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Hydrological and Urban Analysis of Territories under High Water Stress: Nazas and Aguanaval Rivers, Mexico

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Abstract: Hydrological region 36 in Mexico (RH36) faces significant water stress and tends towards agricultural mono-production. Following the regulation of its main rivers, the Nazas and Aguanaval, through dam construction and canalization, the flow of water in the lower basin of the Nazas River has become negligible, which has altered the riverfronts of major cities in the region. Consequently, Torreón, Gómez Palacio, and Lerdo, which are part of the La Laguna Metropolitan Zone (ZML), have expanded into new territories along the riverbanks and adjacent recharge areas. Establishing the boundaries of specific watersheds is crucial for the implementation of targeted rural and urban intervention strategies. This approach enhances understanding of interactions between the natural hydromorphology of a hydrological region, water infrastructure (dams, canals, reservoirs), and the urban and rural landscape. To effectively plan based on watershed boundaries, it is essential to develop hybrid cartographies that integrate urban, architectural, agricultural, and hydrological delineations. These maps provide valuable indicators for watershed-based planning, which facilitates precise hydrological urban restoration strategies tailored to specific basins. This research focuses on developing and presenting such hybrid cartographies, which combine hydrological, rural, and geographic data. This methodology aligns with the overarching objective of mitigating water stress in RH36 and promoting a transition towards more sustainable forms of agriculture.

Keywords: fluvial restoration; rural planning; water stress; water footprint; rural strategies; Nazas River; Aguanaval river; Comarca Lagunera; Región Hidrológica 36; watershed planning

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1. Introduction

In Mexico, hydrological regions are groups of river basins. According to the National Water Commission (CONAGUA), there are 37 recognized hydrological regions [1]. The object of this research is the hydrological region RH36 (93,000 km^2). This region contains the Nazas and Aguanaval river basins located in the northwest area of Mexico. These basins have a high degree of pressure on water resources [2]. The communities in RH36 utilize up to 40% of the available renewable water in the basin for agricultural mono-production [3] to support the manufacture of dairy and goods derived from livestock. In these areas, extensive irrigation canals weave through agricultural fields and urban areas, spanning kilometers [4]. Furthermore, large dams were built for water storage and distribution between 1940 and 1960, primarily serving the agricultural cycles of the irrigation districts [5]. The construction of the dams over the Nazas River (Lázaro Cárdenas Dam, Francisco Zarco Dam) caused a loss of flow in the lower basin of the river in front of the main cities of La Laguna Metropolitan Zone (ZML). The regulation of the rivers also intensified the drying of the Mayrán and Viesca Lagoons, where the Nazas and Aguanaval rivers flow, respectively. In this study, it is argued that the urban logic of RH36 cities was altered with the regulation of the rivers (Figure 1).



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

Figure 1. (**a**) Panoramic view of the Nazas River towards the Calabazas Canyon, 1930. Source: El Siglo de Torreón. Author: unknown. The river takes center stage, serving as the natural boundary and primary water resource for the region's agriculture. It meanders from highlands, cutting through the Calabazas Canyon. (**b**) Panoramic view of the Nazas River towards the Calabazas Canyon, 2019. Source: Google Earth. The river is dried up. The cities have utilized the adjacent surfaces along the riverbank, and the dry riverbed has become a periphery of the La Laguna Metropolitan Zone (ZML).

The aim of this research was to generate a methodology for drawing up water cartographies on specific hydrological regions with scarce cadastral information, using as an example the RH36 and ZML (1.4 million inhabitants). It is recognized that this type of approach is vital to improving rural and urban redevelopment strategies [6] based on fluvial restoration and water stress reduction. The methodology developed in this research could be useful for the analysis of rural and urban fabrics. In these areas, the geostatistical and cadastral data available on the territory need to be incorporated [7]. In Mexico, CONAGUA, the National Institute of Statistics and Geography (INEGI), the National Agrarian Registry (RAN), and the National Water Information System (SINA) are among the main institutions that provide open data for territorial studies. However, at local scales, specific information must be gathered to provide solutions at a morphological rural and urban scale. This is why, when vectorized information does not exist or is not suitable for use within Geographic Information Systems (GIS), it is created using the tools included in GIS software (QGIS-LTR 3.28), within the limits of a specific hydrological region [8].

The hydrological region is approached first through the analysis of geospatial information available in Mexico. The interpretation of this information reveals a series of deficiencies in the various scales of analysis. This is particularly true for local scales where rural and urban elements need to be analyzed within their context. In Mexico, INEGI provides national geospatial data. However, the production of local information depends on decentralized organizations, which is why precise cadastral information on scales like 50:00, 20:00, or smaller is scarce [9]. The development of cadastral information in Mexico is still in progress but the results depend on different administrations and budgets in each local community.

In the case of hydrological region 36, cadastral information is available for some areas, mainly for the major cities in La Laguna Metropolitan Zone. However, this information does not include building footprints. Building footprint information along with block polygons and surfaces is needed to perform morphological studies [10]. For a regional fluvial restoration project [11], sufficient geospatial information is required on all the settlements inside the hydrological region, to gain a better picture of the communities involved in the administration and consumption of water resources. Therefore, it is essential to generate new cartographies to identify the dynamics between the system of settlements and the specific basin and sub-basins to which they belong inside the hydrological region.

Water stress [12] and water quality indicators (chemical oxygen demand [COD], biological oxygen demand [BOD], and total nitrogen [NT] [13] are also essential to understanding the behavior of rural and urban communities in the productive landscape of the ZML (Figure 2), the arid climate (*BWh* in the Köppen climate classification), and the low precipitation (average annual precipitation: 224.6 mm). Agro-production surfaces and their morphological characteristics are important in order to understand the relationships between anthropological activities and the biophysical matrix [14]. Through the process of adding such information to tailored hydro-rural and -urban cartographies, production dynamics can be identified, and the percentage of used and available space in the domains of a specific hydrographic basin can be determined [15]. By incorporating these layers of information, it is possible to understand the settlement and production logics of a set of rural communities and their essential relationship with the water cycle [16].

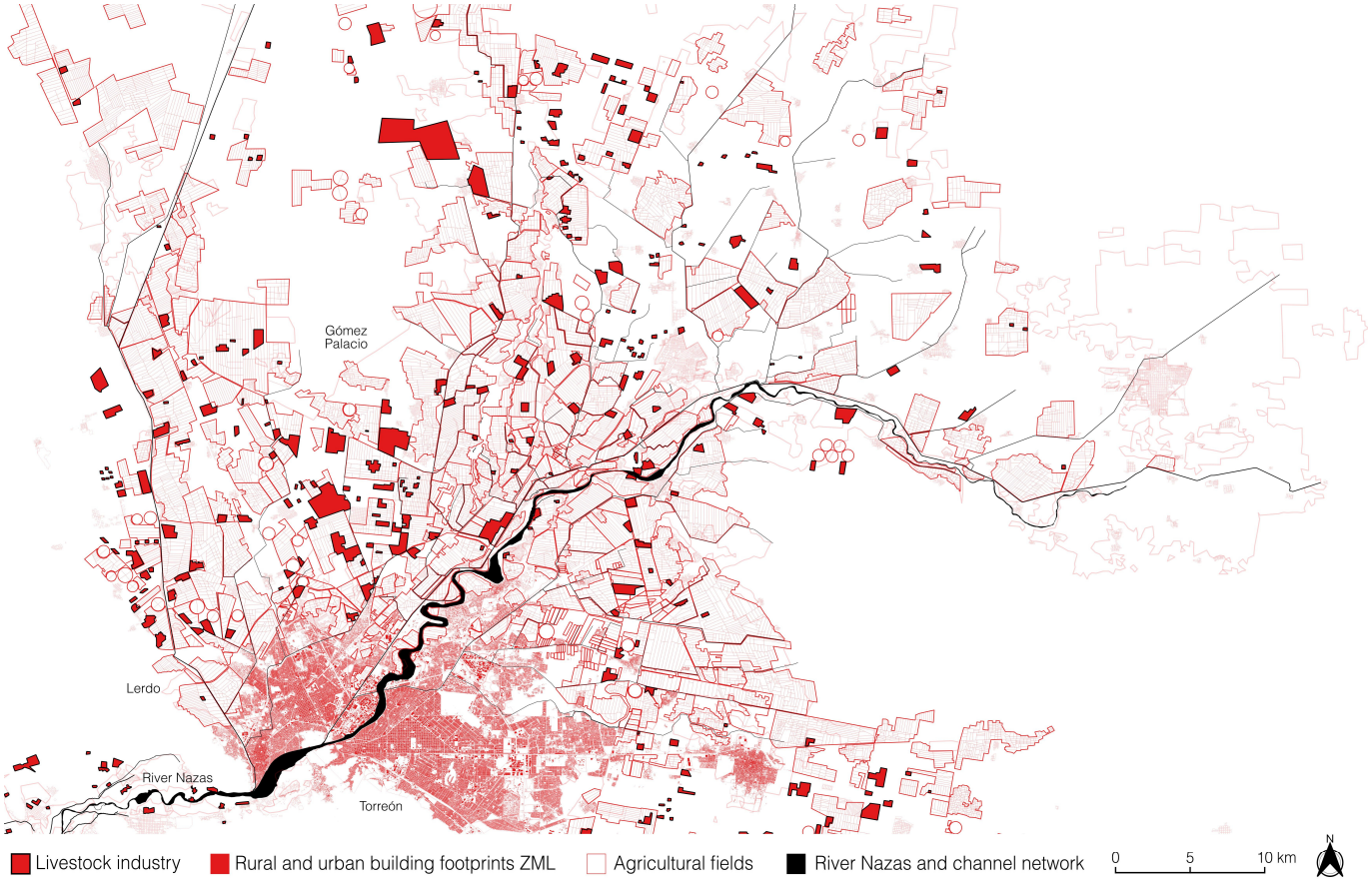


Figure 2. Livestock industry in ZML. Mono-productive agriculture on the lower basin in hydrological region 36 and the water network. Graphic by the authors, based on geospatial data from INEGI and authors' vectorization in QGIS.

According to Eizaguirre, to determine the form of the territory, it is essential to recognize relevant processes in the transformation of the biophysical matrix to understand the formal result of the territorial order [17]. Based on this knowledge and the power of defining the components of the territory [18], alternatives can be drawn up to improve the production dynamics of communities within the limits of hydrographic basins. Without accurate information on the rural, urban, and geographic order, it is difficult to devise a solution that considers the entire system of communities and the natural system. From this territorial perspective, Xabier Eizaguirre's approaches [17,18] constitute a valuable theoretical core, along with contributions from Solà-Morales [19] and Giuseppe Dematteis [20]. Additionally, practical approaches within the Mexican context, such as the efforts of Mario

Schjetnan [21] to evaluate the roots of agricultural landscapes, and more specific analyses such as those of Cháirez Araiza [22] on the study of the impact of river regulation in the Laguna region, also play significant roles.

In this paper, the cartography produced by an analysis of territorial components allows us to visualize a series of hydrological rural maps that together form a knowledge base on hydrological region 36. This knowledge base considers all the communities in the region as a fundamental part of a fluvial restoration project, which can include water stress reduction at the regional scale as one of its main goals [23]. The benefits of using water as the common thread will make it possible to visualize the system of communities in a multi-scale scope, as well as the effects on water flows and the hydrological cycle of the region.

With this information, it will be possible to promote strategies aimed at improving water stability, and urban production and rural production scenarios for all the communities within the water basin limits. Finally, this paper presents the development of a methodology based on four main scales. The goal of this methodology is to generate rural hydrological cartographies, proceeding from the largest territorial scale to a more local rural and urban scale.

2. Research

Outside the context of RH36, projects have been developed for river basin restoration that could be valuable for comparison with the Nazas and Aguanaval rivers. However, it is evident that the conditions specific to La Laguna Metropolitan Zone, such as the nature of the rivers, climate, and agriculture, are distinct. It is acknowledged that hydrological infrastructures (dams and canals) significantly alter the hydrographic network and urban structure. From this perspective, operations such as flow management of rivers, agricultural parks, reconfiguration of recharge areas, and adjustments to hydrological infrastructure can serve as reference points.

In Europe, for instance, agricultural and river parks have been established to introduce less ecologically aggressive control mechanisms. In Barcelona, the Besòs River Fluvial Park [11] was conceived with objectives including ensuring the river's hydraulic capacity, restoring and naturalizing its final stretch at the estuary, and utilizing certain river areas for recreational purposes. Additionally, the Besòs River Hydrological Alert System (SAHBE) has enabled an understanding of river changes and their implications for urban areas. Thus, leisure activities have been successfully integrated with the restoration of the river's estuarine section [24,25].

Similarly, multiple operations have been conducted on the Llobregat River in Barcelona, focusing on its canal and recharge areas. The Special Plan for the Llobregat Agricultural Park stands out as an exemplary project in Catalonia, initiated by the Department of Urbanism at the Universitat Politècnica de Catalunya—BarcelonaTech (UPC) and authored by a group of professors and researchers. Its origins are traced back to the agricultural value of the region and the City Sanitation Project of 1981 [26], followed by the Regional Planning project by Rubió i Tudurí [27].

There are also more comprehensive approaches to rivers, such as the Flood Risk Management Plan (PGRI) of the Ebro River in Spain. Through this framework, the Ebro Resilience Strategy [11] promotes specific lines of action implemented across autonomous jurisdictions. It represents a method for city planning and water network management that involves the participation of various autonomous regions within the river basin.

As previously mentioned, in Mexico and specifically for RH36, it is essential to generate cadastral mapping using available geospatial data. While there are approaches for the semi-automated generation of this information [28,29], these strategies rely on high-resolution satellite imagery. Consequently, vector data for RH36 have been produced using a hybrid model, which incorporates manual vectorization and integrates existing databases from CONAGUA and INEGI. Regarding the integration of cadastral mapping with the hydrographic network, the approaches of Cifuentes [30] highlight the effects of dam construction on the hydrographic system. Furthermore, there is a historical perspective that

emphasizes the understanding of water heritage in cities, such as the case of Madrid, studied in terms of its hydrological past by Bustamante and Aguilar [31], or studies by Álvez, Espinosa, and Castillo on the Chilean region and the Andalién River [32].

The most notable approach to the territory within the context of RH36 is that undertaken by Solà Morales in his study on the identity of the Catalan territory [33]. In constructing the cartography of the Catalan regions, the author described and identified the settlements along with their geography, morphology, and hydrography. Mapping the settlements of RH36 was the first step towards evaluating strategies to restore hydrological balance and reduce water stress in the Nazas and Aguanaval basins.

3. Methodology

To achieve the research objectives, an analytical method was developed for interpreting urban water risk [34]. This method is situated within the paradigm of climate change and urban ecological studies [35]. It emphasizes a transdisciplinary approach with an instrumentalist perspective. The constructed methodology is relevant for river restoration strategies, especially in processes aimed at recovering rivers that face substantial pressures on water resources. In this regard, although the methodology is applied to hydrological region 36, it can be adapted to other regions that experience high levels of water stress.

The methodology of this research involves the integration of novel information into Mexico's cadastral databases, focusing specifically on hydrological region 36. This paper details the generation of vector data using geospatial software, which incorporates tools for satellite analysis such as DEM images [36]. Supervised vectorization is applied to raster data sourced from LANDSAT [37], complemented by database integration, to develop innovative approaches for visualizing water footprint [38] impacts on community structures within the studied hydrological region.

To address the analysis and development of hydrographic mapping in hydrological region 36, a systematic approach was proposed. The first stage involves contextualizing and identifying the components of the watersheds, followed by delineation into four operational scales. This method aims to provide a comprehensive understanding of the region, encompassing its hydrography, urban and rural communities, and hydro-agricultural infrastructure. The information gathered and analyzed during this process will be a knowledge base for future fluvial restoration practices in RH36.

- Context stage, development of the main concepts: hydrological region, hydrographic basin and sub-basin, micro basin, and urban basin. These concepts represent units of analysis in territories under water stress.
- The first scale is of the regional order. The objective is to ascertain the geographical boundaries of the study area. The boundaries of RH36 are defined according to the cartographic projection established by CONAGUA [1] and INEGI [9].
- Second scale: geographic and geomorphologic order. Two main topics are presented. These are the Strahler [39,40] diagram and the urban morphology of the basin and road infrastructure and the water stream network [41].
- The third scale is of the territorial order. In this stage, the system of cities and the quality of the crops in RH36 are evaluated. Additionally, buildings are integrated into the water footprint through the creation of a database that incorporates vectorized buildings in the research process and annual water use per inhabitant based on CONAGUA [1] and INEGI [42] data.
- City scale. The canal network is in contact with buildings. In the lower basin of the Nazas River, where the ZML is located, an extensive network of irrigation canals stretches across the area for crop cultivation [4]. However, these canals face contamination issues within the urban fabric. The infrastructure group is strategically evaluated in the research, as it can potentially restructure urban elements to provide enhanced protection for water resources.

Through a multi-scale analysis of the land use patterns and surface features within the territory, the impacts of Nazas River regulation on the hydrological region can be

observed [43]. This analysis also facilitates the examination of changes in urban components that interact with the canal network. By comparing agricultural and land use patterns with the hydrographic network across the region, opportunities for river restructuring and restoration can be identified, with the aim of enhancing benefits for the populations that reside within the basins [24].

The process of developing cartography at each study scale is detailed further in this text. Initially, boundaries are defined within the context of hydrological region 36, followed by an explanation of the tools employed in each instance. The outcome of this methodological approach yields integrated perspectives of the territory within the regional hydrographic network. These intentionally crafted maps aim to enhance understanding of the agro-production dynamics of the area. Therefore, the objective of this methodological approach is to create a tool that facilitates an understanding of agro-production dynamics in urban and rural settings. Although it is applied to hydrological region 36, it can be adapted to other basins and sub-basins. In this regard, regions with a greater availability of geographic information can make significant contributions to the watershed approach by addressing the restoration of their hydrographic network.

