.36	- 0.05	- 0.13	- 0.20	Medium low	SW efficiency, E infrastructure and OSN

b. Synthesis Map

- Conservation Land limit
- Resource infrastructure
- Public open space networks
- Productive landscapes
- Vulnerable communities within communal lands and indigenous areas



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SUPPORTING INFORMATION FOR:

Otero Peña, D., Perrotti, D. & Mohareb, E. (2021) Advancing urban metabolism studies through GIS data: resource flows, open space networks, and vulnerable communities in Mexico City. *Journal of Industrial Ecology*.

Summary

This supporting information provides supplementary material that complements the methods and findings included in the main research article, including the compiled GIS datasets used in the study, the criteria and sub-criteria used to classify the boroughs, the Borough Pattern Scan detailed calculation by criteria, and a set of maps and tables including details of the selected boroughs analysis by resource flow type.

Table S1. Mexico City GIS compiled datasets and new data plotted on maps (highlighted in gray) used in the study and classified by criteria, type of information, year, units, source, scale and detailed description of the dataset are included.

Mexico City GIS datasets							
Criteria	Type	Data elements	Year *	Units	Source	Scale	Description
WATER	Flows	Water consumption	2016	l/day/cap	SACMEX Sistema de Aguas de la Ciudad de México	Borough	Drinkable water consumption of households, public services, industries, agriculture, and the commercial sector. It includes the total leakage in the distribution system (approximately 42% of the total piped flow; SACMEX, 2018).
WATER	Infrastructure	Extraction wells	2016	l/day/cap	SACMEX Sistema de Aguas de la Ciudad de México (GEO COMUNES)	Borough	-
WATER	Infrastructure	Treatment Plants	2016	l/day/cap	INEGI Instituto Nacional de Estadística, Geografía e Informática	Borough	-
WATER	Infrastructure	Aqueducts	2012	l/day/cap	SACMEX Sistema de Aguas de la Ciudad de México	Borough	Cutzamala, Lerma and other water distribution systems.
WATER	Infrastructure	Water pump facilities	2015	l/day/cap	INEGI Instituto Nacional de Estadística, Geografía e Informática	Borough	-
WATER	Infrastructure	Water tanks	2015	l/day/cap	INEGI Instituto Nacional de Estadística, Geografía e Informática	Borough	-
WATER	Infrastructure	Administrative and storage facilities	2015	Units	INEGI Instituto Nacional de Estadística, Geografía e Informática	Borough	-
WATER	Flows	Wastewater discharge	2016	l/day/cap	SEDEMA Secretaría del Medio Ambiente	Borough	Wastewater discharge of industries, public services and the commercial sector.
WATER	Infrastructure	Dams	2015	m3/cap	SACMEX Sistema de Aguas de la Ciudad de México (GEO COMUNES)	Borough	-
WATER	Infrastructure	Main collectors	2015	km	SACMEX Sistema de Aguas de la Ciudad de México	Borough	-
WATER	Infrastructure	Wastewater pump Facilities	2015	l/day/cap	INEGI Instituto Nacional de Estadística, Geografía e Informática	Borough	-
WATER	Infrastructure	Sewage treatment plants	2015	Units	INEGI Instituto Nacional de Estadística, Geografía e Informática	Borough	-
WATER	Infrastructure	Retention basins	2018	Units	INEGI Instituto Nacional de Estadística, Geografía e Informática	Borough	-
ENERGY	Flows	Electricity consumption	2017	kWh/year/cap	CFE Comisión Federal de Electricidad	Borough	Electricity consumption of households, public services, industry, agriculture, and the commercial and transportation sectors.
ENERGY	Infrastructure	Electrical power plant (turbogas)	2015	kWh/year/cap	INEGI Instituto Nacional de Estadística, Geografía e Informática	Borough	-
