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Mapping Urban Water Balance to support the integrated design of water cycles in the peri-urban areas

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Mapping Urban Water Balance to support the integrated design of water cycles in the peri-urban areas

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Abstract. The paper tests the effectiveness of a methodology used to analyze the water element in the urban context, in supporting design choices oriented toward sustainable water management. In particular, it presents a mapping technique of the variables used for calculating the UWB (Urban Water Balance) using the open data available for Milan. The methodology is applied to a peri-urban area of the city's southern outskirts, the Corvetto/Chiaravalle district. The availability of the data has allowed identifying the minimum spatial area on which to carry out a balance of water flows using open-source GIS in the census block (CB). The methodology's effectiveness in supporting the design choices was verified on two specific census blocks, the first representing the diffuse residential built area, the second an existing farmhouse no longer productive with residential functions. The main design strategy's goal was to reduce water withdrawal from the aqueduct and reuse part of the outgoing water to limit the discharge into the sewage system as much as possible.

1. Introduction

In recent years, it has become increasingly evident that water-related issues within our cities are becoming more urgent and require a vision that allows us to recognize the problems it generates, as well as highlight the numerous potentials that arise from its proper management, including its physical, environmental, social, and economic impacts on the context. We are witnessing the increasingly evident effects of climate change, which intersect with water elements in urban areas, creating a chain of events, actions, and possibilities that urge us to rethink water balance more sustainably and adapt to an ever-changing climate crisis.

This paper aims to provide specific information in urban areas (maps) to support public administrations and designers in defining strategies aimed at the sustainable use of this common resource [1] [2]. Mapping significant elements at the urban level, particularly within specific census blocks ("cells" within the urban fabric that describe particular conditions related to both the physical characteristics of the area and the social aspects of the resident population) (www.istat.it), allows us to consider the actual conditions and potentials of the area. It also enables the design of possible scenarios for a proper water balance that can respond to ongoing changes, particularly those related to climate.

A couple of aspects represent the frame of this work:
Starting from the impacts of climate change on the city of Milan, it is interesting to recall the strategies implemented by the public authorities in public spaces and the external environment, the effects of which are now evident throughout the year. While a few years ago, the most apparent effects were related to the increase in the urban heat island effect and summer heatwaves (for which significant investments are being made in planting thousands of trees and where water can be considered to alleviate the heat stress), we are increasingly experiencing effects linked to, on the one hand, the increase in episodic

weather events with large amounts of water that the increasingly paved surfaces and the sewer system are unable to manage adequately; on the other hand, we are experiencing a shortage of rainfall throughout the year, which has had, until now, significant repercussions on agriculture and urban green irrigation (in the city of Milan, in 2022, more than 4,000 young trees died due to drought).

The second aspect is related to an inspiring experience highlighting the need to rethink synergistically water use, that has been developed for the "Tres Barrios-Amate" neighborhood in Seville, thanks to the participation of local creators, neighbors, and young people from the local association *A.E.S. Candelaria*. The project was awarded by the EU under the "New European Bauhaus Awards" program. The project, called "Gardens in the Air," aimed, among other objectives, to utilize the "waste" water produced by air conditioners during the summer season for maintaining private green spaces on balconies. Apart from the quantitative data (which we will discuss later), it is important to emphasize that the strategy, seemingly confined to the realm of private households, achieves, as the project creators argue, "a membrane of biodiversity that, like a Trojan horse, helps minimize the need to use these appliances, while creating a cooler and more habitable external landscape for all." They also remind us that, as Louis Luis Kahn claimed, "the street is a consensual room, a common room whose walls are made available by those who inhabit it, ceded to the city for its collective use."

2. Methodology

The methodology has been implemented in a specific area of Milan, at the edge between the urban context and the rural area of Parco Agricolo Sud. This area is particularly interesting because it is characterized by a high-density residential fabric and agricultural farms, often no longer in use or seeking a new identity, thus requiring reinterpretation. Being a fringe area, it is quite distinct from the rest of Milan. For instance, according to the 2021 data from Arpa Piemonte (arpa.piemonte.it), land use -calculated as the ratio between the waterproof (paved and built area) and the whole area- is 0.58 for the entire Municipality of Milan, with values ranging from 0 to 1, where 0 corresponds to the unused and permeable area, and 1 corresponds to entirely impervious areas.

Two census blocks highly diverse have been chosen as case studies; while the first represents the municipal average (0.57), the second is 0.76, indicating a land use below 1%. The first block refers to the urbanized area of 18.759sm with 485 inhabitants; the second one, the farm block is about 234.732sm with 50 inhabitants.