4. Context: Units of Analysis in Territories under High Water Stress

In addition to physical limits, the theoretical–conceptual limits of the hydrographic basins are recognized. These units of analysis define the scope of the research. The defined borders of the hydrographic basins determine the number of rural and urban communities to be evaluated for the total scope of the region. The scope of the study encompasses communities, their roads, and production surfaces. The purpose is to recognize a focus on hydrological regions and their basins as a starting point for water basin restoration. According to Cotler and Caire [44], planning and management in the context of a basin provides a global, systemic vision of the territory. Within basin planning, the main polluting sources, their intensities, and impacts on the eco-hydrological dynamics can be observed. Figure 3 presents the concepts of hydrological administrative regions (RHA) and hydrological regions (RH) developed by CONAGUA in Mexico. The graphic shows how hydrological regions integrate the geographic basins on their geographic limits, instead of political subdivisions conformed by municipalities in the RHA. Therefore, using the hydrological region as the study object enhances understanding of the hydrographic system. For this paper, RH36 was selected.

4.1. Hydrological Regions in Mexico

In the Mexican territory, 37 hydrological regions (RH) have been identified (Figure 4 and Table 1). These regions are subcategorized as basins and sub-basins, to integrate the hydrographic systems. The limits of these regions are represented by the geographic borders of the basins they group. The following graphic and table present the hydrological regions defined by CONAGUA [1] in Mexico and their main characteristics. The RH36 focus of this study is highlighted.

Hydrological region 36 encompasses the Nazas and Aguanaval river basins, both of which are endorheic, culminating in closed systems that discharge into internal lagoons within the low plains of the region. This hydrological feature characterizes these basins as closed systems. RH36 spans across the states of Durango, Coahuila, and Zacatecas. La Laguna Metropolitan Zone is situated on the boundary between Durango and Coahuila. Given the national-level management of water resources, it is feasible to establish interstate coordination models and implement strategies across multiple jurisdictions. RH36 was selected as the primary unit of study due to its alignment with the geographical boundaries of these basins.

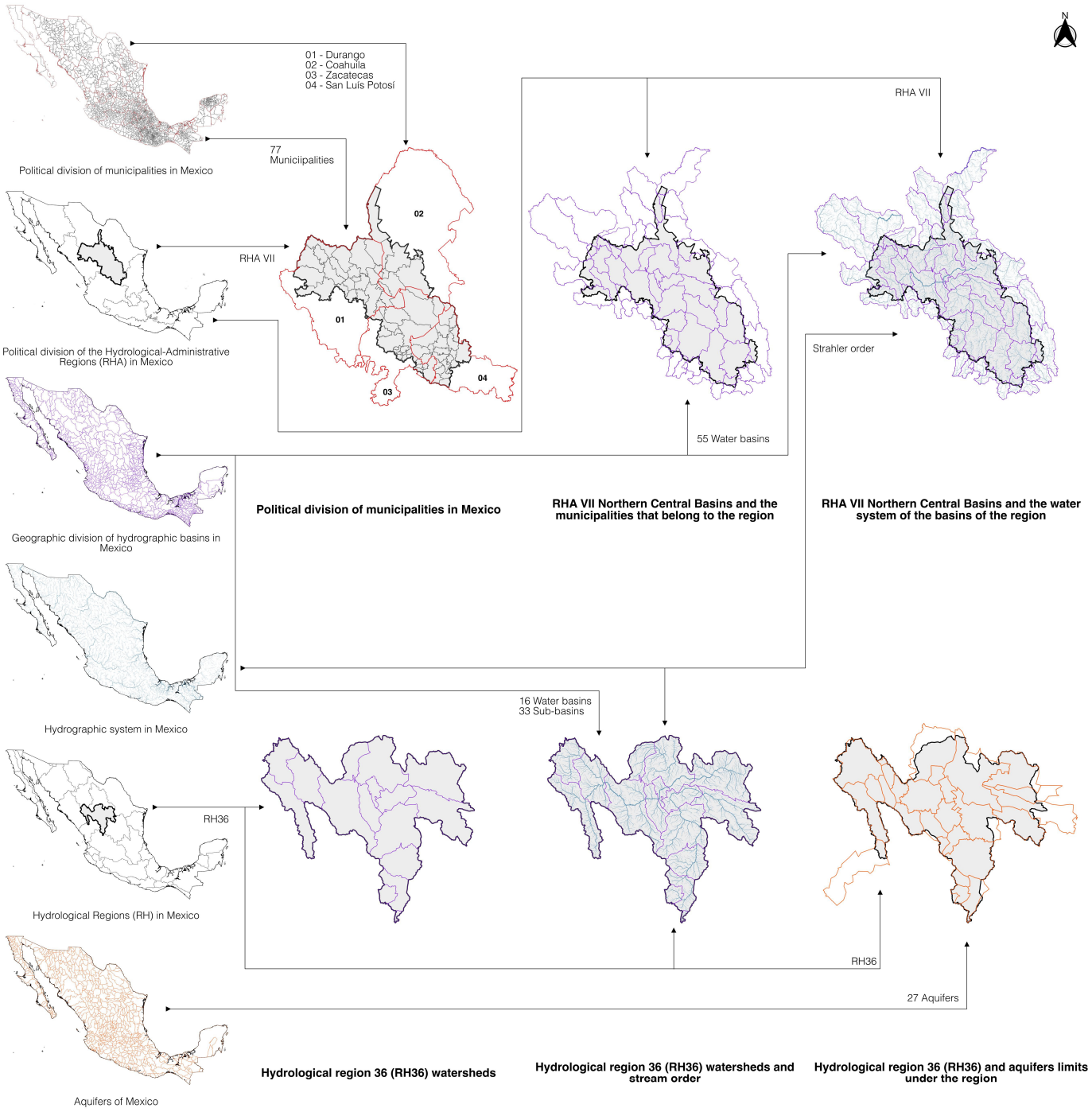


Figure 3. Mexican context. Hydrological administrative regions (RHA). Hydrological regions (RH). Aquifers. Graphic by the authors, based on geospatial data from the National Information System (SINA).

Durango contains the main reservoirs of the Nazas River, namely Lázaro Cárdenas and Francisco Zarco. Coahuila boasts the predominant irrigation canal infrastructure in the region, while Zacatecas concentrates on the Aguanaval River basin. Agriculture predominates as the primary economic activity in the region, focused primarily on fodder production for livestock. Coahuila and Durango have significant livestock and dairy industries within their urban–industrial zones. The majority of water resources are allocated to support these activities. The region experiences considerable hydrological stress, directly linked to its agroindustrial activities.

Table 1. The 37 hydrological regions identified by the National Water Commission. On table number 36 is the RH36 object of this study. Table by the authors, based on geospatial data from the National Information System (SINA).

No.	Hydrological Region	Normal Precipitation 1991–2020 (mm)	Average Internal Surface Natural Runoff (hm^3/year)	Imports (+) o Exports (−) from Other Countries (hm^3/year)	Average Total Surface Natural Runoff (hm^3/year)	Number of Basins	Area (km^2)
1	B.C. Noroeste	195	359	17	376	16	28.5
2	B.C. Centro-Oeste	119	244	-	244	16	44.3
3	B.C. Suroeste	202	380	-	380	15	29.7
4	B.C. Noreste	137	140	-	140	8	14.4
5	B.C. Centro-Este	132	103	-	103	15	13.6
6	B.C. Sureste	283	198	-	198	14	11.5
7	Río Colorado	98	77	1.8	1.9	4	6.9
8	Sonora Norte	294	211	-	211	9	61.4
9	Sonora Sur	474	4.8	-	4.8	16	139.4
10	Sinaloa	709	14.6	-	14.6	30	103.5
11	Presidio-San Pedro	805	8.9	-	8.9	26	51.7
12	Lerma-Santiago	722	13.2	-	13.2	58	132.9
13	Río Huicicila	1.31	1.3	-	1.3	6	5.2
14	Río Ameca	1.07	2.3	-	2.3	9	12.2
15	Costa de Jalisco	1.1	3.5	-	3.5	11	12.9
16	Armería-Coahuayana	978	3.4	-	3.4	10	17.6
17	Costa de Michoacán	916	1.6	-	1.6	6	9.2
18	Balsas	947	18.6	-	18.6	15	118.2
19	Costa Grande de Guerrero	1.2	5.2	-	5.2	28	12.1
20	Costa Chica de Guerrero	1.2	18.5	-	18.5	32	39.9
21	Costa de Oaxaca	962	2.5	-	2.5	19	10.5
22	Tehuantepec	990	3.1	-	3.1	15	16.4
23	Costa de Chiapas	2.3	12.5	1.6	14.1	25	12.3
24	Bravo-Conchos	418	5.7	353	5.3	37	229.7
25	San Fernando-Soto la Marina	719	4.6	-	4.6	45	54.9
26	Pánuco	858	20.4	-	20.4	77	96.9
27	Norte de Veracruz (Tuxpan-Nautla)	1.5	15.0	-	15.0	12	26.6
28	Papaloapan	1.5	47.4	-	47.4	18	57.3
29	Coatzacoalcos	2.1	34.7	-	34.7	15	30.2
30	Grijalva-Usumacinta	1.8	72.8	44.0	116.9	83	102.5
31	Yucatán Oeste	1.2	735	-	735	7	25.4
32	Yucatán Norte	1.2	22	-	22	2	58.1
33	Yucatán Este	1.2	1.1	-	1.1	6	38.3
34	Cuencas Cerradas del Norte	361	1.4	-	1.3	22	90.8
35	Mapimí	299	225	-	225	6	62.6
36	Nazas-Aguanaval	380	1.8	-	1.8	16	93.0
37	El Salado	435	219	-	219	8	87.8
	Total	740	322.1	47.2	369.2	757	1959.2



Figure 4. The 37 hydrological regions identified by the National Water Commission. In orange: the RH36 object of this study. Graphic by the authors, based on geospatial data from the National Information System (SINA).

4.2. Hydrographic Basin

Hydrological Region 36 is a hydrographic system consisting of 5 basins and 33 sub-basins (Figure 5), according to the information from the hydrographic network developed by INEGI (geospatial information for the year 2010). The hydrological system of RH36 is composed of two rivers and their sub-basins: Nazas and Aguanaval.

Water basins preserve certain geomorphological characteristics. This attribute is particularly useful within the spectrum of rural and urban studies, to delimit elements to be analyzed that require intervention within a region. In this paper, the basin was used as a first approximation to the territory.

According to López and Patrón [45], hydrographic basins can be considered the fundamental unit for planning and managing natural resources within a territory. They also describe the basin as a critical space for assessing adaptation to climate change. From their perspective, utilizing the basin as a unit of study enables an understanding of the relationship between upper and lower basins, and thereby explicitly addresses planning issues. This approach offers a more comprehensive understanding of the ecosystem.

This research underscores the fundamental role of studying hydrological infrastructure in comprehending the distribution of water resources in hydrological region 36. Dams and canals, which have altered the region's territorial dynamics, are regarded as urban projects due to their potential to influence community settlement patterns.

This perspective integrates key water storage facilities. It initially addresses them at the regional scale to elucidate the conveyance of water flows to cities, rural communities, and agricultural areas. Moreover, examining hydrological infrastructure highlights activities with significant water consumption. This allows the establishment of strategies to promote activities that are aimed at reducing high water stress in the context of arid communities.

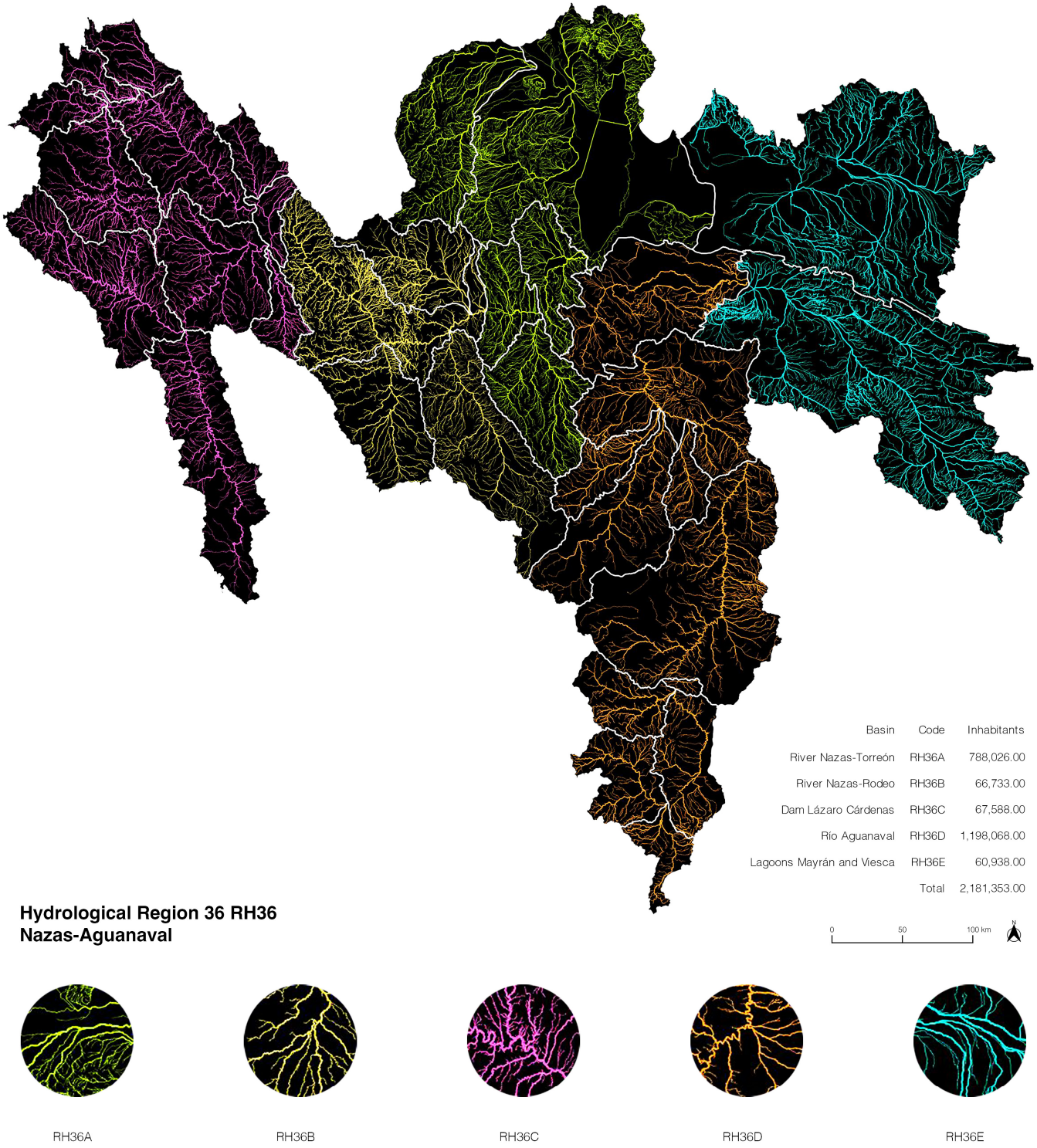


Figure 5. Basins that comprise the hydrological region 36 Nazas–Aguanaval. Graphic by the authors, based on geospatial data from INEGI. Hydrographic network scale 1:50,000, Edition 2.

Figure 6 shows the main dams located in RH36. Basin RH36C represents the high sub-basins of the Nazas River. The main dam Lazaro Cardenas is located within its limits. Basin RH36B is the medium basin of the same river. In the limit between RH36B and RH36A, a second dam is located, called Francisco Zarco. Basin RH36D contains the high and medium basins of the Aguanaval River; in this basin, five dams are located. RH36E is the low basin of the hydrographic system. This is the basin where both rivers flow in the Lagunas Mayrán and Viesca, now deserted areas.