ENERGY	Infrastructure	Electrical substations	2015	KVA/cap	INEGI Instituto Nacional de Estadística, Geografía e Informática	Borough	-
ENERGY	Infrastructure	Waste-to-energy electrical plant	2017	kWh/year/cap	CONACYT Consejo Nacional de Ciencia y Tecnología	Borough	-
ENERGY	Infrastructure	Electical power lines	2018	km	INEGI Instituto Nacional de Estadística, Geografía e Informática	Borough	-
SOLID WASTE	Flows	Municipal solid waste (MSW) generation	2017	kg/day/cap	PAOT Procuraduría Ambiental y del Ordenamiento Territorial	Borough	MSW data are classified by source and type of waste (e.g. organic, inorganic including recycling options).
SOLID WASTE	Flows	Construction solid waste (CSW) generation	2017	kg/day/cap	SEDEMA Secretaría del Medio Ambiente	Borough	CSW data includes the private and public sector.
SOLID WASTE	Infrastructure	Transfer stations	2010	kg/day/cap	PAOT Procuraduría Ambiental y del Ordenamiento Territorial	Borough	-
SOLID WASTE	Infrastructure	Recycling plants	2018	kg/day/cap	SEDEMA Secretaría del Medio Ambiente	Borough	-
SOLID WASTE	Infrastructure	Compaction plants	2018	kg/day/cap	SEDEMA Secretaría del Medio Ambiente	Borough	-
SOLID WASTE	Infrastructure	Compost plants	2016	kg/day/cap	SEDEMA Secretaría del Medio Ambiente	Borough	-
SOLID WASTE	Infrastructure	Landfills	2018	Units	SEDEMA Secretaría del Medio Ambiente	ZMVM	-
OSN	-	Topography	-	m	PAOT Procuraduría Ambiental y del Ordenamiento Territorial	Mexico City	Contour lines every 20 m
OSN	Infrastructure	Crops landuse cover map	2008	km ²	PAOT Procuraduría Ambiental y del Ordenamiento Territorial	Mexico City	-
OSN	Infrastructure	Pasture grassland landuse cover map	2008	km ²	PAOT Procuraduría Ambiental y del Ordenamiento Territorial	Mexico City	-
OSN	Infrastructure	Forests landuse cover map	2008	km ²	PAOT Procuraduría Ambiental y del Ordenamiento Territorial	Mexico City	-
OSN	Infrastructure	Urban tree cover map	2016	km ²	PAOT Procuraduría Ambiental y del Ordenamiento Territorial	Mexico City	-
OSN	Infrastructure	Non productive grassland urban cover map	2016	m ² /inhab	PAOT Procuraduría Ambiental y del Ordenamiento Territorial	Mexico City	-
OSN	Infrastructure	Public green spaces	2017	m ² /inhab	CDMX Gobierno de la Ciudad de México	Borough	Parks and gardens.
OSN	Infrastructure	Public blue spaces	-	m ² /inhab	PAOT Procuraduría Ambiental y del Ordenamiento Territorial	Borough	Rivers, streams, channels, and lakes. Not included culverted rivers and streams.
OSN	Infrastructure	Public gray spaces	2017	m ² /inhab	CDMX Gobierno de la Ciudad de México	Borough	Squares and pedestrian walkways. Not included the street network.
OSN	Infrastructure	Private green spaces	2017	m ² /inhab	CDMX Gobierno de la Ciudad de México / INEGI	Borough	Residential and commercial gardens and parks.
OSN	Infrastructure	Nature reserves	2013	m ² /inhab	PAOT Procuraduría Ambiental y del Ordenamiento Territorial	Borough	-
OSN	Infrastructure	Streets	2016	km ²	PAOT Procuraduría Ambiental y del Ordenamiento Territorial	Mexico City	-
-	-	Informal settlements	2010	km ²	PAOT Procuraduría Ambiental y del Ordenamiento Territorial	Borough	Areas covered by informal settlements.
-	-	High-density AGEB	2015	km ²	GEOCOMUNES Urban Collective	AGEB	-
-	-	High urban marginality index	2010	km ²	CONAPO Consejo Nacional de la Población	AGEB	-
-	-	Indigenous areas (Pueblos Originarios)	2012	km ²	PAOT Procuraduría Ambiental y del Ordenamiento Territorial	Borough	Areas covered by indigenous areas.
-	-	Communal lands	2018	km ²	RAN Registro Agrario Ncional	Borough	Areas covered by communal lands.