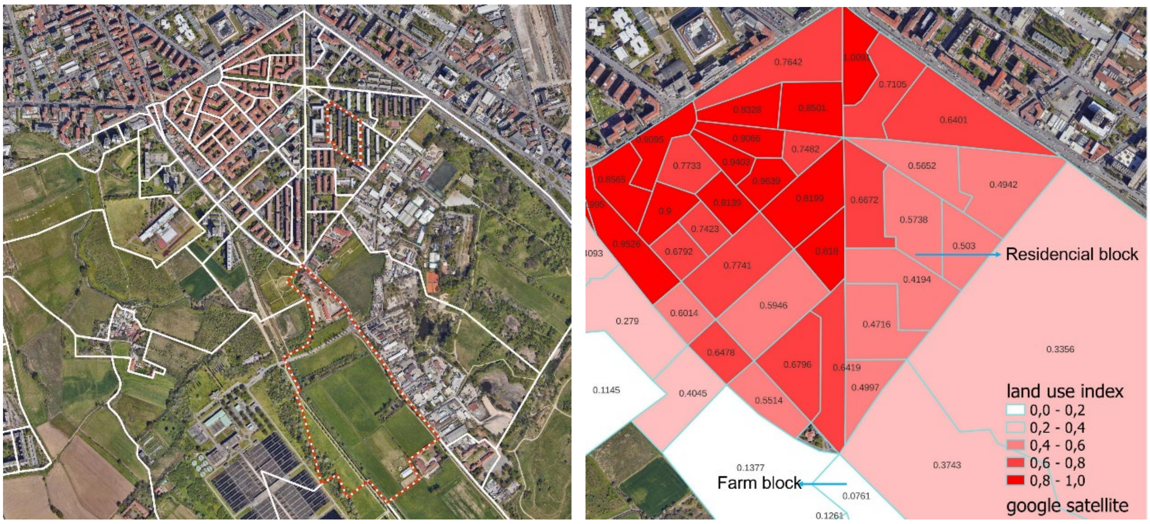

Figure 1. Map of the selected areas inside the Corvetto neighborhood as case studies (on the left) and mapping of land use index based on available open data, consisting of the ratio between the waterproof area and the whole area. 0 is the unused area, 1 corresponds to the 100% of waterproof surfaces (the picture on the right; authors' elaboration).

The methodology used consists of two main steps. The first is oriented to mapping the variables helpful in calculating the UWB; in the second, these variables are used to develop improvement scenarios of water use, focusing on two census blocks (CB) as case studies.

The first phase collects, processes, and locates the variables helpful in calculating the UWB using specific thematic maps, organizing them into two macro-categories relating to input and output.

The Urban Water Balance (UWB) applies the mass conservation principle to transferring water through a specific catchment [3]. It can be written as $P+I+F=E+R+\Delta W+\Delta A$, where P is precipitation, I is the urban piped water supply, F is the water released due to human activity, E is evapotranspiration, r is runoff, ΔW is the net change in water storage, and ΔA is the net advection of moisture in and out of the control volume. The second phase tests these variables to verify improvement solutions' applicability to the analyzed building. This step focuses on defining different usage scenarios starting from the data associated with the census block.

2.1 UWB variable mapping

The following paragraphs describe the calculation procedures to map the main variables considered. Specifically, we have selected those variables internal to the Urban Water Balance (UWB) that can be mapped based on the available open data for the city of Milan. The objective of using the mapping of these variables to support improvement strategies in the project has led to a focus on P, I, F, R, differentiating them into outgoing and incoming flows:

Inputs: water inflow from the water supply system, water captured from rooftops, water captured from impervious surfaces.

Outputs: water discharged from households into the sewer system (including rainwater from rooftops and impervious surfaces). This decision enabled the adoption of a simplified helpful indicator for comparing the improvement strategies implemented, which assesses the percentage reduction of income and outcomes compared to the mapped data relating to the current state (sustainable UWB in Table 2).

2.1.1 I - Imported water flows (input). These mapped thematic elements refer to the quantity of water extracted from the aqueduct per census section. The calculation was performed by multiplying the number of inhabitants by the average annual amount of water consumed per person (https://www.mmspa.eu/). Specifically, the estimate was derived as follows: 0.225 m^3 multiplied by 365 days equals 82.125 m^3.