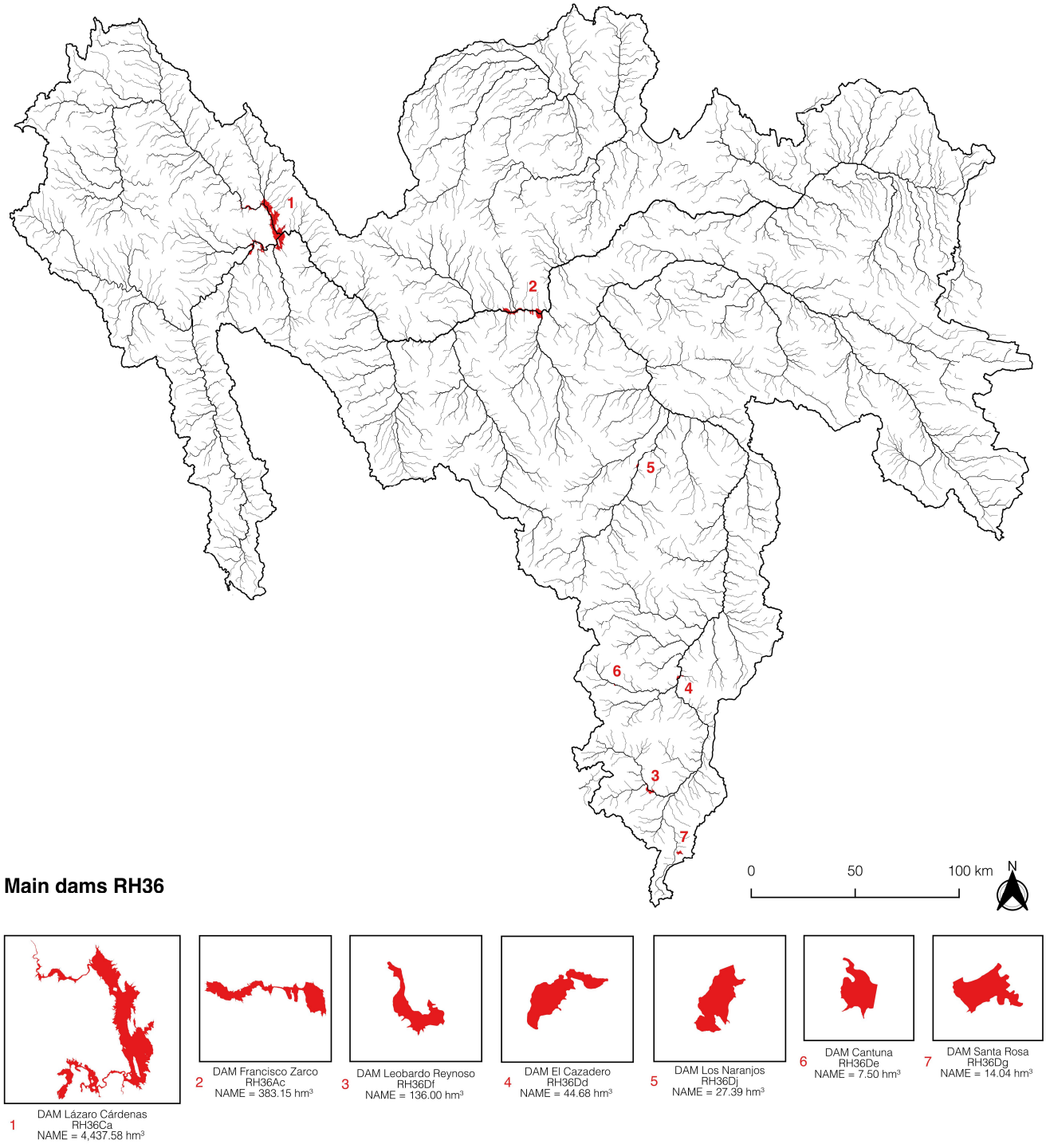


Figure 6. Main dams located in hydrological region 36 (RH36). Graphic by the authors, based on geospatial data from INEGI and CONAGUA.

4.3. Hydrographic Sub-Basin

The sub-basin is the scale after the basin. Sub-basins are also defined by their geomorphological properties. Following the hierarchy of the geographic network, the geospatial information available for RH36 is integrated using Quantum Geographic Information System (QGIS-LTR 3.28) software, from which the surfaces and limits are calculated. According to the European Parliament's definition [46], a sub-basin refers to the land where all surface runoff travels through a network of streams, rivers, and ultimately lakes, converging on a specific point in a watercourse, which is typically a lake or a confluence of rivers.

Hydrological region 36 contains 33 sub-basins according to INEGI information available in its vectorized form. To calculate the number of inhabitants of each sub-basin, a database has been generated by adding the attributes of the 2020 geostatistical framework through the Single Catalog of Keys for State, Municipal, and Local Geostatistical Areas (*Catálogo Único de Claves de Áreas Geoestadísticas Estatales*, *Municipales*, *y Localidades*) (Figure 7). The area of each sub-basin can be calculated from the properties of the geometry provided in the vectorized information from INEGI. The resulting map unifies geographical and cadastral information. This type of map is important in order to visualize the basins and sub-basins that have a higher concentration of population, and therefore a higher degree of domestic water consumption. Notably, the sub-basins RH36A, the north of RH36D, and RH36E comprise the lower basin of RH36, and they also comprise more than 90% of the population in the entire region.

4.4. Micro-Basin

At the micro-basin scale, areas of study should be determined through specific standards, since the geospatial information on micro-basins is not included in the Hydrographic Network, Edition 2 (Figure 8). The geospatial data for micro-basins can be generated from the geodata of the sub-basin to which the micro-basin belongs. To achieve this, it is necessary to focus on a specific water stream at a smaller scale. The micro-basin constitutes a reduced domain that is suitable for partial rural and urban planning actions.

According to Sanchez [47], the planning unit is the watershed, yet the fundamental unit for management and intervention is the micro-watershed. Here, production can be effectively managed and visualized in relation to water flow. To comprehensively describe land uses, it is essential to scale up to represent plots or production units, regardless of their size.

To identify a micro basin inside a defined water basin by INEGI and CONAGUA, first, the geomorphologic limits of the sub-basins contained within the specific watershed need to be added. With the addition of a digital elevation model (DEM) and the vectorized Strahler network, the boundary of the micro-basin can be generated. This process, together with the addition of agricultural surfaces and rural and urban fabrics, is helpful to perform small-scale analyses and identify general factors that contribute to water stress.

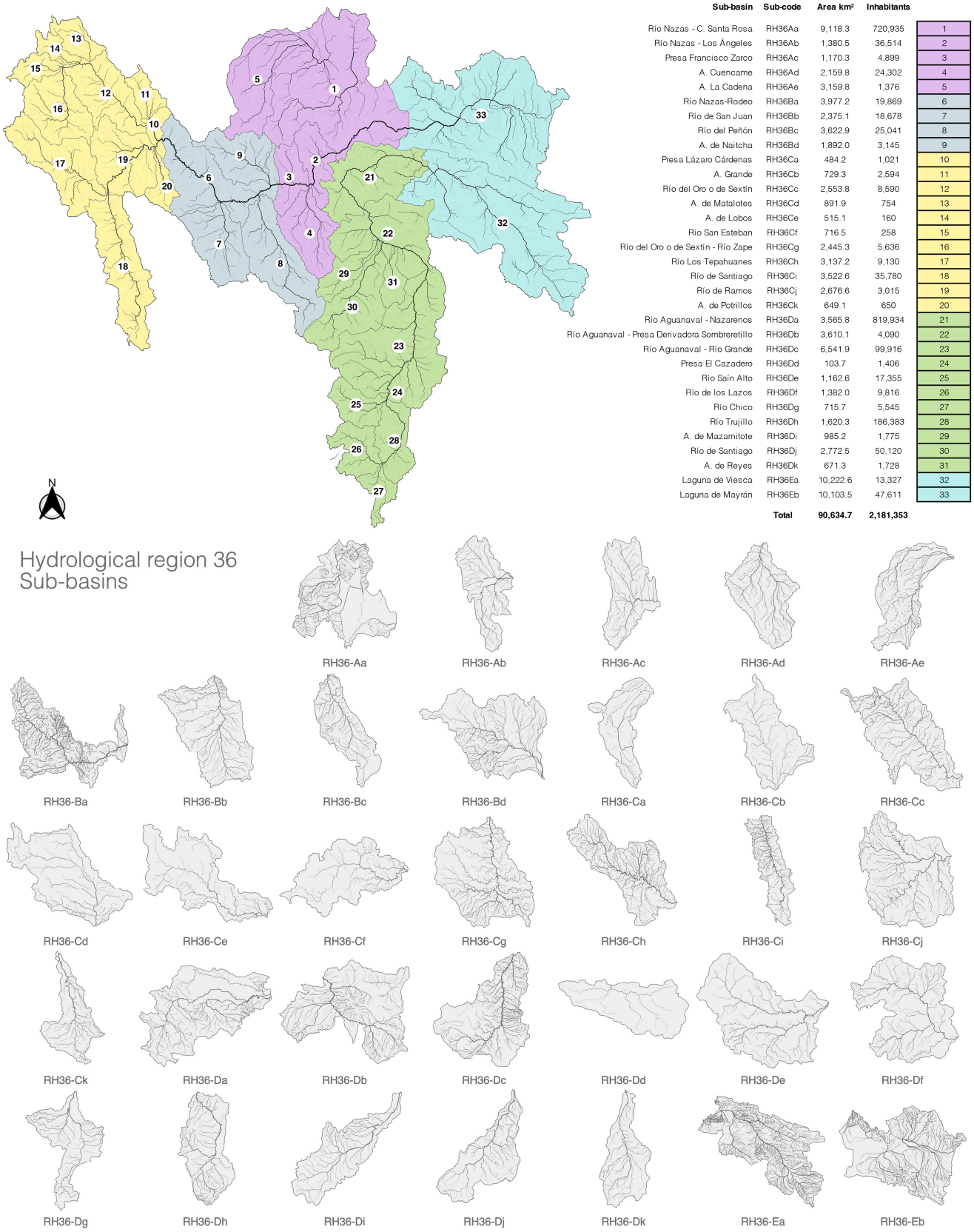
With this approach, it is possible to work on a multi-scale level from the regional scale to the rural and urban scale and vice versa. Therefore, through a methodologic process based on the water network structure, we can identify dynamics in water flow usage in the entire region by observing the interactions between production surfaces and hydrologic infrastructure, like dams and canals.

4.5. Urban Basin

According to Agredo [48], it is in the hydrographic basin where rural and urban processes of human communities originate and interact with the hydrological network. Social, economic, political, and cultural activities are supported by artificial technological systems developed at the expense of the natural system. Therefore, it is considered a fundamental approach to understanding hydrological phenomena at the scale of the city and its elements. This reveals fundamental impacts on the implementation of development strategies. The urban basin is the last boundary that is considered within the hierarchical order of hydrological regions in this paper (Figure 9).

On this scale of order (city—architecture), the dynamics of water consumption uses that are closer to the citizens can be observed. For example, construction typologies can be examined, and the amount of water needed for the individual construction materials determined. This information can be used to approximate the water footprint per m^3 of construction. Another example of analysis at this scale is the relationship between buildings and canals through façade fronts. The type of soil, waterproofing, urban basin drainage, infiltration, and recharge capacities, with their disruptions to the hydrological cycle, can also be observed. The results obtained from the analyses carried out between the very fabric of

the cities and the road structure that joins them can provide relevant information for the reordering and identification of harmful trends within the hydrological cycle of a given basin.



Sub-basin	Sub-code	Area km²	Inhabitants	
Río Nazas - C. Santa Rosa	RH36Aa	9,118.3	720,935	1
Río Nazas - Los Ángeles	RH36Ab	1,380.5	36,514	2
Presa Francisco Zarco	RH36Ac	1,170.3	4,899	3
A. Cuencame	RH36Ad	2,159.8	24,302	4
A. La Cadena	RH36Ae	3,159.8	1,376	5
Río Nazas-Rodeo	RH36Ba	3,977.2	19,869	6
Río de San Juan	RH36Bb	2,375.1	18,678	7
Río del Peñón	RH36Bc	3,622.9	25,041	8
A. de Naitcha	RH36Bd	1,892.0	3,145	9
Presa Lázaro Cárdenas	RH36Ca	484.2	1,021	10
A. Grande	RH36Cb	729.3	2,594	11
Río del Oro o de Sextín	RH36Cc	2,553.8	8,590	12
A. de Matalotes	RH36Cd	891.9	754	13
A. de Lobos	RH36Ce	515.1	160	14
Río San Esteban	RH36Cf	716.5	258	15
Río del Oro o de Sextín - Río Zape	RH36Cg	2,445.3	5,636	16
Río Los Tepahuanes	RH36Ch	3,137.2	9,130	17
Río de Santiago	RH36Ci	3,522.6	35,780	18
Río de Ramos	RH36Cj	2,676.6	3,015	19
A. de Potrillos	RH36Ck	649.1	650	20
Río Aguanaval - Nazarenos	RH36Da	3,565.8	819,934	21
Río Aguanaval - Presa Derivadora Sombreretillo	RH36Db	3,610.1	4,090	22
Río Aguanaval - Río Grande	RH36Dc	6,541.9	99,916	23
Presa El Cazadero	RH36Dd	103.7	1,406	24
Río Saín Alto	RH36De	1,162.6	17,355	25
Río de los Lazos	RH36Df	1,382.0	9,816	26
Río Chico	RH36Dg	715.7	5,545	27
Río Trujillo	RH36Dh	1,620.3	186,383	28
A. de Mazamitote	RH36Di	985.2	1,775	29
Río de Santiago	RH36Dj	2,772.5	50,120	30
A. de Reyes	RH36Dk	671.3	1,728	31
Laguna de Viesca	RH36Ea	10,222.6	13,327	32
Laguna de Mayrán	RH36Eb	10,103.5	47,611	33
	Total	90,634.7	2,181,353	

Figure 7. Sub-basins of hydrological region 36, Nazas–Aguanaval. Graphic by the authors.

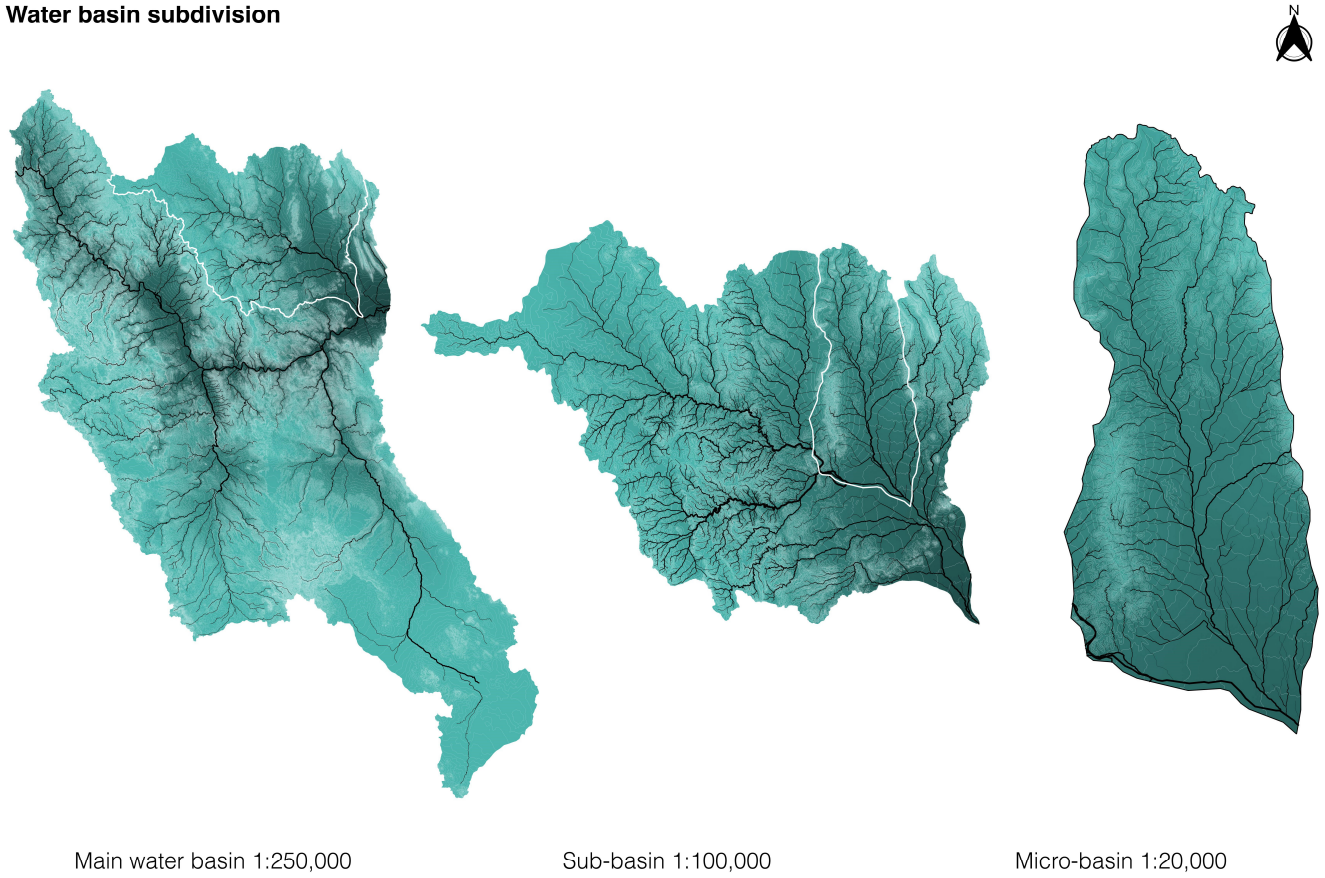


Figure 8. Hierarchical structure of the hydrographic basin. Water basin B (Nazas river, Rodeo), Sub-basin Bd (Naitcha stream). Graphic by the authors, based on geospatial data from INEGI.

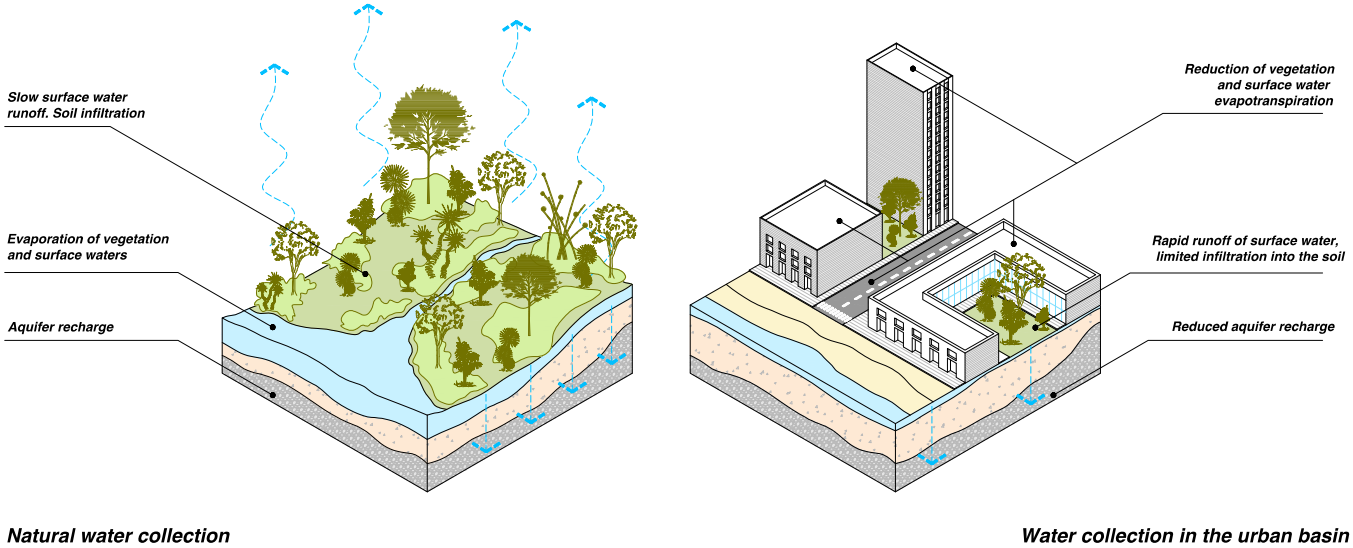


Figure 9. Schematic model of an urban basin to exemplify the disruption of the hydrographic network. Graphic by the authors.