* Data was scaled up or down based on the year 2015 population totals.

Table S2. *Criteria and sub-criteria used to classify the boroughs. Each criterion is characterised by sub-criteria, which are described using spatially-explicit data.*

Resource consumption/generation by type of flow			
<i>Criteria</i>	Water flows	Energy flows	Solid waste flows
<i>Sub-criteria</i>	. Drinkable water consumption . Wastewater outflows	. Electricity consumption	. MSW generation . CSW generation
Resource infrastructure by type of flow			
<i>Criteria</i>	Water infrastructure	Energy Infrastructure	Solid waste infrastructure
<i>Sub-criteria</i>	. Aqueducts (water distribution) . Water wells/extraction systems . Capacity of drinkable water treatment plans . Water pump facilities . Water tanks . Wastewater treatment plants . Dams	. Electricity generation by fossil fuel and waste -to-energy plants . Capacity of the electrical substations	. Transfer stations processing . Compaction plants processing . Recycling plants processing Compost plants processing . Total amount of illegal dumping sites
Open space networks (OSN), vulnerable communities, communal lands, and indigenous areas total amount of surface areas			
<i>Criteria</i>	OSN	Vulnerable communities	Communal lands and indigenous areas
<i>Sub-criteria</i>	. Public green spaces (parks and gardens) . Gray spaces (squares) . Blue spaces (rivers, streams, channels, and lakes) . Private green spaces (gardens) . Nature reserves	. Informal settlements . High urban marginality index	. Communal lands . Indigenous areas

Table S3. Borough Pattern Scan detailed calculation by criteria. All values for each sub-criteria are highlighted in red and classified by borough.

Borough Pattern Scan calculation

Index formula Variables	Water (W)		W infrastructure					W infrastructure index = (W1+W2+W3+W4+W5+W6+W7)/7				
	W flows											
	W1	W2	W1	W2	W3	W4	W5	W6	W7			
Boroughs	Water consumption (l/day/cap)	Waste water discharge (l/day/cap)	Aqueducts capacity (l/day/cap)	Extraction wells (l/day/cap)	Treatment plants capacity (l/day/cap)	Water pump facilities (l/day/cap)	Water tanks (l/day/cap)	Sewage treatment plants (l/day/cap)	Dams (l/day/cap)			
Álvaro Obregón	0.57 321	0.16 6	0.05 122	0.23 114	0.00 0	0.51 537	0.18 454	0.23 32	1.00 3994.76			
Azacapotzalco	0.72 404	0.43 16	0.00 0	0.44 220	0.15 24	0.00 0	0.00 0	0.04 5	0.00 0			
Benito Juárez	0.73 406	0.39 14	0.00 0	0.28 143	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0			
Coyoacán	0.63 355	0.19 7	0.00 0	0.64 324	0.00 0	0.22 236	0.00 0	0.80 114	0.00 0			
Cuajimalpa de Morelos	0.52 293	0.19 7	0.31 655	0.05 26	0.00 0	0.95 1,011	0.31 773	0.00 0	0.00 0.10			
Cuauhtémoc	0.59 332	0.67 25	0.00 0	0.07 34	0.00 0	0.00 0	0.00 0	0.03 4	0.00 0			
Gustavo A. Madero	0.42 237	0.10 4	0.00 0	0.01 7	0.13 20	0.05 49	0.06 160	0.32 45	0.00 0			
Iztacalco	0.39 219	0.14 5	0.00 0	0.13 66	0.31 49	0.07 74	0.00 0	0.38 54	0.00 0			
Iztapalapa	0.42 235	0.10 4	0.00 0	0.17 87	1.00 156	0.22 236	0.06 138	1.00 142	0.00 0			
Magdalena Contreras	0.99 554	0.08 3	0.27 563	0.04 21	0.93 145	1.00 1,062	0.51 1,262	0.12 18	0.00 0			
Miguel Hidalgo	0.90 502	1.00 37	0.00 0	0.45 228	0.00 0	0.22 237	0.09 211	0.31 44	0.00 0.77			
Milpa Alta	0.73 410	0.02 1	1.00 2,082	0.34 169	0.00 0	0.00 0	1.00 2,471	0.26 38	0.00 0			
Tláhuac	0.38 210	0.06 2	0.00 0	0.16 79	0.92 143	0.37 398	0.02 61	0.90 128	0.00 0			
Tlalpan	1.00 560	0.18 7	0.31 648	0.54 272	0.00 0	1.00 1,062	0.47 1,153	0.04 5	0.00 0			
Venustiano Carranza	0.36 203	0.13 5	0.06 0	0.06 30	0.10 16	0.13 135	0.01 26	0.00 0	0.00 0			
Xochimilco	0.67 374	0.08 3	0.07 150	1.00 505	0.35 54	0.39 415	0.22 555	0.26 37	0.00 1.54			