2.1.2 Harvested from Roof Surfaces (input). Locally available water through precipitation. Making this information available requires associating the amount of rain reaching the roofs monthly and annually with the geometric data relating to buildings (https://geoportale.comune.milano.it/sit/). Regarding the data referring to the monthly average, the open data website of the municipality of Milan reports the monthly average of the atmospheric precipitation values (https://dati.comune.milano.it) (Table1). Rainfall was measured in the urban area of Milan between 2008 and 2014; Table 1 shows an average annual quantity equal to 1006 mm, with monthly average values that fluctuate depending on the month, from 48 in August to 97 mm in April, except for November where values around 170 mm are recorded.

Table 1. Pluviometric data in mm/month relating to the rainfalls in the urban area in Milan. The data reports the average year between January 2008 and December 2014 (Comune di Milano, 2022).

Average 2008/14	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**TOT year**
	79,9	**74,1**	**75,7**	**97,4**	**91.8**	**79,9**	**76,4**	**48,1**	**63,2**	**69,1**	**172,2**	**78,8**	**1006,6**

Mapped thematic elements related to variable P, refer to the monthly and annual water collected by the rooftops. In the case of the annual quantity, the surface area of the rooftops is multiplied by 1.0066 m^3 (the average yearly precipitation calculated over the time interval 2008-2014).

2.1.2 Water discharged into the sewage system from residential dwellings (output). For the calculation, 90% of the incoming water (I) was considered. The remaining hypotetical 10% is the water for drinking, cooking and cleaning activities, plants.

2.1.3 F- water realized due to human activities (output). The map shows the amount of water produced by the air conditioning system. Data associated with the energy needs for summer cooling, if combined with information concerning air humidity, can be used to calculate the water produced by condensation from the air conditioning systems of the buildings.

The quantity of water produced by the air conditioning systems is an important aspect to keep in mind, from a systemic perspective, that is to allow that the adoption of re-naturalization strategies positively affects the reduction of energy consumption related to summer air conditioning and at the same time, to negatively impact on the use of water from the aqueduct to irrigate the green walls.
The quantity of water depends on climatic conditions, particularly air temperature and relative humidity. Regarding the case study mentioned in the introductory notes, an estimated water collection of 1-2 liters per hour was calculated in the city of Seville, with a hot and dry climate.

In this initial phase of mapping this variable, a setpoint temperature of 26°C was considered, resulting in 510 hours of cooling demand for a dwelling. Therefore, it was hypothesized that an air conditioning system would release 1 liter of water per hour (a value lower than the estimated range for the case study mentioned in the introduction). Considering the number of households per census section, it was possible to calculate an initial reference value. This value is obtained by multiplying the number of households by the m^3 of water associated with one household, which is 510/1000 = 0.51 (222 hours only in July).

2.1.4 R - runoff (output). Runoff refers to the various contributions to the sewer system related to the runoff from impervious open spaces. The quantities intercepted from the impervious surfaces were calculated by associating the monthly and annual rainfall amounts with different types of mapped impermeable soil (roadways, pedestrian paths, public and private waterproof open spaces). For annual time intervals, the total area within the census block was multiplied by the amount of water captured annually per square meter of the horizontal surface, which is 1.0066 m^3.

Figure 2. Census block representative of the average in the neighborhood. The numerical values reported in the circles describe, from top to bottom, the yearly quantities of m^3 of water, per block on the left, and inhabitant on the right. The values from top to bottom are as follows: the amount of water captured from rooftops (P), the amount of water taken from the water supply system (I), the amount of water produced by air conditioning systems (F),

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and the amount of water intercepted by impervious surfaces in open spaces (excluding public driveways and walkways, denoted as R).

Figure 3. The portion of the census section selected as the second case study for the existing farmhouse P is the water captured from rooftops, (I) is the amount of water taken from the water supply system, (F) is the amount of water produced by air conditioning systems, and R the amount of water intercepted by impervious surfaces in open spaces (excluding public driveways and walkways).

3. Results and future scenarios

The mapping of the variables that affect the UWB and their use to develop improvement scenarios applied to the case study enabled highlighting the relationships between the various subsystems, verifying the seasonal flows, and understanding possible synergies between open and indoor spaces in the sustainable use of water flows.

The two areas selected differ regarding morphology and land use (the rural area characterized by low density urban fabric compared to the typical residential high-rise buildings). Consequently, the mapped quantities present different values. It is evident the difference, especially in the use of the water from the aqueduct (I), an amount directly linked to the number of residents in the area; the coexistence of water flow and population data on the same GIS platform (Figure 4) has enabled the extraction of effective indicators to identify appropriate strategies.