In the urban basin, the degree of disruption to the natural system is higher than on the territorial scale. However, unlike large areas at the territorial scale, the urban scale offers greater control over drainage systems and support for water flows. Consequently, in territories under water stress, attention to solutions that promote recharge and re-naturalization of environmental catchment surfaces is relevant, especially if large urban

populations are concentrated within these surfaces. This is the case of the lower basin located in hydrological region 36 where the populations of Torreón, Gomez Palacio, Lerdo, and Matamoros are situated. These communities together form the metropolitan area of La Laguna (ZML) which has around 90% of the population concentrated in the lower sub-basin of the Nazas and Aguanaval rivers.

5. Regional Scale

As Eizaguirre [18] explained, geomorphology teaches us that certain geographical, biotic, geological, and anthropic factors trigger a series of constructive and destructive processes, which are in constant dynamics. Therefore, the terrestrial surface that we observe is not a fixed reality, it is in permanent mutation. This reality guides us towards reading the components of the territory in isolation and in their hierarchical order over time.

Geographical representations are used in this research to understand the hierarchical structure of the hydrological region. An example of this is the specific large-scale regional maps drawn and based on available satellite information. Generally, to work in these dimensions, satellite data can be directly integrated into QGIS through plugins such as quickmapservices (this tool adds the ability to insert images from services like Landsat). However, when satellite captures are available with a higher degree of precision for certain areas, it is advisable to work with this information. For example, in Catalonia, the Cartographic and Geological Institute of Catalonia (ICGC) has a catalog of orthophotos, aerial images, and monthly captures from the sentinel-2 satellite. In the case of hydrological region 36, satellite information from Google Earth and the quickmapservices tool are used. The information is integrated into the Lambert Conformal Conic projection (LCC) Datum: ITRF2008, Ellipsoid: GRS80 because the geospatial data provided by INEGI is generated in this projection (Figure 10). The result is information that is standardized to the cartographic language of the Mexican Institute of Statistics.

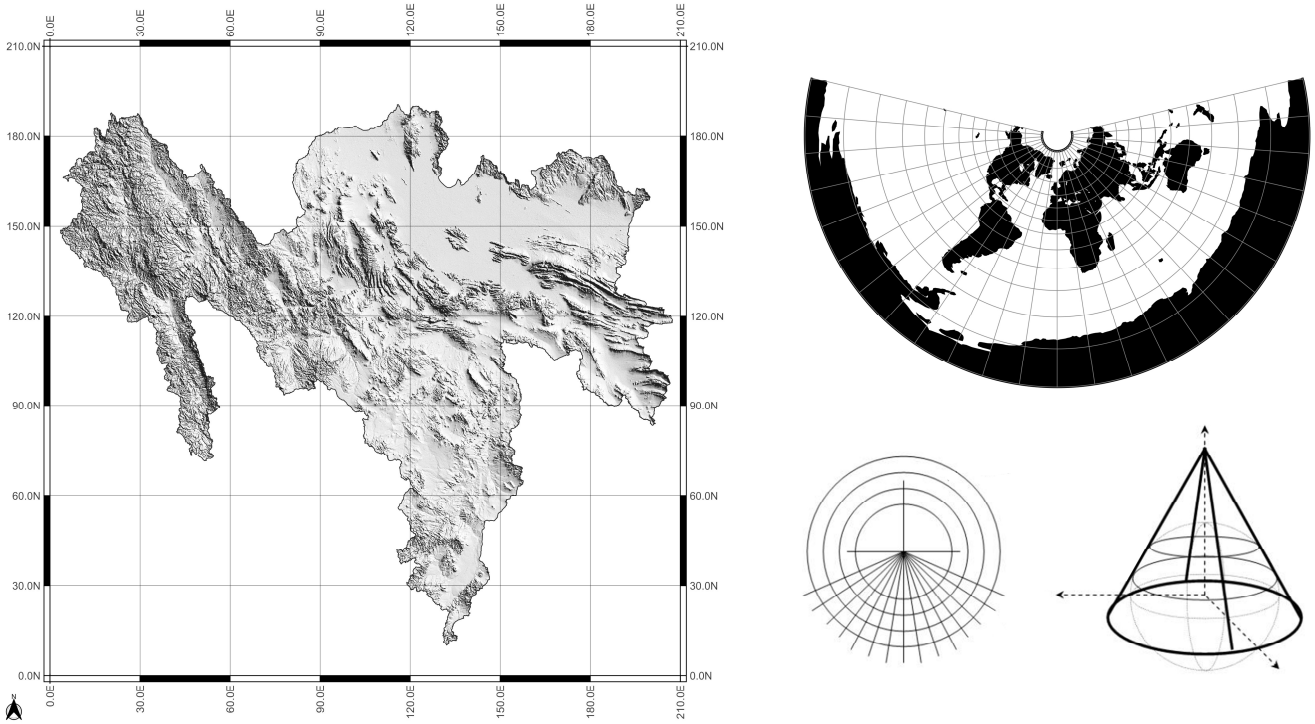


Figure 10. Digital elevation model (DEM) image of hydrological region 36 in the Lambert Conformal Conical projection. Graphic by the authors, based on geospatial data from INEGI and edited from the aforementioned sources.

This is the first approach to the hydrological region under study. In this scale, large flat areas and elevations can be appreciated, and some locations of the hydrological infrastructure and the main geological characteristics can also be identified. In the figure, from left to right: the higher sub-basins; and in the top right corner: the lower sub-basins.

6. Geographic and Geomorphologic Scale

6.1. The Strahler Diagram and the Urban Morphology of the Basin

The benefit of combining hydrographic, urban, and agricultural information within the same cartography is that it allows us to visualize the anthropized percentage of a specific hydrographic basin and the degrees of soil permeability according to the type of cover. These indicators influence the fluvial recharge dynamics of the groundwater levels and, consequently, the continuity of the hydrological cycle. Additionally, through them, settlement patterns and the degree of pressure on both surface and underground water resources can be identified. Figures 11 and 12 are maps of the sub-basin RH36De. This type of approach should be implemented in the 33 sub-basins in hydrological region 36.

To understand the complexity and hierarchy of hydric ramifications in a defined river basin, the numerical form of Strahler was used [49]. Information on hydrographic networks regarding Strahler values can be obtained from specialized sources such as the National Water Commission in Mexico (CONAGUA). However, if these data are not available for a certain region, they can be calculated through DEM images and QGIS software. In the case of Mexico, general information can be accessed on a geographic scale. Nevertheless, the hydrographic network provided by INEGI is not suitable for urban studies.

Once the hydrographic network has been incorporated within a defined cartographic projection, the available geospatial data need to be added from the rural and urban settlements under analysis. To achieve this, access vector information is required from the urban and rural blocks, which in this case comes from the INEGI geostatistical framework [42]. These two layers of information are fundamental to understanding settlement locations throughout the entire basin and sub-basins. Along with this information, site levels can be added for a better understanding of the geomorphological characteristics of a basin and sub-basin.

Regarding the production surfaces, the vector layers provided by the National Agrarian Registry (RAN) of Mexico are added to the water structure network. The integrated information belongs to the categories of areas divided into plots, RHA [1] irrigation units, and irrigation districts. This is the plot information that is available at this geographic scale for the Mexican territory. It is important to focus on production surfaces since they are the spaces with the greatest consumption of water resources in the basin [1]. With the addition of this layer of information, the main anthropized surfaces in the basin under study can be identified. In general, it is evident that major settlements are located along the main water streams of the hydrographic system. At this scale, a pattern of location among the majority of settlements and their surfaces is recognizable. This information allows us to understand rural and urban locations as part of a whole system that is dependent on the water cycle.

Figure 11 shows the cartographic model achieved by integrating geospatial information for the Saín Alto River sub-basin, which belongs to the Aguanaval River basin in the state of Zacatecas, Mexico. In this map, the main urban and rural communities defined by INEGI are incorporated. In addition, major water bodies and dams belonging to the hydrologic infrastructure of the RH36 are visible. In Figure 11, the sub-system of settlements and their geographic limits can be evaluated to organize planning strategies at the regional scale. This type of approach is linked to a general understanding of the hydrological region and the goals of fluvial restoration and water stress reduction. The information constructed at this stage is the first step for smaller scales of analysis.

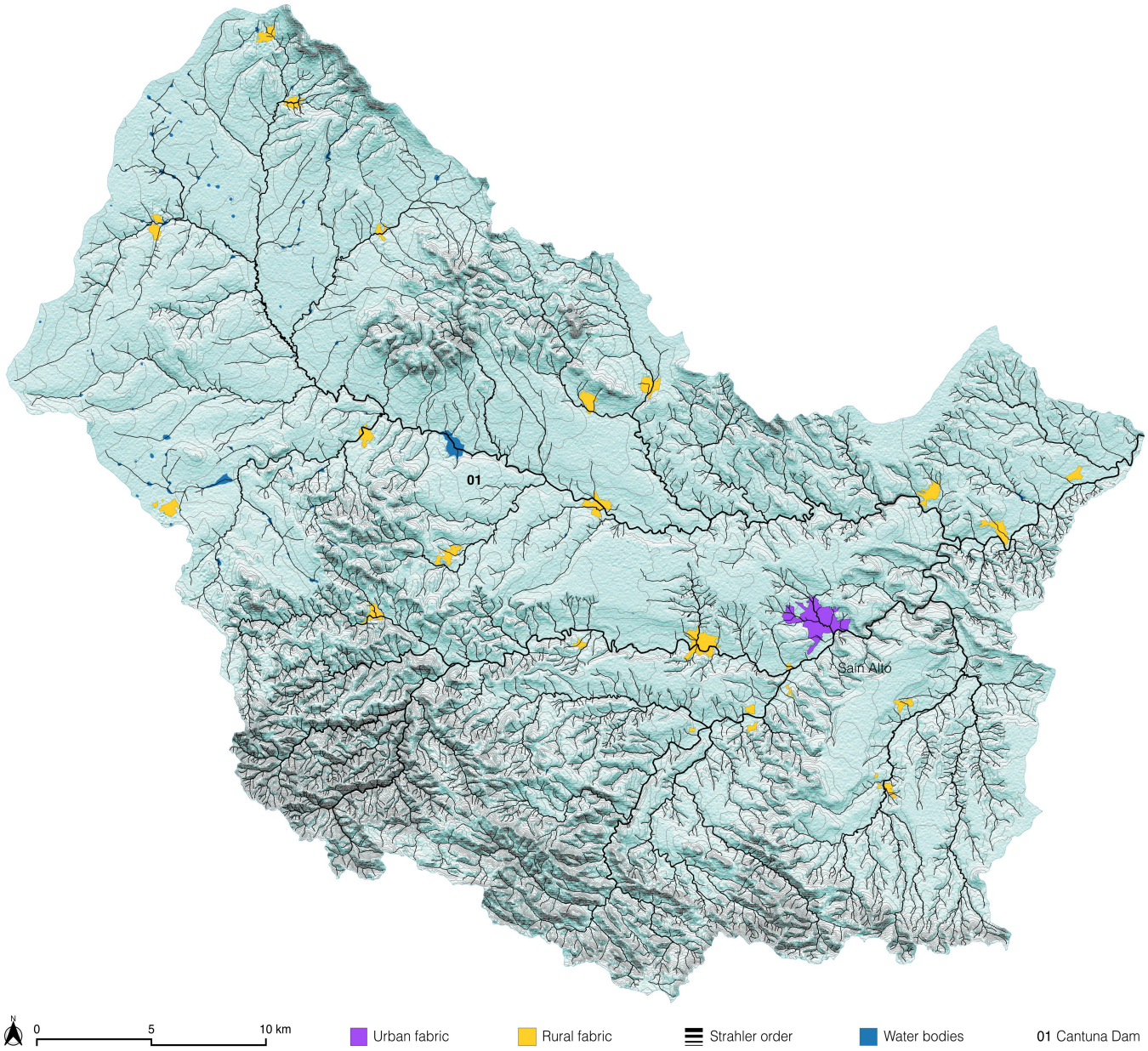


Figure 11. Strahler number interpretation in the RH36De sub-basin, which belongs to basin D: Aguanaval River. Graphic by the authors, based on geospatial data from the INEGI geostatistical framework.

The River Saín Alto sub-basin belongs to the Aguanaval River basin. It has an area of 1662.64 km^2. In this area, 23 settlements are located, of which, 22 are rural and 1 urban, called Saín Alto. In this sub-basin, there is low agricultural capacity, which corresponds to 23.53% of the total area. A total of 76.47% can be considered less anthropized or with a higher permeability index. The RH36De sub-basin has approximately 17,355 inhabitants. The urban population of Saín Alto in this sub-basin has 21,844 inhabitants in an area of 1,418,291 km^2 (Figure 12). In the cartographies produced in this article for the RH36De, the geomorphologic characteristics of the hydrographic basin and the communities' rural and urban isolates can be observed. It is visible in RH36De how the communities are at the limits of the main streams of the hydrographic network.

Through the integration of agricultural surfaces in a map of a specific sub-basin, it is possible to visualize how recharged surfaces are covered with agricultural land to supply

rural and urban needs. Water resources then become a necessity to feed cattle to produce beef and milk using thousands of liters of fresh water.

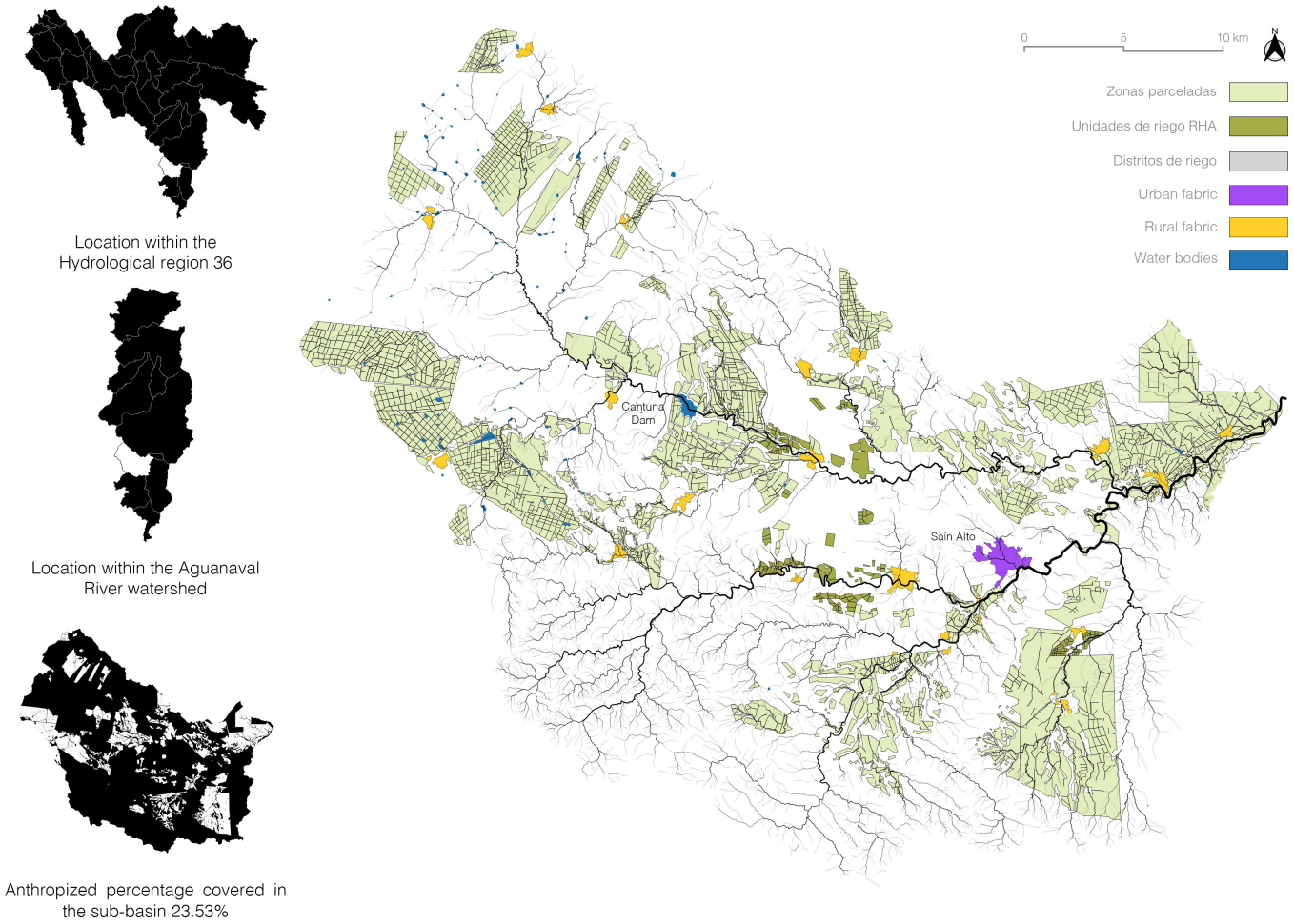


Figure 12. Sub-basin RH36De. Anthropized percentage and categories of agro-production surfaces. Graphic by the authors: Incorporation of geospatial information from the INEGI, SINA, and RAN.