Index formula Variables	Energy (E)		Solid Waste (SW)			SW infrastructure				
	E flows		SW flows							
	E1	E2	SW1	SW2	SW3	SW1	SW2	SW3	SW4	SW5
Boroughs	Electricity consumption (kWh/day/cap)	Electrical power plant (kWh/day/cap)	Waste-to-energy electrical plant (kWh/day/cap)	Electrical substations (kVA/cap)	Municipal SW generation (kg/day/cap)	Construction SW generation (kg/day/cap)	Transfer stations (kg/day/cap)	Compaction plants (kg/day/cap)	Recycling plants (kg/day/cap)	Compost plants (kg/day/cap)
Álvaro Obregón	0.30 1,404	0.00 0	0.00 0	0.13 0.93	0.37 0.91	0.00 0	0.64 12.93	0.00 0	0.00 0	0.00 0.08
Azacapotzalco	0.50 2,529	0.00 0	0.00 0	0.00 0.51	0.52 1.30	0.00 0	1.00 20.32	0.00 0	0.00 0	0.00 0
Benito Juárez	0.59 2,767	0.00 0	0.00 0	0.12 0.82	0.69 1.72	0.46 0.29	0.42 8.8	0.00 0	0.00 0	0.00 0
Coyoacán	0.37 1,726	0.00 0	0.00 0	0.21 1.47	0.54 1.34	0.06 0.04	0.81 16.52	0.00 0	0.00 0	0.00 0
Cuajimalpa de Morelos	0.52 2,442	0.00 0	0.00 0	1.00 6.97	0.38 0.94	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0.21
Cuauhtémoc	0.80 3,740	1.00 1,070	0.00 0	0.39 2.70	1.00 2.49	0.00 0	0.64 12.94	0.00 0	0.00 0	0.00 0
Gustavo A. Madero	0.23 1,088	0.00 0	0.00 0	0.06 0.44	0.60 1.50	0.04 0	0.07 1.37	0.54 2.04	1.00 21.10	0.00 0.05
Iztacalco	0.26 1,215	0.00 0	0.00 0	0.23 1.59	0.50 1.24	0.18 0.12	0.00 0	0.00 0	0.00 0	0.00 0
Iztapalapa	0.23 1,063	0.00 0	0.00 0	0.15 1.04	0.50 1.24	0.00 0	0.33 6.73	1.00 3.80	0.00 0	0.00 0.01
Magdalena Contreras	0.14 649	0.00 0	0.00 0	0.13 0.89	0.43 1.08	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0
Miguel Hidalgo	1.00 4,672	0.00 0	0.00 0	0.14 0.94	0.92 2.28	0.00 0	0.50 10.18	0.00 0	0.00 0	0.00 0
Milpa Alta	0.08 371	0.00 0	1.00 0.46	0.00 0	0.35 0.88	0.00 0	0.20 4.13	0.00 0	0.00 0	0.00 0.32
Tláhuac	0.12 558	0.00 0	0.00 0	0.00 0	0.40 1.00	0.00 0	0.00 0	0.00 0	0.00 0	0.00 0
Tlalpan	0.27 1,275	0.00 0	0.00 0	0.03 0.20	0.52 1.29	0.00 0	0.26 5.35	0.00 0	0.00 0	0.00 0
Venustiano Carranza	0.44 2,051	0.00 0	0.00 0	0.06 0.45	0.81 2.02	1.00 0.63	0.56 11.28	0.00 0	0.00 0	1.00 21,356.87
Xochimilco	0.15 702	0.00 0	0.00 0	0.15 1.02	0.90 2.24	0.50 0.31	0.41 8.39	0.00 0	0.00 0	0.00 0.17