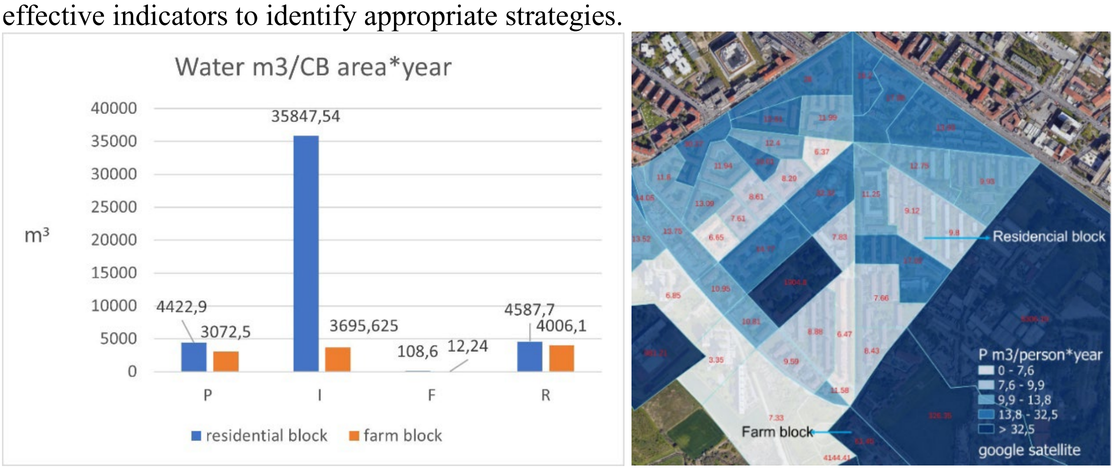

Figure 4. On the left the graph relating to the current state, which shows the quantities relating to the UWB of the CBs chosen as case studies; on the right map of P (Water collected by roof surfaces per person).

In the first census block (Table 2), the quantities expressed per person associate a value of 9,12 m³/person/year with the amount of rainwater captured from rooftops. With the primary goal of reducing the quantity of drinking water and, therefore, per capita consumption, we can conclude that rainwater harvesting from rooftops is insufficient, i.e., it is lower than the water required for toilets (approximately 10 m³/person/year). To compensate it, the proposal is to intercept the rainwater that reaches the ground (excluding first-flush water), store it, and later reuse it. Another resource is the wastewater from the air conditioning system.

Table 2: Water balance per year equation in the two areas. It is possible to read the improvement (sustUWB) obtained by the implementation of some SUDS and strategies to save water inside the buildings.

water_m3/pers*year	P	I	F	R	UWB	SustUWB	Improvement
residential block	9,12	73,917	0,22	9,46	92,717	72,618	21,68%
farm block	61,45	73,917	0,24	80,12	215,727	76,323	64,62%

In the case of the second CB, there are residences and offices and the farmhouse is no longer productive. The roofs provide significantly more water, approximately 60m³ per person, more than 6 times the available amount in the first census section. The use of water collected from the roof is sufficient to meet the demand for toilet flushing. It can also be utilized for activities beyond residential purposes aimed at enhancing the environmental sustainability of the inhabitants, such as urban agriculture. The mapped data has revealed interesting information regarding the characteristics of the relevant outdoor space. The substantial amount of water entering the sewer system through runoff, 80 m³ per person, indicates the need for a modification in soil permeability to reduce the proportion of impervious surfaces. This could be achieved by implementing sustainable strategies, such as rain gardens or other Sustainable Urban Drainage Systems (SUDS) types [4][5]. In this proposal, different surfaces have been considered in the 2 census blocks converted in SUDS, in particular, 15% in the residential area and 20% in the farm block. Such solutions would improve the open spaces in terms of environmental impact and water management and enhance the liveability and architectural quality.

Conclusions

The paper has highlighted the close relationship between urban development, lifestyles, and water, often considered a critical issue and a resource of little value. The current state of two areas within the municipality of Milan, as well as interventions aimed at improving water balance by saving drinking water and managing excess water sustainably, have been represented through GIS mapping and the use of open data provided by the Municipality of Milan. The results have revealed how improvement strategies have different effects depending on the urban and morphological configuration.

By associating the data with the census block, the numerical values related to the Urban Water Balance (UWB) have been translated into quantitative indicators for better understanding, such as the quantities of water entering and leaving the relevant block per person. The employed methodology encourages the exploration of new and different scenarios that can address and delve into other themes, which can be further mapped. These themes may include the use of materials, energy production and water storage systems for managing extreme weather events, and other topics currently less explored but oriented towards activating local circular economies, all related to water, such as urban agriculture.

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