According to CONAGUA [1], Mexico ranks seventh in the world ranking of countries with the highest water extraction and percentage of agricultural, industrial, and public supply use, with a total of 87.84 billion m^3/year. Of this total, 76% is destined for agricultural use, 9.6% for industrial use, and the remaining 14.4% for public supply. Mexico is also ranked seventh worldwide in area with irrigation infrastructure, with 25,670 hectares of cultivated area, of which, 6460 represent the area with irrigation infrastructure under control, which is 25.16% of the total. Additionally, the United Nations World Water Development Report [50] suggests that by 2050 agriculture will need to produce 60% more food globally, and 100% more in developing countries.

At this scale of work, a three-dimensional view of the sub-basin offers a useful perspective to visualize the set of urban and rural communities, and their crops and locations with respect to the main water bodies (Figure 12). Three-dimensional axonometry is considered more useful than a two-dimensional section, mainly because it better shows the topography and continuity of the streams and their links with population centers.

This 3D volumetric model is generated from the interpretation of elevation levels in the z dimension from either topographic vector information or the extraction of contour lines from a DEM raster image (Figure 13). In addition, the water network organized on the Strahler order is emulated in this three-dimensional simulation. With this setup, the territory of the sub-basin can be understood as an entire system with a hydrographic

network. The Oro River is the main water stream in this sub-basin. Urban and rural communities are structured along this water axis, where lower elevations are best suited for agricultural activities. The consumption of water resources for domestic and production activities in the lower lands of the sub-basin adds water stress to the system and delays the natural recharge of the region's aquifers due to the impermeabilization of the soil, mainly with agricultural surfaces.

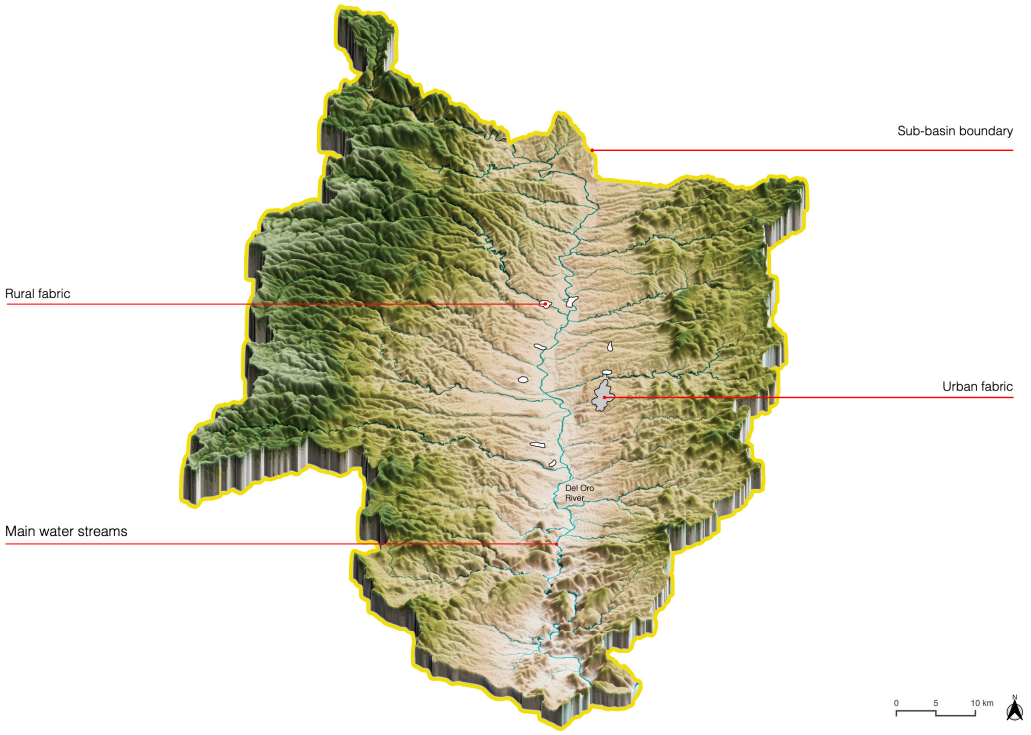


Figure 13. Sub-basin RH36Cc, sub-basin River del Oro or River Sextin in 3D. Graphic by the authors, generated from the DEM file and Photoshop complement 3D map generator.

In this type of map, the hydrographic basin and its spatial organization can be observed on a geographical scale, as well as the available open spaces. Together with the cartography generated at a regional scale, the dynamics between sub-basins can be analyzed, as well as the surface flows of water resources through the hydrological infrastructure. This type of graphic is useful for identifying the settlement patterns in each sub-basin of hydrological region 36. It is also useful to analyze all the rural and urban communities as a whole system that is dependent on the major stream of water. At this scale, sub-basin planning is possible, if partial planning is a part of a regional planning strategy.

6.2. Road Infrastructure and the Water Stream Network

In a water basin under a high degree of pressure, interactions with the road infrastructure need to be observed. The communication nodes between settlements, together with the vectors, represent an articulated system superimposed on the hydrographic network. The intentional cartographic representation of these two elements makes it possible to visualize conflict zones. For this cartography, in addition to integrating the hydrographic network, the road network provided by the vector information of the geostatistical framework developed by INEGI is added (Figure 14).

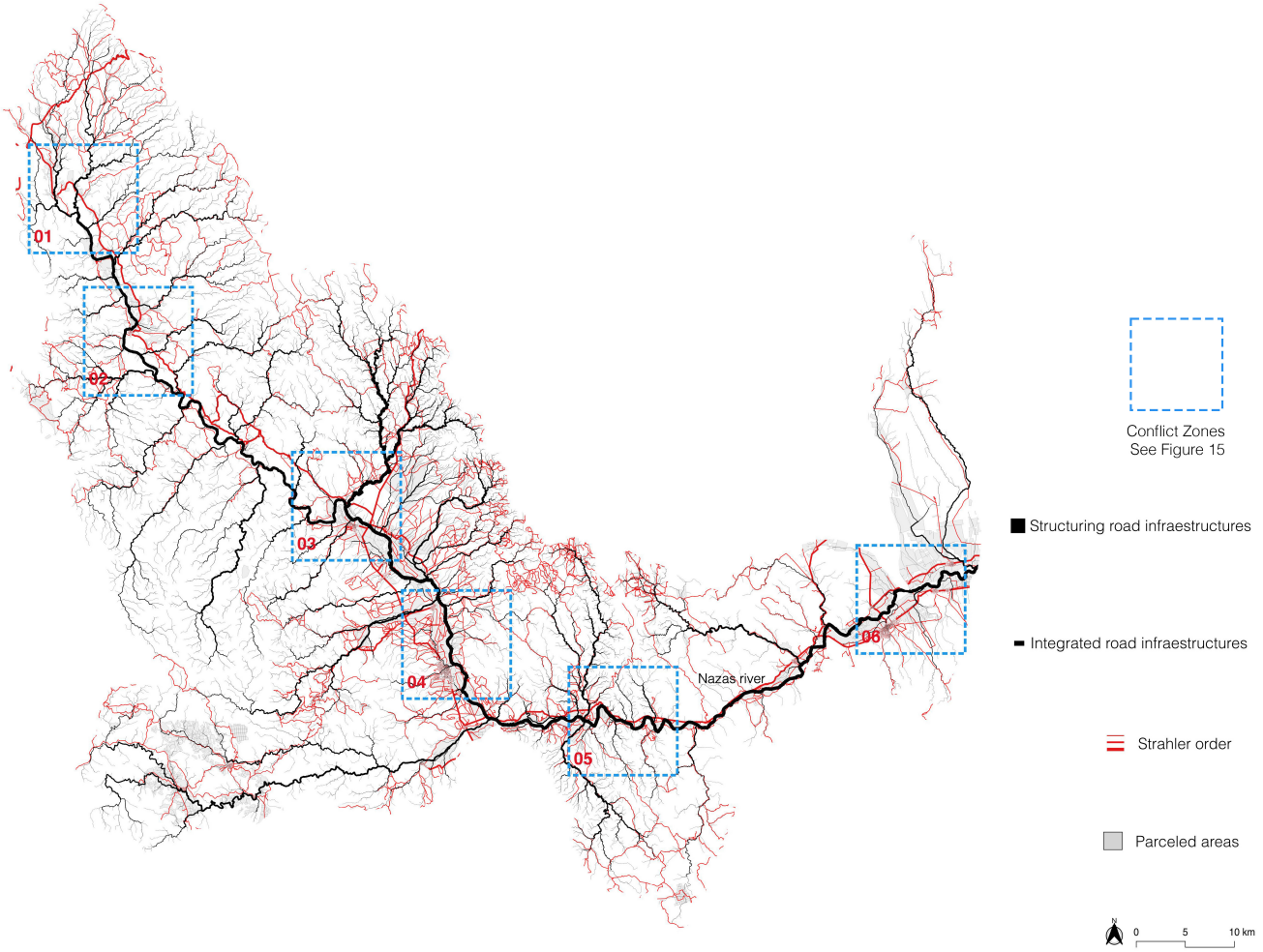


Figure 14. Sub-basin RH36Ba River Nazas-Rodeo. Interaction between the water network and road infrastructures. Conflict zones. Graphic by the authors, based on geospatial data of INEGI.

Conflict zones can be recognized as areas where the interaction of specific variables can generate stress on water resources. Among the elements that interact are structuring road infrastructures, integrated road infrastructures, rural fabric, urban fabric, dams, and canals (Figure 15).

The way in which the road network articulates the rural and urban communities, and their production surfaces is linked to the geomorphological conditions of the territory. Consequently, it is related to the water network and the basin's fluvial recharge system. When both systems come into conflict, higher stress is added to the hydrologic system, which disrupts natural water streams with road intersections and pollution on riversides with the addition of incompatible programs on the main recharge surfaces. These types of situations can affect the hydrological cycle. The structuring pathways can organize the growth of the communities, but this condition conflicts with the water basin's capacity to support water consumption. This type of cartography is useful to identify areas of improvement in the road infrastructure on the lower lands. In general, roads and main water streams share the lower elevations in a topographic section. In hydrologic region 36, this phenomenon indicates that water streams in the region are highly anthropized on their flows and recharge surfaces, due to the concentration of rural, urban, and agro-production elements that interact with the main zones where water catchment flows naturally.

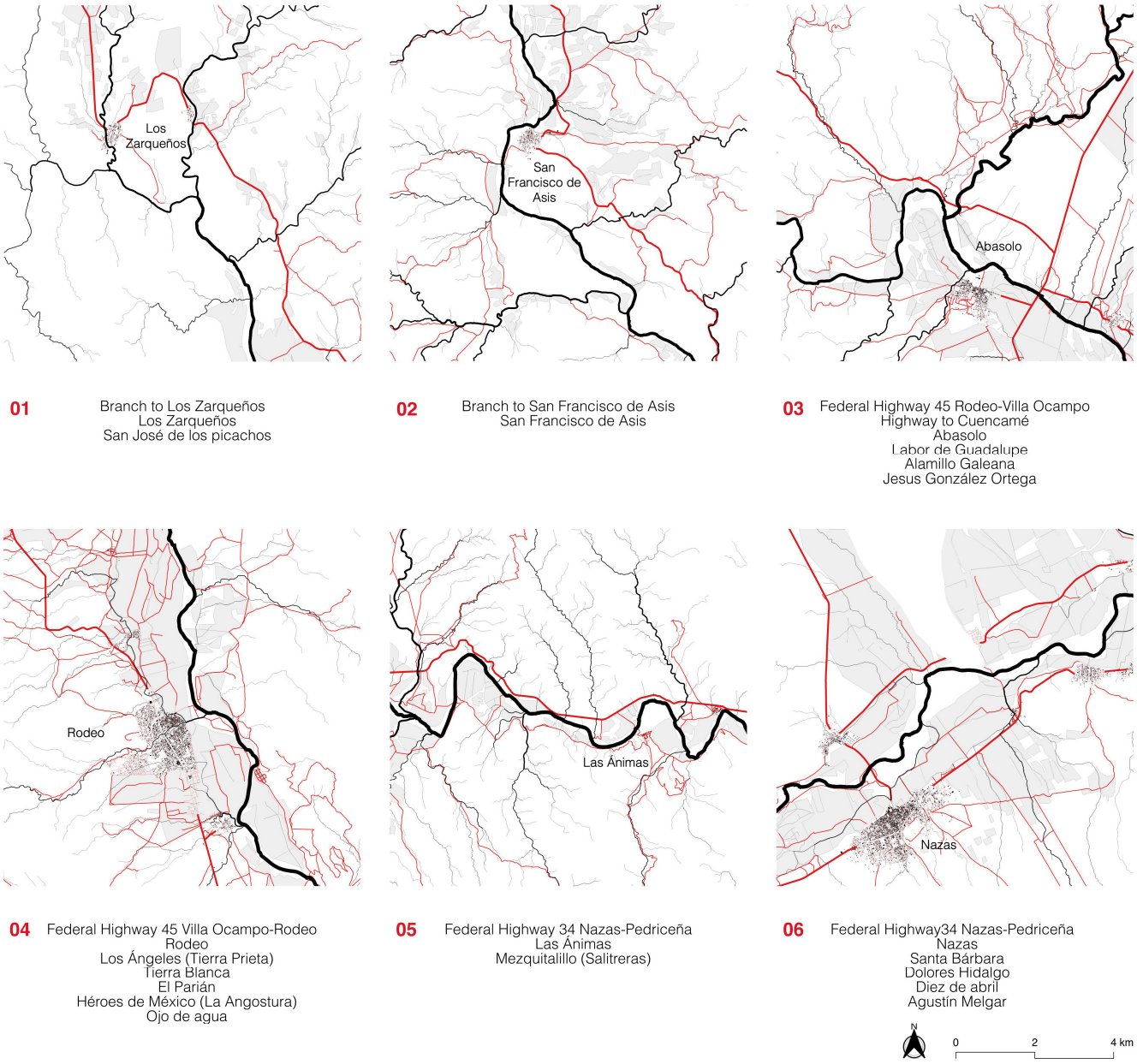


Figure 15. Main areas of conflict between the road infrastructure network and the water network in the sub-basin RH36Ba. Graphic by the authors, based on geospatial data of INEGI.

7. Territorial Scale

7.1. System of Cities and the Quality of Their Crops

To generate a map in which the size and shape of the crops of a certain community or set of communities can be represented, precise cadastral information is required. There are some cases where these data are not available and must be generated using GIS software. One of the techniques that can be used is based on algorithms under the concept of a normalized difference vegetation index (NDVI) [51]. This is one of the most widely used indexes, whose function is to provide information on plant productivity (calculated for each pixel). This is achieved through a ratio between the red and near-infrared bands of the image, due to the contrasting reflectance of both. The range of values that each pixel can take oscillates between −1 and 1, depending on the vigor of the vegetation contained in each one [8].

The NDVI is a tool used to determine the type of land cover, according to the following formula:

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{Red})/(\mathrm{NIR} + \mathrm{Red})$$

There are other methods for calculating land cover type and software for generating the results. For this case, QGIS was selected, with its System for Automated Geoscientific Analyses (SAGA) tools and the information from Landsat7 [52], due to the accessibility of the information.

The information needed to calculate the NDVI are the red and infrared bands generated by remote sensing and available through the information obtained by Landsat7. These bands can be downloaded from the United States Geological Survey (USGS) viewer (earthexplorer, USGS). The images obtained are processed within QGIS through the SAGA tool that includes the vegetation index algorithm (slope-based). Alonso [53] has developed a fully detailed method for the use of NDVI tools within QGIS.

The above method is useful when information on vegetation cover is not available. In the case study in Mexico, both INEGI and RAN provide information on land classification at geographic scales. To work at a territorial scale, accurate cadastral information must be obtained for the locations under study. When this information is not available, it can be generated through the supervised vectorization of satellite images.

Within QGIS, the satellite information obtained from sources such as Google, NASA, and USGS is integrated through the quickmapservices plugin. Once the satellite information is embedded within the workspace, building layers can be generated through the supervised vectorization of specific polygons. Although this process requires more work time, it becomes more accurate for smaller scales (1:10,000) and therefore is also useful for cadastral generation. For the construction of the building footprint information, a supervised vectorization method is used in QGIS software (Figure 16). The layers of the buildings are generated from the projection of the satellite image in the background.