Open Space Networks (OSN)					
OSN areas					
Index formula	OSN index = (OSN1+OSN2+OSN3+OSN4+OSN5)/5				
Variables	OSN1	OSN2	OSN3	OSN4	OSN5
Boroughs	Public green spaces (m²/hab)	Public blue spaces (m²/hab)	Public grey spaces (m²/hab)	Private green spaces (m²/hab)	Nature reserves (m²/hab)
Álvaro Obregón	0.38 2.67	0.00 0	0.06 0.02	0.33 8.51	0.03 38.04
Azacapotzalco	0.34 2.39	0.00 0	0.25 0.09	0.40 10.33	0.00 0
Benito Juárez	0.16 1.10	0.00 0	0.03 0.01	0.03 0.70	0.00 0
Coyoacán	1.00 7.04	0.00 0	0.53 0.20	0.34 8.70	0.00 0
Cuajimalpa de Morelos	0.40 2.81	0.00 0	0.00 0	1.00 25.75	0.14 213.54
Cuauhtémoc	0.15 1.03	0.00 0	1.00 0.37	0.11 2.77	0.00 0
Gustavo A. Madero	0.12 0.85	0.03 0.21	0.17 0.06	0.24 6.17	0.01 9.98
Iztacalco	0.03 0.24	0.00 0	0.23 0.08	0.31 7.96	0.00 0
Iztapalapa	0.24 1.68	0.02 0.18	0.02 0.01	0.33 8.55	0.00 2.58
Magdalena Contreras	0.04 0.27	0.00 0	0.00 0	0.16 4.02	0.13 187.11
Miguel Hidalgo	0.49 14.49	0.00 0	0.06 0.02	0.60 15.51	0.00 0
Milpa Alta	0.00 0.03	0.00 0	0.19 0.07	0.05 1.25	1.00 1,47.32
Tláhuac	0.31 2.17	1.00 8.31	0.09 0.03	0.39 10.08	0.03 42.18
Tlalpan	0.71 5.00	0.00 0	0.39 0.15	0.54 14.00	0.19 282.06
Venustiano Carranza	0.44 3.07	0.03 0.26	0.63 0.23	0.35 8.90	0.00 0
Xochimilco	0.07 0.53	0.67 5.56	0.00 0	0.23 5.90	0.05 72.99

Figure S1. Boroughs with high water consumption index: S1a) Azcapotzalco, S1b) Cuauhtémoc, S1c) Tlalpan; utility infrastructures are highlighted in the map.