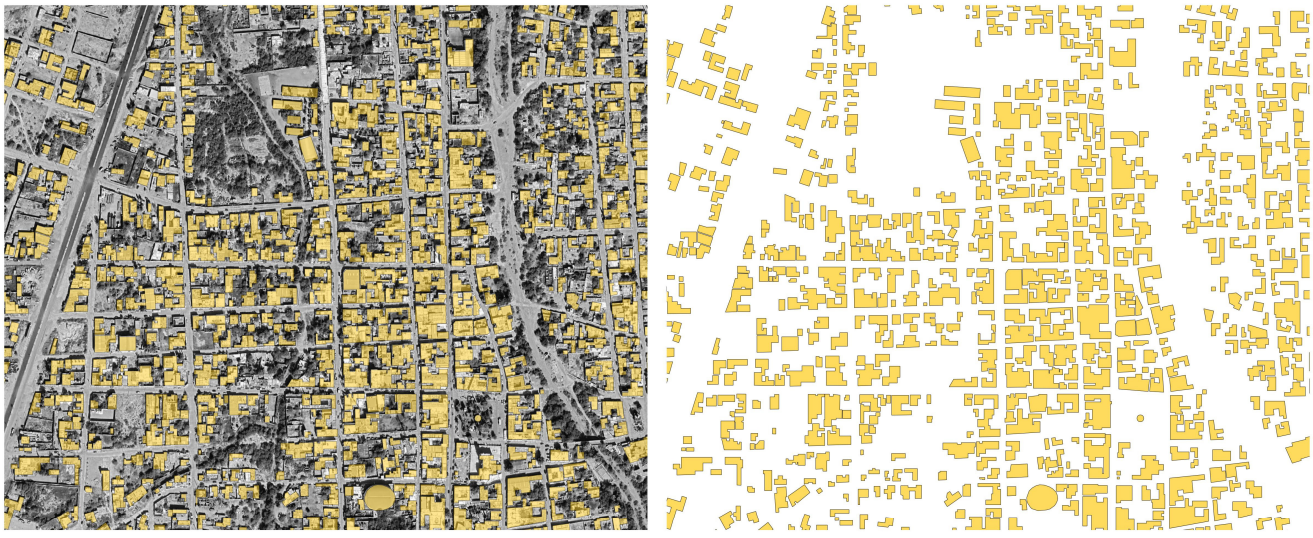


Figure 16. Building footprint vectorization process within QGIS. Graphic by the authors.

Once building footprint information is produced via vectorization over recent satellite imagery, this layer of information can be added to the hydrological structure of a subbasin (Figure 17). The construction of building footprint information is fundamental to performing morphological analyses and interventions in rural areas (Figure 18).

Code	Location	Type	Inhabitants	Area km²
RH36Bb/1	Adolfo López Mateos (Aguinaldo)	R	620	0.43
RH36Bb/2	Atotonilco	R	179	0.19
RH36Bb/3	Buenavista (Porcion II)	R	nd	0.10
RH36Bb/4	Charco Hondo	R	105	0.08
RH36Bb/5	Ciénega Grande	R	678	0.48
RH36Bb/6	Colonia Benito Juárez	R	110	0.06
RH36Bb/7	Coneto de Comonfort	U	857	0.73
RH36Bb/8	Diez de Octubre (San Lucas de Ocampo)	R	1,445	1.48
RH36Bb/9	Doroteo Arango (Ciénega de Basoco)	R	70	0.06
RH36Bb/10	El Aguaje	R	129	0.07
RH36Bb/11	El Chabacano	R	204	0.15
RH36Bb/12	El Resbalón	R	291	0.15
RH36Bb/13	El Saucito	R	42	0.06
RH36Bb/14	El Terrero	R	240	0.32
RH36Bb/15	Estancia Blanca	R	222	0.14
RH36Bb/16	Francisco de Ibarra (El Ranchito)	R	267	0.26
RH36Bb/17	Francisco Javier Mina (Corralejo)	R	970	0.00
RH36Bb/18	Francisco Primo Verdad (Menores de Abajo)	R	688	0.41
RH36Bb/19	Francisco Zarco (Tatantón)	R	208	0.09
RH36Bb/20	González Ortega (Santa Rosalía)	R	294	0.18
RH36Bb/21	Hermenegildo Galeana	R	228	0.35
RH36Bb/22	Ignacio López Rayón (Potrero de los Higos)	R	195	0.23
RH36Bb/23	José María Patoni (Menores de Arriba)	R	517	0.38
RH36Bb/24	La Cuesta de Palmitos	R	103	0.04
RH36Bb/25	Las Morenas (La Rosa)	R	88	0.08
RH36Bb/26	Leandro Valle	R	408	0.29
RH36Bb/27	Leona Vicario	R	476	0.25
RH36Bb/28	Linares del Río	R	351	0.26
RH36Bb/29	Llano del Pino	R	154	0.08
RH36Bb/30	Los Lobos	R	145	0.16
RH36Bb/31	Nogales	R	1,063	0.59
RH36Bb/32	Otilio Montaño (La Boquilla)	R	208	0.13
RH36Bb/33	Pánuco de Coronado	R	1,442	0.23
RH36Bb/34	Pípila (Chiganayo)	R	179	0.98
RH36Bb/35	Pueblo Nuevo Francisco de Ibarra (El Crucero)	R	282	0.53
RH36Bb/36	Río Grande	R	186	0.05
RH36Bb/37	San Agustín de Ocampo	R	229	0.14
RH36Bb/38	San Francisco Javier de Lajas (Lajas)	R	530	0.58
RH36Bb/39	San Juan del Río del Centauro del Norte	U	3,161	4.27
RH36Bb/40	Santa Isabel del Resbalón	R	121	0.08
RH36Bb/41	Sauz de Abajo	R	369	0.19
RH36Bb/42	Sauz de Arriba	R	148	0.14
RH36Bb/43	Tesvino	R	106	0.09
RH36Bb/44	Toledo	R	230	0.12
RH36Bb/45	Valle Nacional (El Banco)	R	140	0.06
			17,879	15.73

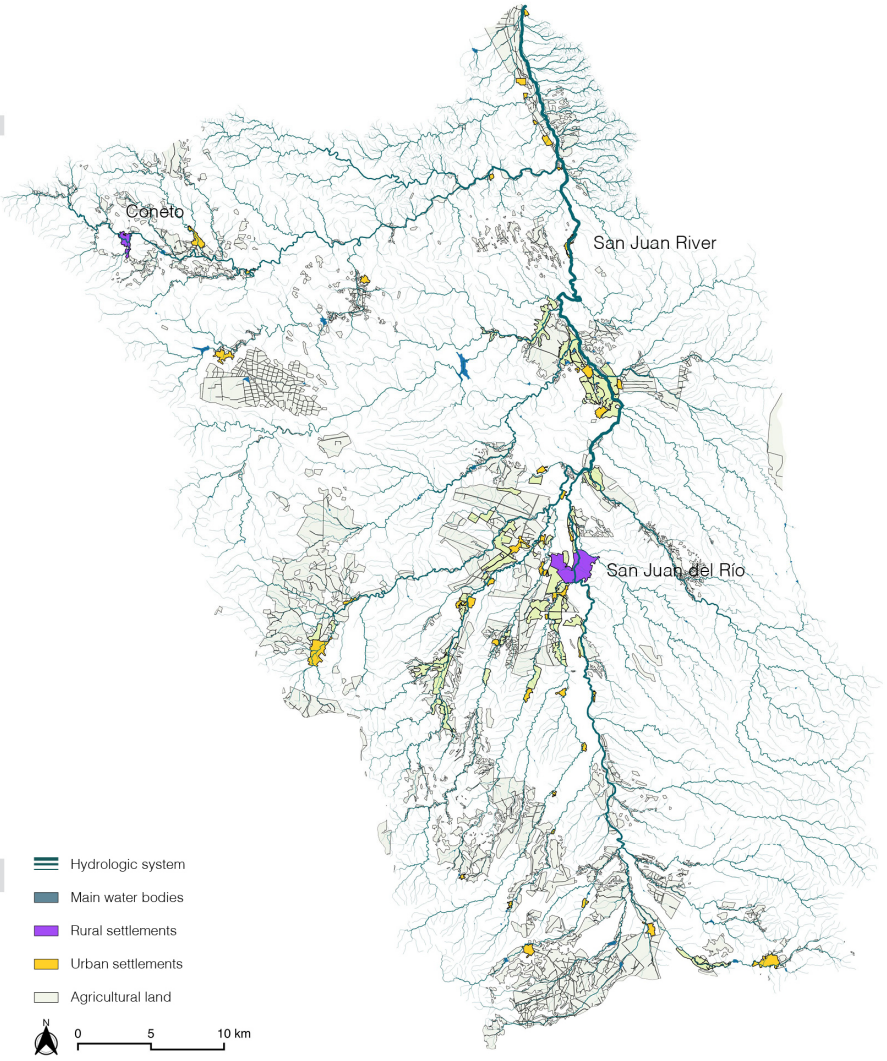


Figure 17. Sub-basin RH36Bb San Juan River. Settlement system and hydrographic network. Graphic by the authors: Supervised vectorization in GIS from satellite images.

By adding the vector data on agricultural crops, building footprints, and the hydrographic network, the settlement dynamics close to streams and recharge surfaces can be visualized (Figure 19). Additionally, if other attributes are added, for example, vector information such as type of crop or type of irrigation, a more precise image of the use of water resources in a system of communities can be obtained. This type of cartography integrates the morphology of urban and rural communities with morphologic features and types of crops, which results in surfaces of anthropized land cover. Based on these coverages, permeability indexes can be recognized in the main aquifer recharge zones and the uses of the riparian landscape in the case of rural and urban systems close to the river.



Figure 18. Sub-basin RH36Bb San Juan River. Graphic by the authors.

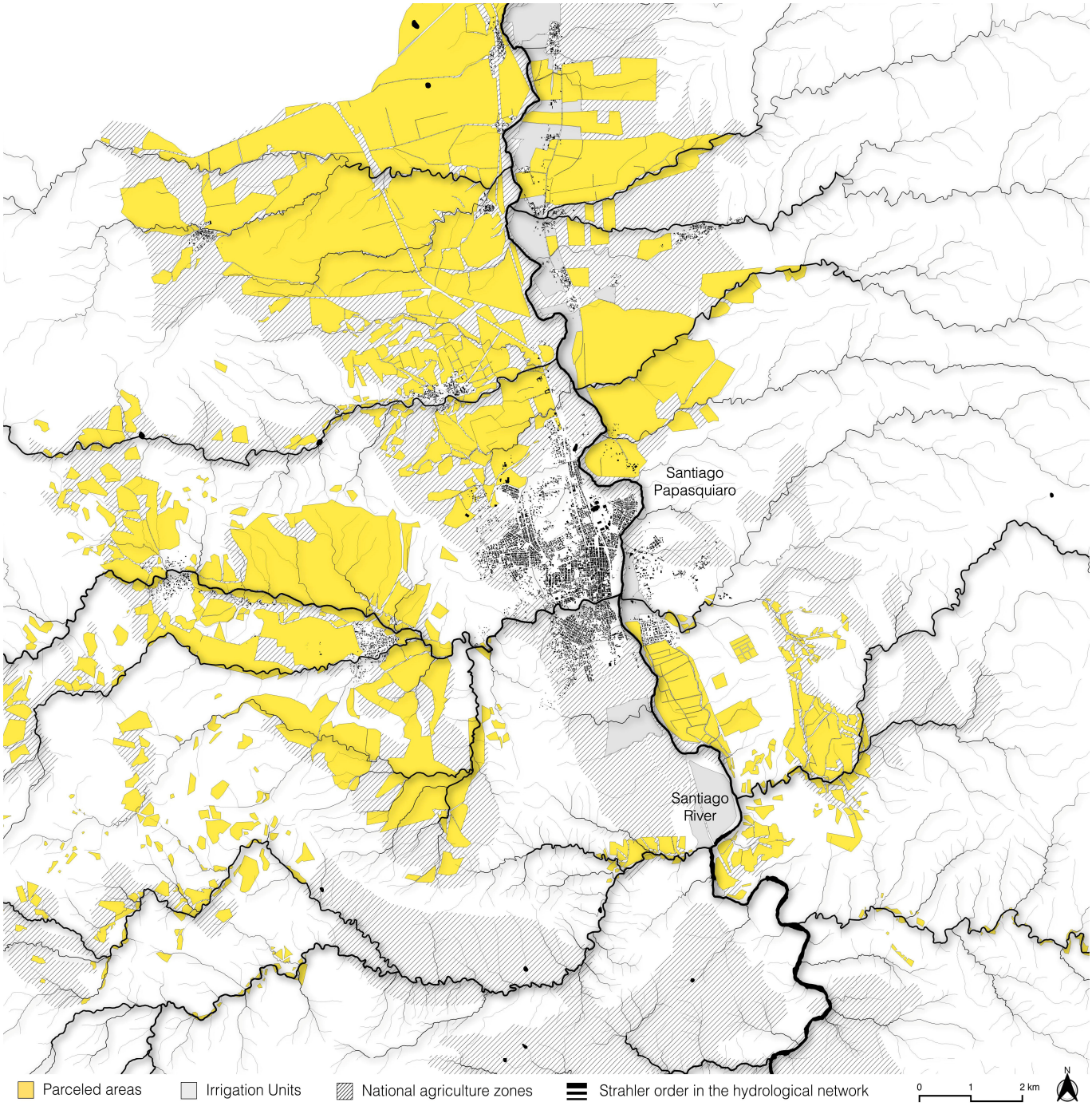


Figure 19. Sub-basin RH36Ci River de Santiago. Major communities and agro-production surfaces. Graphic by the authors.

7.2. Water Footprint Applied to Building Footprints

To integrate the water footprint into buildings, cadastral information is required at the building level or can be generated through supervised vectorization on satellite information. Knowing the annual average of the water footprint [54] per person, cartographies can be drawn that show, within a specific community, the annual dynamics in the use of water resources by inhabitants within the building layer. To achieve this, it is necessary to know, in addition to the annual water footprint per person, the number of people who live in a certain building or group of buildings in a block. In the Mexican case, these data can be incorporated from the census information generated through the National Housing

Inventory (INV). According to Hoekstra [38,54], the water footprint of a product is the volume of freshwater used to produce the product, measured throughout the entire supply chain. The water footprint can be understood as a multidimensional indicator that shows the volumes of water consumption by source and the volumes contaminated by type of contamination. All components of a total geographical and temporal water footprint are specified. In this regard, the work of Arjen Hoekstra is fundamental to understanding water use in the supply chain, and it can be applied to rural and urban planning that aims to reduce water stress on basins. Another possibility in the generation of cartography that incorporates data on the consumption of water resources is the application of the water footprint to the building footprints of a certain population. For this kind of approach, a person's water footprint can be added. Hoekstra and Chapagain [55] defined this as the volume of freshwater used to produce the goods and services consumed by this person, company, or country.

For the specific Mexican context, Arreguín [56] has developed (according to Hoekstra's water footprint approach) an approach to calculate water footprint per capita. The author argues that since not all the goods consumed in a country are produced there, the water footprint is calculated considering the use of domestic water resources and those from abroad. The water footprint includes surface water, groundwater, and soil moisture. For Arreguín, in the Mexican context, the water footprint is calculated as domestic consumption of water resources, minus virtual water exports, plus virtual water imports. Domestic consumption in Mexico is estimated at 76,100 hm^3 per year. To calculate the water footprint per capita, the next formula is used by Arreguín (2007) following Mekonnen and Hoekstra's guidelines. This is a useful adaptation to the Mexican context. With the results obtained, this indicator can be added to the building footprints generated in the previous images.

$$\begin{gathered} HH = Cd - Exp + Imp \\ Cd = \text{domestic consumption in } hm^3/\text{year} \\ Exp = \text{export of virtual water in } hm^3/\text{year} \\ Imp = \text{import of virtual water in } hm^3/\text{year} \end{gathered}$$

Water footprint per capita

$$\begin{gathered} HHpc = HH/inhab \\ HHpc = \text{water footprint per capita} \\ inhab = \text{population of Mexico in millions of inhabitants} \end{gathered}$$

For Mekonnen and Hoekstra [38], the global average water footprint, associated with consumption and estimated for the period 1996–2005, is 1385 m^3 per person per year. For Mexico, it is 1978 m^3. The process of integrating water footprint into building footprints can be carried out either by adding the information directly to the vector database of the buildings or by means of the specific coordinates of each polygon through the join attributes by location algorithm within QGIS. The join attributes by location algorithm complements a certain database that contains the attributes of certain vector information.

That is, knowing the precise coordinates within the same cartographic projection can complement a type of information with data obtained from another source (Figures 20 and 21).

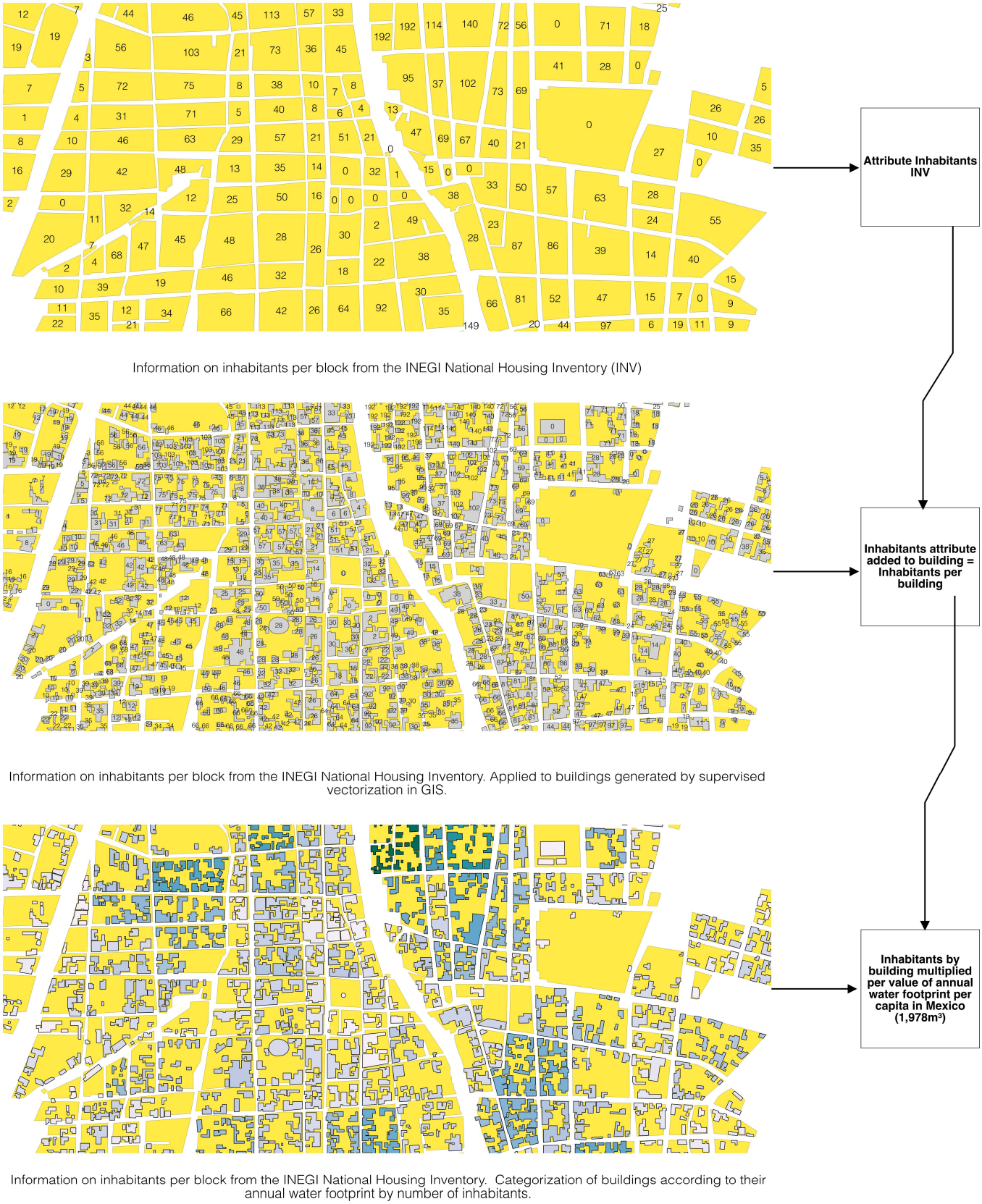


Figure 20. Process in QGIS for the integration of the water footprint in the building layer. RH36Ad.4 Cuencamé of Ceniceros inhabitants. Graphic by the authors.

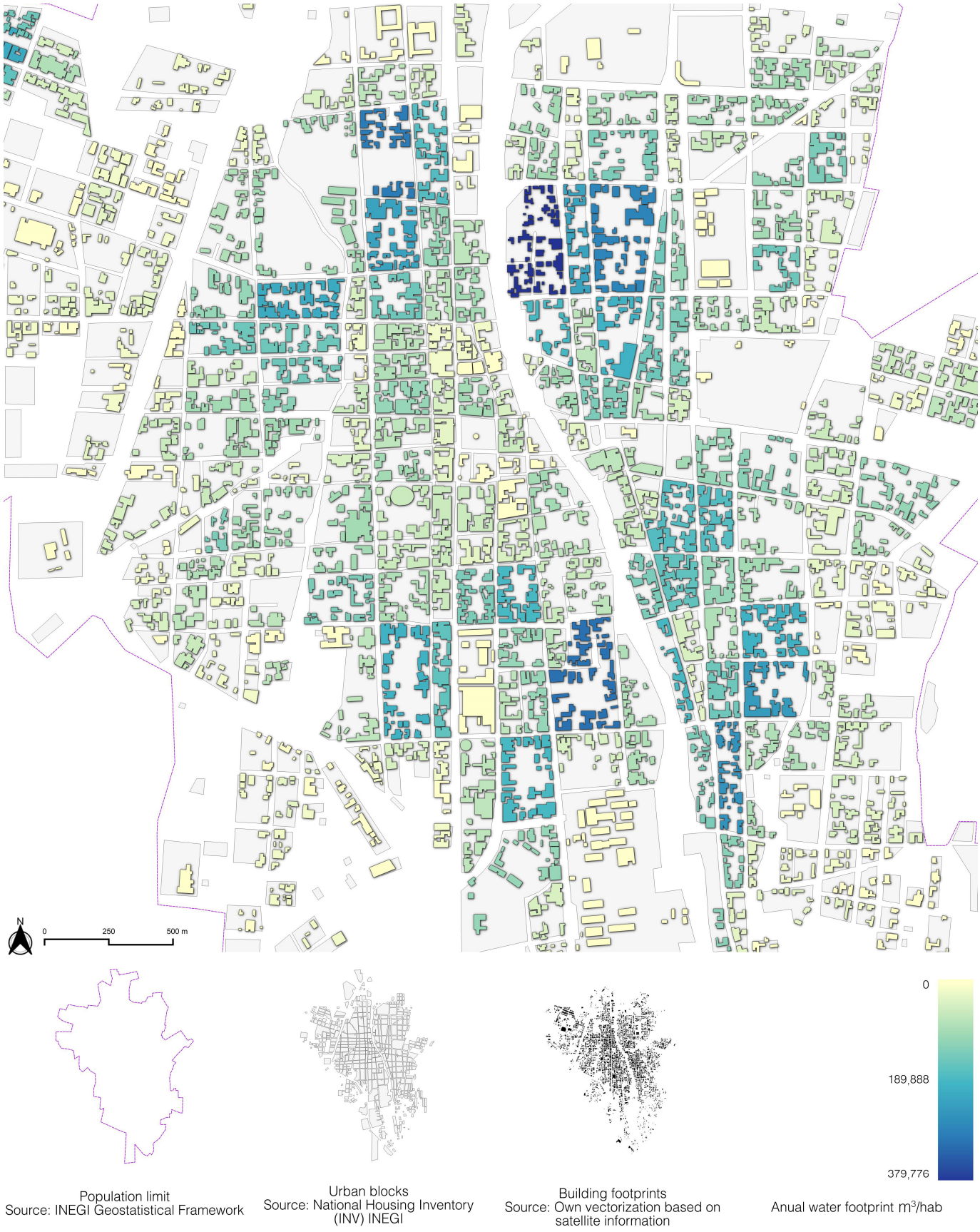


Figure 21. RH36Ad.4 Cuencamé de Ceniceros urban community. Annual water footprint m^3 inhabitants/block. Graphic by the authors.

8. City Scale: Canal Network in Contact with Buildings

In RH36, the analysis of the interaction between buildings and canals is fundamental, considering that the irrigation district network 017 located in RH36 has over 1200 km of canals and drains [57]. The treatment of streets and façade fronts must focus on the preservation of water resources and their distribution, mainly in highly populated areas where water flows are vulnerable to the economic dynamics of urban centers (Figures 22–24).

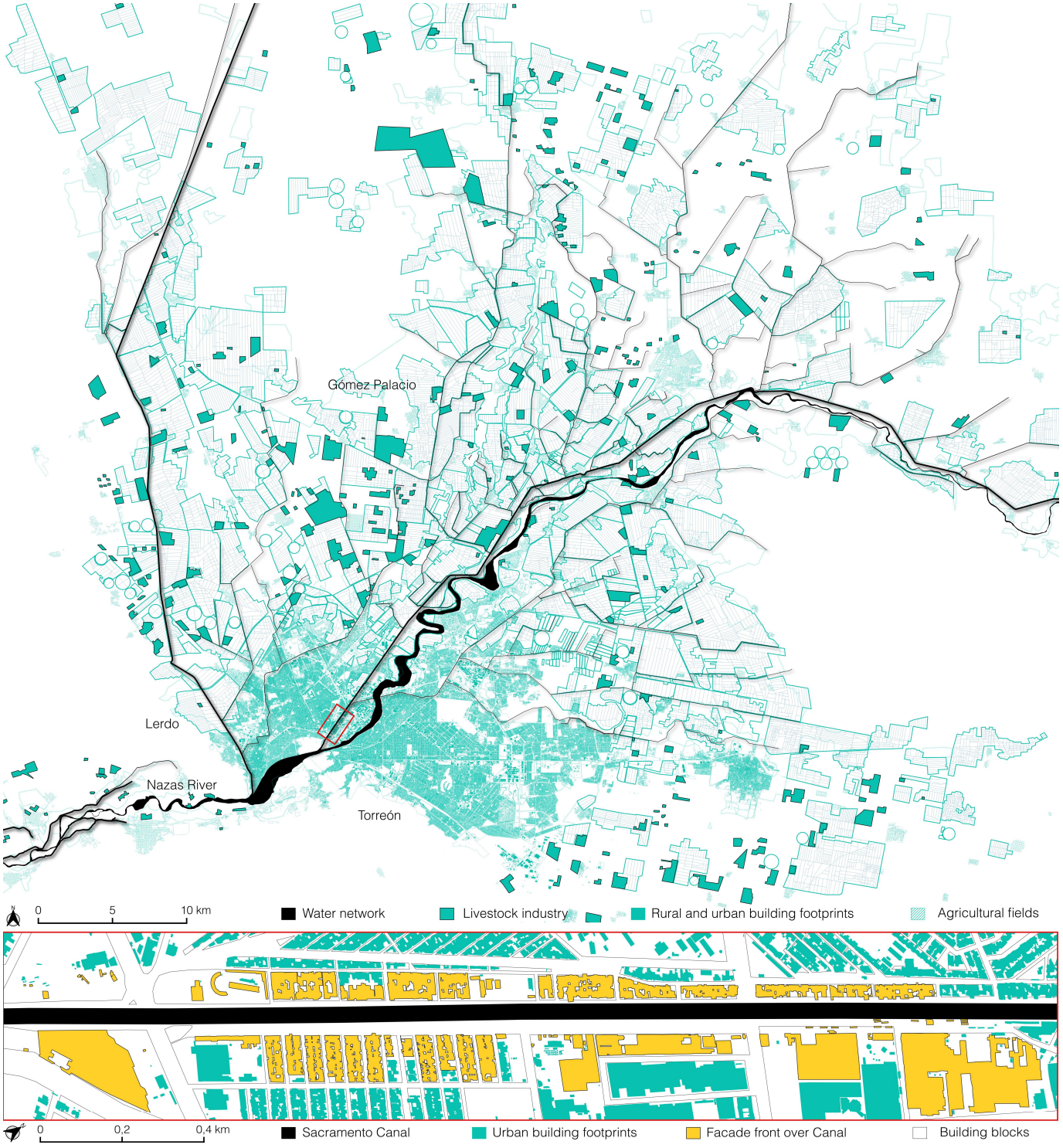


Figure 22. Buildings facing the Sacramento Canal in the city of Gomez Palacio. Sub-basin RH36Aa. Graphic by the authors.

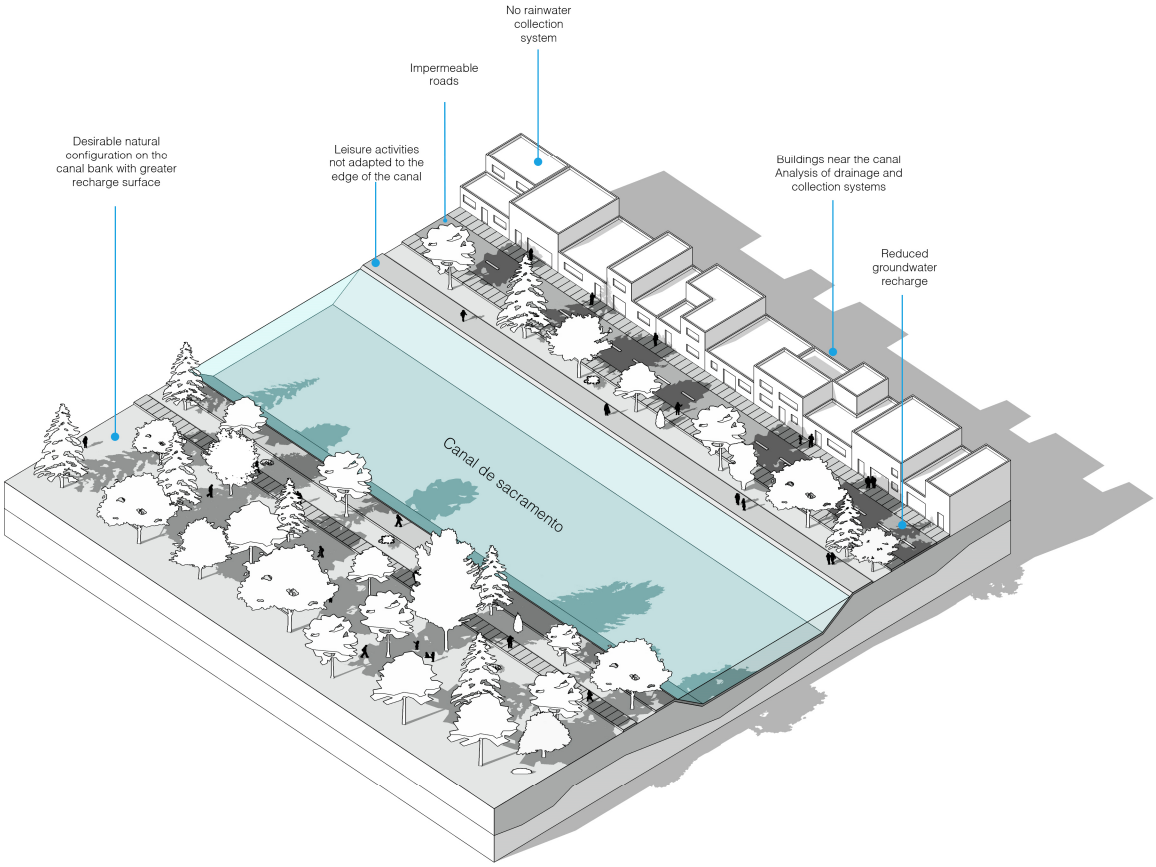


Figure 23. Three-dimensional axonometric of the current state of the Sacramento Canal. Graphic by the authors.



Figure 24. Sacramento Canal. Detail of a crossing and buildings in front of the artificial watercourse. Photography by the authors.

9. Discussion and Conclusions

The methodology developed in this paper is valuable for establishing rural development strategies that effectively mitigate the impacts of water stress in highly controlled hydrological regions. Dams and canals significantly influence both rural and urban organization over time. Therefore, hydrological planning and regional rural and urban planning should collaborate within the basin, sub-basins, and micro-basins to conserve natural stream networks and recharge surfaces. The introduction of rural and urban layers and volumes with varying permeability characteristics compared to the natural vegetative layer of the region alters the dynamics of the hydrological cycle. This alteration occurs either through the introduction of new surfaces with reduced infiltration rates into the soil or through the disruption of water flows within the hydrographic network. This phenomenon is illustrated through the cartographic techniques presented in this study.

In conclusion, GIS software tools enable the identification of agro-production models within settlements of a specific basin. Within these models, rural and urban water dynamics that operate throughout the entire hydrological network can be determined. Employing water as the central theme of the cartographic narrative facilitates the management of diverse scales of information and enhances the visualization of water consumption patterns by communities within their respective contexts. As illustrated in the figures presented in this article, various methods of representing morphological data and water statistics contribute to understanding water flow dynamics across an entire hydrological region.

In regions that experience significant water stress, every liter of water must be carefully managed to optimize its use. This approach can serve as an initial step towards revising building regulations to promote and regulate construction practices that respect the hydrological cycle more effectively. This research demonstrates a series of cartographic analyses within the boundary of hydrological region 36. It offers insights into water-related challenges such as protecting the hydrographic network. These issues emerge in conflict areas with road infrastructure development, impermeabilization of recharge surfaces in urban areas, and extensive agricultural zones near riverbanks and irrigation canals.

Furthermore, despite the absence of vector data in certain geographic regions, GIS techniques allow for the generation of information layers that are suitable for geographic and territorial analysis. While the precision of data at local scales may not match that of territory-level information, it serves as a foundational tool for urban studies. This is particularly relevant in contexts where cadastral data at the plot level and building footprints are inadequate for GIS use or remain inaccessible in computer-aided design software. Consequently, methods exist to conduct morphological analyses with a watershed approach starting from satellite data, which are typically accessible worldwide through resources from NASA and USGS. At local scales (city and architecture), there is considerable importance in integrating key indicators of water resource consumption with the materiality and urban fabric of architecture. This integration allows an assessment of the impact of traditional construction systems on water consumption and their implications for water resources within a micro-basin.

This article aims to complement existing knowledge produced by professional cartographers through specific case studies. The findings are pertinent for rural and urban studies within a basin framework, incorporating geographical constraints and encompassing data and indicators on water usage in rural and urban contexts. These hybrid cartographic representations of territories and their communities under water stress are exploratory and experimental in nature.

Finally, it is concluded that to restore the water balance within a hydrological region and its hierarchical subdivisions, a thorough analysis of each rural and urban community, their agro-production areas, and the hydrological infrastructures providing water services is essential. The analysis of a hydrographic basin must include statistical water data and the interpretation of water flow patterns. Integrating building and agricultural information with hydrological infrastructure allows for the visualization of agricultural activity as the primary user of water resources across the entire region. Rural and urban communities

within the basin are reliant on agricultural surfaces, which effectively makes all agricultural land part of the urban fabric. Consequently, dams and canals are integral components of urban infrastructure.