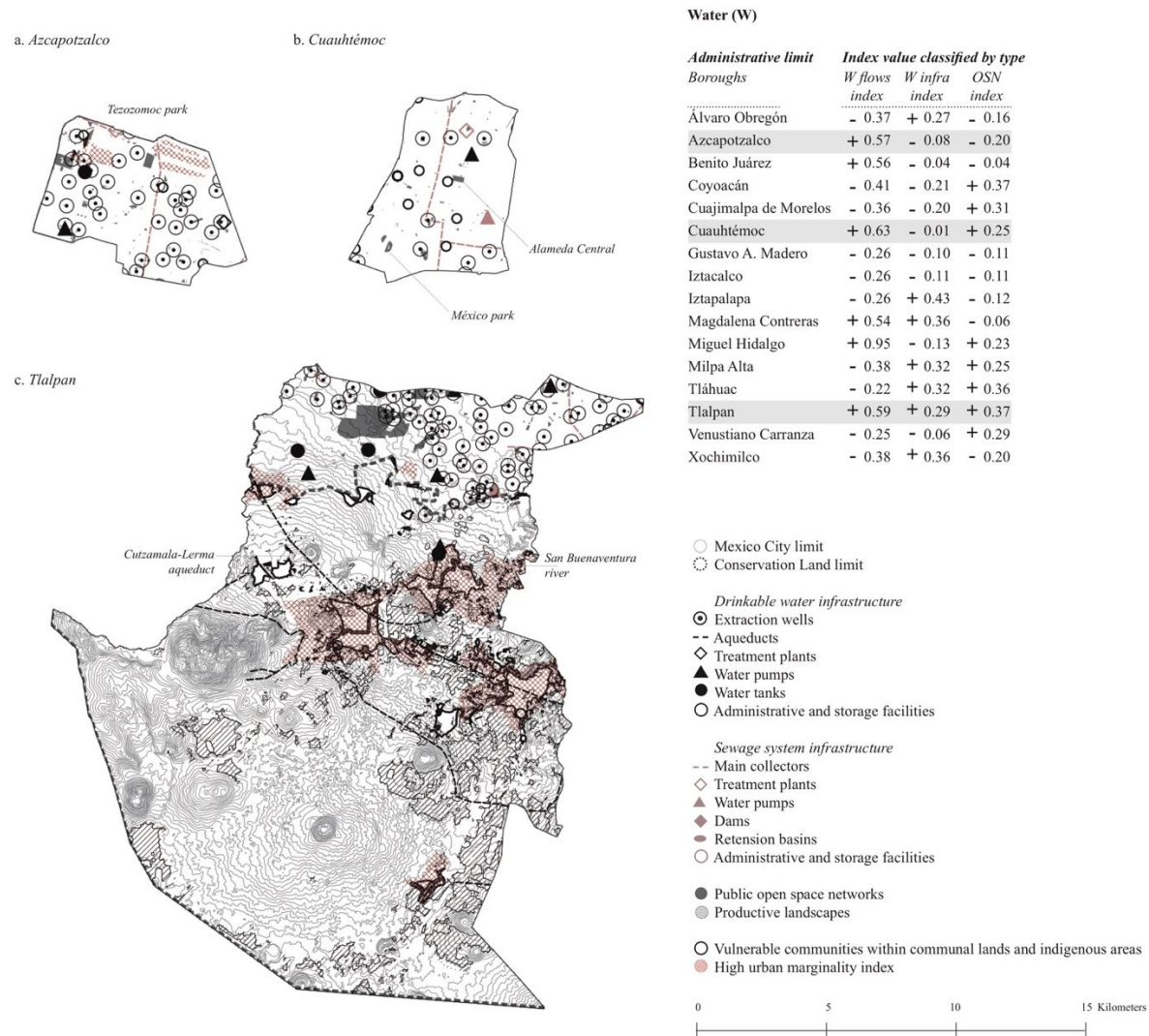


Figure S2: Boroughs with high energy consumption index: S2a) Benito Juárez, S2b) Cuauhtémoc, S2c) Milpa Alta; utility infrastructures are highlighted in the map.