Understanding all communities within hydrological region 36 as components of a settlement system dependent on a technical water network, which goes beyond political boundaries, is crucial for developing regional plans that are focused on conserving and restoring water streams and recharge surfaces and reducing water stress in the hydrological cycle. This holistic approach can guide adaptations in construction and production systems to mitigate the impacts of river regulation via dams and canals, as well as the effects of climate change in semi-arid regions. The cartographic methods developed in this study for the context of hydrological region 36 enable the interpretation of settlement patterns within each sub-basin. Ultimately, such information serves as an analytical foundation to advance in river restoration strategies. The findings align closely with publications by authors such as Araiza and Viqueira [22,58] on urban studies concerning La Laguna Metropolitan Zone, as explored by Carmona O'Reilly [59] and Briones [60]. Consequently, it is imperative to emphasize the ongoing need for multidisciplinary studies to address water stress reduction effectively. This research argues that despite the inadequate cadastral and cartographic databases in Mexico, particularly in RH36, hydro-urban analyses can still be conducted using GIS software and satellite imagery. Moreover, integrating the hydrographic network into rural, urban, and agricultural studies is crucial for understanding regional flow dynamics. Studies like those by Dodge and Perkins [61] on Manchester highlight the significance of hydrological infrastructure in urban history. Similarly, Lopez's [62] work on Mexico City's hydrological past complements visions described in architect Alberto Kalach's book [63], Ciudad Futura.

The vector-based information generated in this study does not aim to replace the work of Mexican cartographers or cartographic institutes but rather complements existing databases within the same framework. For rural populations with limited budgets, the approach taken in this research can prove useful in creating intentional cartographic bases aimed at protecting the hydrographic network and curbing expansion toward riverbanks and main streams. Viewing all populations as interconnected systems that are dependent on the hydrographic network within basins and sub-basins can facilitate inter-provincial collaboration and the development of restructuring strategies focused on conserving the hydrological cycle and proper water resource management. Nevertheless, it is acknowledged that as long as RH36 communities maintain a predominantly single-product orientation rooted in intensive agriculture [64], transitioning to more sustainable environmental models will be challenging. Therefore, establishing minimum guidelines is essential to progress in mitigating water stress across various fronts, with agricultural production [65] being one of the most critical areas of focus.

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References

1. CONAGUA. *Estadísticas del Agua en México. (Water Statistics of Mexico)*; CONAGUA: México City, Mexico, 2018.
2. Caravantes, R.E.D.; Peña, L.C.B.; Cejudo, L.C.A.; Flores, E.S. Presión antropogénica sobre el agua subterránea en México: Una aproximación geográfica. *Investig. Geográficas Boletín Del Inst. De Geogr.* **2013**, *82*, 93–103. [CrossRef]
3. Salazar, J.A.G.; Soria, E.G.; Hernández, M.F. Demanda y distribución del agua en la Comarca Lagunera, México. *Agrociencia* **2006**, *40*, 269–276.

4. Domínguez, M.G.; Cohen, I.S.; Herrera, G.G.; Díaz, L.M.; Calzada, R.T.; Martínez, M.H. Evaluación De La Eficiencia De Riego En El Módulo IV Del Distrito De Riego 017 Comarca Lagunera, México. *Rev. Chapingo Ser. Zonas Arid.* **2010**, *9*, 99–106.
5. Muro-Pérez, G.; Sánchez-Salas, J.; Alba-Ávila, J.A. Desarrollo agroindustrial: Reseña y perspectiva en la Comarca Lagunera, México. *Rev. Chapingo Ser. Zonas Áridas* **2012**, *11*, 1–7. [CrossRef]
6. Llop, T.C. Guía metodológica. Análisis de la ciudad Latinoamericana. In *Máster en Desarrollo Urbano y Territorial Gestión y Transformación de las Ciudades en Países Desarrollo*; UPC: Barcelona, Spain, 2008.
7. Al-Hameedawi, A.; Mohammed, S.J.; Thamer, I. Updating cadastral maps using GIS techniques. *Eng. Technol. J.* **2017**, *35 Pt A*, 246–253. [CrossRef]
8. Moreno Fernández, S.E.; Traba Díaz, J. Aplicaciones de SIG y teledetección en ecología: Manual de prácticas en QGIS. *(GIS and Remote Sensing Applications in Ecology: Manual of Practices in QGIS)*. 2022. Available online: http://hdl.handle.net/10486/701301 (accessed on 14 April 2023).
9. INEGI; Cartografía Catastral Diagnostico Nacional. *(Cadastral Cartography National Diagnosis)*. 2015. Available online: https://www.inegi.org.mx/app/biblioteca/ficha.html?upc=702825076023 (accessed on 10 February 2024).
10. Pinho, P.; Oliveira, V. Cartographic analysis in urban morphology. *Environ. Plan. B Plan. Des.* **2009**, *36*, 107–127. [CrossRef]
11. Prominski, M.; Stokman, A.; Stimberg, D.; Voermanek, H.; Zeller, S.; Bajc, K.; Zheng, N. *River. Space. Design: Planning Strategies, Methods and Projects for Urban Rivers Third and Enlarged Edition*; Birkhäuser: Berlin, Germany, 2023.
12. Oswald, U. *Water Resources in Mexico: Scarcity, Degradation, Stress, Conflicts, Management, and Policy*; Springer: London, UK, 2011.
13. Coulter, C.B.; Kolka, R.K.; Thompson, J.A. Water quality in agricultural, urban, and mixed land use watersheds 1. *JAWRA J. Am. Water Resour. Assoc.* **2004**, *40*, 1593–1601. [CrossRef]
14. Perfecto, I.; Vandermeer, J. The agroecological matrix as alternative to the land-sparing/agriculture intensification model. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 5786–5791. [CrossRef] [PubMed]
15. Gardon, F.R. Land prioritization: An approach to the effective environmental planning of hydrographic basins. *Environ. Manag.* **2021**, *67*, 623–631. [CrossRef]
16. Cabello Villarejo, V.; Madrid Lopez, C. Water use in arid rural systems and the integration of water and agricultural policies in Europe: The case of Andarax river basin. *Environ. Dev. Sustain.* **2014**, *16*, 957–975. [CrossRef]
17. Eizaguirre i Garaitagoitia, X. Los Componentes Formales del Territorio rural: Los Modelos de Estructuras Agrarias en el Espacio Metropolitano de Barcelona: La Masia Como Modelo de Colonización en Torelló [en línia]. Tesi Doctoral, UPC, Escola Tècnica Superior d'Arquitectura de Barcelona, Barcelona, Spain, 1990. Available online: http://hdl.handle.net/2117/93189 (accessed on 29 June 2024). [CrossRef]
18. Eizaguirre, X. *El territorio como Arquitectura*; Laboratori d'Urbanisme de Barcelona (UPC): Barcelona, Spain, 2021.
19. Solà-Morales, M. The culture of description. *Perspecta* **1989**, *25*, 16–25. [CrossRef]
20. Dematteis, G. En la encrucijada de la territorialidad urbana. In *Lo Urbano en 20 Autores Contemporáneos*; Ramos, Á.M., Choay, F., Eds.; UPC: Barcelona, Spain, 2004; Volume 7.
21. Schjetnan, M. Landscape design and agriculture: A Mexican perspective. In *The Culture of Cultivation*; Routledge: London, UK, 2020; pp. 48–63.
22. Araiza, C.C.; Viqueira, J.P.; Jiménez Sánchez, L.; Martínez Saldaña, T.; Tijerina Chávez, L.; Collado, J. El impacto de la Regulación de los Ríos en la Recarga a los Acuíferos: El Caso Del Acuífero Principal de la Comarca de La Laguna. Ph.D. Thesis, Colegio de Postgraduados, Montecillo, Mexico, 2005.
23. Pacheco-Treviño, S.; Manzano-Camarillo, M.G. The Socioeconomic Dimensions of Water Scarcity in Urban and Rural Mexico: A Comprehensive Assessment of Sustainable Development. *Sustainability* **2024**, *16*, 1011. [CrossRef]
24. Pol Masjoan, M.; Alarcón i Puerto, A.; Puig i Pons, F. Recuperación medioambiental del tramo final del río Besòs. *OP Rev. Del Col. De Ing. De Caminos Canales Y Puertos* **1999**, *46*, 80–87.
25. Maaß, A.L.; Schüttrumpf, H.; Lehmkuhl, F. Human impact on fluvial systems in Europe with special regard to today's river restorations. *Environ. Sci. Eur.* **2021**, *33*, 119. [CrossRef]
26. Yacamán, O.C.; Moratalla, A.Z. *El Parque Agrario: Una figura de Transición Hacia Nuevos Modelos de Gobernanza Territorial y Alimentaria*; Heliconia: Madrid, Spain, 2015.
27. Sabaté Bel, J. *Reflexiones en Torno al Proyecto Urbanístico del Parque Agrario*; Heliconia: Madrid, Spain, 2015; Volume 1, pp. 93–111.
28. Wassie, Y.A.; Koeva, M.N.; Bennett, R.M.; Lemmen, C.H.J. A procedure for semi-automated cadastral boundary feature extraction from high-resolution satellite imagery. *J. Spat. Sci.* **2018**, *63*, 75–92. [CrossRef]
29. Khadanga, G.; Jain, K. Cadastral parcel boundary extraction from UAV images. *J. Indian Soc. Remote Sens.* **2021**, *49*, 593–599. [CrossRef]
30. Cifuentes, M.R.; Cisneros Basualdo, N.E.; Ruíz de Galarreta, V.A.; Gabellone, N.A.; Rodríguez, C.I. Hydrological consequences of land use changes on a dammed urban basin. *Sustain. Water Resour. Manag.* **2024**, *10*, 1–14. [CrossRef]
31. Blanco, A.; De Bustamante, I.; Pascual-Aguilar, J.A. Using old cartography for the inventory of a forgotten heritage: The hydraulic heritage of the Community of Madrid. *Sci. Total Environ.* **2019**, *665*, 314–328. [CrossRef] [PubMed]
32. Álvez, A.; Espinosa, P.; Castillo, R.; Iglesias, K.; Bañales-Seguel, C. An Urgent Dialogue between Urban Design and Regulatory Framework for Urban Rivers: The Case of the Andalién River in Chile. *Water* **2022**, *14*, 3444. [CrossRef]
33. Solá-Morales, M. La identidad del territorio catalán. Las comarcas. In *Quaderns DArquitectura*; Colegio Oficial de Arquitectos de Cataluña y Baleares: Barcelona, Spain, 1981; Volume 1, p. 3.

34. Hoekstra, A.Y.; Buurman, J.; Van Ginkel, K.C. Urban water security: A review. *Environ. Res. Lett.* **2018**, *13*, 053002. [CrossRef]
35. Forman, R.T. *Urban Ecology: Science of Cities*; Cambridge University Press: Cambridge, UK, 2014.
36. Ratti, C.; Di Sabatino, S.; Britter, R. Urban texture analysis with image processing techniques: Winds and dispersion. *Theor. Appl. Climatol.* **2006**, *84*, 77–90. [CrossRef]
37. Weng, Q. Modeling urban growth effects on surface runoff with the integration of remote sensing and GIS. *Environ. Manag.* **2001**, *28*, 737–748. [CrossRef] [PubMed]
38. Mekonnen, M.M.; Hoekstra, A.Y. The green, blue and grey water footprint of crops and derived crop products. *Hydrol. Earth Syst. Sci.* **2011**, *15*, 1577–1600. [CrossRef]
39. Horton, R.E. Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. *Geol. Soc. Am. Bull.* **1945**, *56*, 275–370. [CrossRef]
40. Strahler, A.N. Hypsometric (area-altitude) analysis of erosional topography. *Geol. Soc. Am. Bull.* **1952**, *63*, 1117–1142. [CrossRef]
41. Raiter, K.G.; Prober, S.M.; Possingham, H.P.; Westcott, F.; Hobbs, R.J. Linear infrastructure impacts on landscape hydrology. *J. Environ. Manag.* **2018**, *206*, 446–457. [CrossRef] [PubMed]
42. INEGI (Instituto Nacional de Estadística y Geografía) Marco Geoestadístico. Available online: https://www.inegi.org.mx/temas/mg/ (accessed on 3 June 2023).
43. Contreras-Balderas, S.; Lozano-Vilano, M.; Garcia-Ramirez, M.E. Historical changes in the index of biological integrity for the lower Rio Nazas, Durango, Mexico. *Am. Fish. Soc. Symp. Am. Fish. Soc.* **2005**, *45*, 225.
44. Cotler, H.; Caire, G. *Lecciones Aprendidas del Manejo de Cuencas en México*; INE: México City, Mexico, 2009.
45. López, R.F.P.; Patrón, E.R. *Cuencas hidrográficas. Fundamentos y Perspectivas Para su Manejo y Gestión*; SEMARNAT: México City, Mexico, 2013.
46. Europeas. Diario oficial de las comunidades. In *Directiva 2000/60/CE del Parlamento Europeo y del Consejo, de 22 de Diciembre de 2000, por la Que se Establece un Marco Comunitario de Actuación en el Ámbito de la Política de Aguas*; Directiva 2000/60/CE; Boletín Oficial del Estado: Madrid, Spain, 2000.
47. Vélez, S.; Núñez, G.; María, R.; Trujano, P. La Cuenca Hidrográfica Unidad Básica de Planeación y Manejo de Recursos Naturales. 2003. Available online: https://www.sidalc.net/search/Record/KOHA-OAI-ECOSUR:47326 (accessed on 9 March 2023).
48. Agredo Cardona, G.A. La Cuenca Urbana Como Unidad Territorial para la Planificación del Desarrollo Sostenible en Ciudades de Media Montaña del Trópico Andino. Propuesta de una Metodología de Planificación y Diseño de la Estructura Construida, Circulatoria, Verde e Hídrica en cuencas Urbanas De ciudades de Media Montaña Andina en Colombia: Caso Manizales [en línia]. Tesi Doctoral, UPC, Institut Universitari de Recerca en Ciència i Tecnologies de la Sostenibilitat, UPC, Barcelona, Spain, 2013. Available online: http://hdl.handle.net/2117/95036 (accessed on 7 June 2024). [CrossRef]
49. Kruszewski, P. *A Probabilistic Exploration of The Horton-Strahler Number for Random Binary Trees*; McGill University: Montreal, Canada, 1996; Volume 30, pp. 443–456.
50. Connor, R. *The United Nations World Water Development Report 2015: Water for a Sustainable World*; UNESCO Publishing: Paris, France, 2015; Volume 1.
51. Meneses-Tovar, C.L. NDVI as indicator of degradation. *Unasylva* **2011**, *62*, 39–46.
52. Wulder, M.A.; Roy, D.P.; Radeloff, V.C.; Loveland, T.R.; Anderson, M.C.; Johnson, D.M.; Healey, S.; Zhu, Z.; Scambos, T.A.; Pahlevan, N.; et al. Fifty years of Landsat science and impacts. *Remote Sens. Environ.* **2022**, *280*, 113195. [CrossRef]
53. Alonso, D. Mapping Gis. NDVI: Qué es y cómo calcularlo con SAGA desde QGIS. *(Mapping Gis. NDVI: What it is and how to calculate it with SAGA from QGIS)*. 2016. Available online: https://mappinggis.com/2015/06/ndvi-que-es-y-como-calcularlo-con-saga-desde-qgis/ (accessed on 12 June 2023).
54. Hoekstra, A.Y. Virtual water: An introduction. *Virtual Water Trade* **2003**, *13*, 108.
55. Hoekstra, A.Y.; Chapagain, A.K.; Aldaya, M.M.; Mekonnen, M.M. *The Water Footprint Assessment. Manual Setting the Global Standard*; EarthScan: Washington, DC, USA, 2011.
56. Arreguín, C.F.; López, P.M.; Marengo, M.H.; Tejeda González, C. Agua virtual en México. 2007. Available online: http://cenca.imta.mx/pdf/agua_virtual.pdf (accessed on 5 February 2023).
57. Hernández, M.F.; Alhers, R. *Naturaleza y Extensión del Mercado del Agua en el DR 017 de la Comarca Lagunera, México*; Instituto Internacional del Manejo del Agua: México City, Mexico, 1999.
58. Araiza, C.C.; Viqueira, J.P. El entarquinamiento: El caso de la comarca lagunera. *Boletín Del Arch. Histórico Del Agua* **2004**, *24*, 85–97.
59. Carmona O'Reilly, S.A. Modelos Urbanos Morfológico-Estructurales: El Desarrollo de la Zona Metropolitana de La Laguna. Tesis Doctoral, Universidad Autonoma Metropolitana, Ciudad de México, Mexico, 2018.
60. Briones, M.R. Reconstrucción de la variabilidad climática para el oeste de Chihuahua, México, empleando un enfoque dendrocronológico [en línia]. Tesi doctoral, UPC, Institut Universitari de Recerca en Ciència i Tecnologies de la Sostenibilitat. 2021. Available online: http://hdl.handle.net/2117/361631 (accessed on 14 November 2023). [CrossRef]
61. Dodge, M.; Perkins, C. Maps, memories and Manchester: The cartographic imagination of the hidden networks of the hydraulic city. In *Mapping Cultures: Place, Practice, Performance*; Palgrave Macmillan: London, UK, 2012; pp. 101–120. [CrossRef]
62. López, J.F. The Hydrographic City: Mapping Mexico City's Urban Form in Relation to Its Aquatic Condition. Doctoral Dissertation, Massachusetts Institute of Technology, Cambridge, MA, USA, 2013; pp. 1521–1700. Available online: http://hdl.handle.net/1721.1/84364 (accessed on 1 September 2023).

63. Kalach, A. *México, Ciudad Futura*; RM: México City, Mexico, 2013.
64. Karp, D.S.; Rominger, A.J.; Zook, J.; Ranganathan, J.; Ehrlich, P.R.; Daily, G.C. Intensive agriculture erodes β-diversity at large scales. *Ecol. Lett.* **2012**, *15*, 963–970. [CrossRef] [PubMed]
65. Cerano, P.J.; Villanueva, D.J.; Valdez, C.R.D.; Constante, G.V.; González, B.J.L.; Estrada, Á.J. Precipitación reconstruida para la parte alta de la Cuenca de Río Nazas, Durango. *Rev. Mex. De Cienc. For.* **2012**, *3*, 7–23.

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