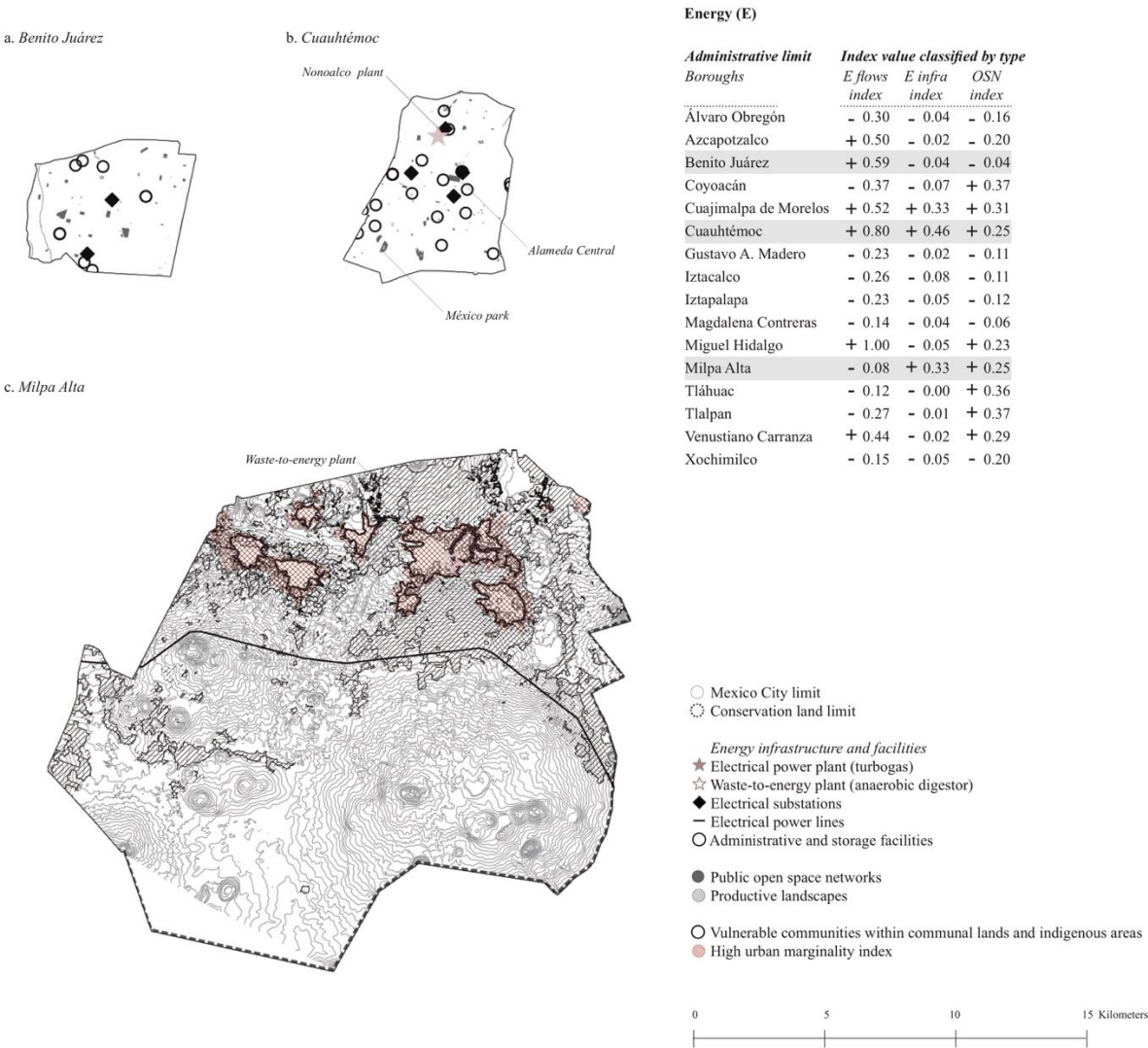


Figure S3: Boroughs with high/low solid waste generation index: S3a) Iztapalapa, S3b) Gustavo A. Madero, S3c) Xochimilco; utility infrastructures are highlighted in the map.

