A MEASURE OF THE POTENTIAL POLLUTANT LOAD OF URBAN WASTEWATER

Stefano Tersigni, Valerio Adolini, Francesco Isidori

Abstract. Water resource management is a crucial process for ensuring sustainable development and the achievement of the goals set by the 2030 Agenda. Preserving the integrity of ecosystems dependent on the water cycle over time is essential for achieving and maintaining collective, economic, and social well-being. As part of this context, this work aims to quantify the potential pollutant load of urban wastewater, generated at the municipal level and analyzing its distribution in the national territory. The tool adopted to achieve this goal is the estimation of Total Urban Equivalent Inhabitants (TUEI), a quantity that takes into account not only the resident population but also other categories of individuals contributing to the production of biodegradable pollutant loads, such as the tourism sector, commuter flows, industrial activities, accommodation, and catering establishments. The main contribution of the analysis is therefore to define the need for urban wastewater treatment from various pollution-generating sources, meeting the current needs of the Regions and the Ministry of Environment and Energy Security responding to European Urban Waste Water Treatment Directive. The estimation was produced for the year 2021, integrating information from multiple sources. Furthermore, different levels of territorial aggregation were considered. In particular, estimates in the domains of interest (municipal, provincial, regional) are obtained from data related to census sections. With this methodology, attempts were made to introduce elements useful for measuring TUEI and improving the assessment of pollutant loads, a complex topic that still presents critical elements in the availability and usability of sources and deserves further investigation.

1. Introduction and aim

Water is a key element for life and has always played a significant role in the social and economic development of society. It fosters prosperity by meeting essential needs, ensuring health, economic development, food and energy security. If water resources management infrastructure is properly developed, it can promote growth and prosperity by storing a reliable water supply and providing it to various economic sectors. Similarly, safe, accessible and well-functioning water supply and sanitation systems improve the quality of life for all citizens (UNESCO, 2024). In this regard, the focus of international institutions on the centrality of water in development processes is evidenced by the Sustainable Development Goals, collected in the ambitious Agenda 2030 program. A crucial aspect of this project is specifically dedicated to water resources and aims to ensure availability and sustainable management of water and sanitation for all. In this context, in order to get closer to achieving the aforementioned goals, it is essential to build a reliable estimate of the potential pollutant load generated in the territory to support decision-makers in designing appropriate treatment plants and minimising the percentage of untreated wastewater.

Wastewater carries numerous pollutants: biodegradable organic material, nutrients, bacteria and viruses, solvents, detergents, fats, oils, metals, micropollutants from pharmaceuticals and plastics, and other organic and inorganic substances derived from households and industries (Halleux, 2023). Therefore, adequate treatment of wastewater is vital to protect human and environmental health. Lack of sanitation can cause pollution of rivers, lakes, seas and drinking water, leading to diseases in humans (European Environment Agency, 2019) and limits in social development. The estimation of the potential pollutant load of a territory's wastewater is carried out by calculating a particular statistical measure, that of equivalent inhabitants. Equivalent inhabitants represent an estimate of the biodegradable organic load produced by domestic and economic activities. In detail, according to Directive 91/271/EEC concerning urban wastewater treatment, “one equivalent inhabitant (E.I.) is the biodegradable organic load having a 5-day biochemical oxygen demand (BOD_5) of 60 g of oxygen per day” (Directive 91/271/EEC). Estimating the number of equivalent inhabitants allows the assessment of the overall load on a territory.

In Italy, however, there is no nationally shared methodology for calculating equivalent inhabitants. Each region adopts its own methodology and communicates the result to central institutions, preventing comparisons between different geographical areas. The purpose of this work is therefore to propose a uniform and nationally shared methodology capable of quantifying the potential pollutant load of territories during the week of maximum plant load and providing initial indications on actions to be taken.

In the second paragraph, the methodology implemented for calculating Total Urban Equivalent Inhabitants (TUEI) will be described, providing information on the data sources used.

The third paragraph is devoted to the analysis of the results obtained through the application of the proposed method paying particular attention to the different TUEI components and the deviation from the loads manageable by the existing plants at the regional level.

Finally, advantages and disadvantages of the methodology will be reported in the last paragraph, but above all possible developments in order to better investigate a topic, central to the challenge towards sustainability in the coming years.

2. Methodology: sources and choices

In the TUEI estimation methodology proposed here, biodegradable pollutants in urban wastewater are considered. Therefore, wastewater produced by domestic and assimilated activities is considered, but also discharges from tourist, hotel, school and micro-enterprise activities that operate within urban centers and discharge into the sewer system, having qualitative characteristics equivalent to human metabolism or domestic activities (ISTAT, 2009). By integrating information derived from ISTAT surveys with additional elements from the scientific literature, the calculation is carried out with reference to the year 2021, examining the "maximum load" week, which is the week of the year with the highest pollutant load (in terms of flow rate or BOD_5 concentration). This week usually coincides with the period of maximum attendance.

The pollutant load component due to domestic activities is obtained by considering both the legal population surveyed in the territory and the present and nonresident population, i.e. individuals present in the municipality but having their usual residence in another municipality or abroad (ISTAT, 2023), as well as the amount of commuting worker and students. The reference source for the legal population is the *Censimento permanente della popolazione*. Since data for the present but non-resident population is not available for the year considered, it is estimated using a linear regression model between the resident population and the present but non-resident population from the last available year (2011)[1]. In these cases, each inhabitant constitutes a unit of equivalent population. To obtain information regarding commuting, the origin-destination matrix of 2011 is considered (ISTAT, 2011). The estimation of the relative pollutant load, subtracted from the departure municipality and added to the arrival municipality, does not refer to the entire day but to an estimated period of 8 hours for workers and 6 hours for students. The data obtained is then adjusted in proportion to the resident population in 2021.

Regarding the impact of the tourism and hotel sector, the number of beds available in accommodation facilities is supplemented by the potential population

[1] The regression model was constructed region by region. For Lazio, the capital Rome was excluded from the calculation of coefficients, while it was included to estimate the value of the municipality in 2021.

present for tourism or vacation in private dwellings and the contribution from discharges related to food service activities, bars, and their staff. The source for the number of beds is the ISTAT survey "Capacity of Accommodation Establishments," covering 2021, in which hotels, guesthouses, camping, vacation villages and private homes used on an entrepreneurial basis for seasonal rentals are examined (ISTAT, 2021). Beds in farmhouses and mountain lodges are excluded as they are usually located in areas not served by the sewerage system. The estimation of the pollutant load from restaurant and bar activities is derived by considering both the number of staff employed in these activities, obtained from the Asia archive for the year 2021, and the estimated number of place settings. An additional step involves weighting the territories based on their tourism vocation (ISTAT, 2022) a coefficient of 1 is assigned to territories with a higher tourism incidence, while a coefficient of 0.9 is assigned to the others. For estimating the potential population present for tourism or vacation in private homes, the number of unoccupied dwellings is considered, multiplied by the average number of people present in occupied dwellings recorded in the same municipality. Based on a pilot study, three different coefficients are applied to account for the fact that, on average, not all secondary homes are inhabited or used. These coefficients primarily account for demographic variation, as there is a strong correlation between lower occupancy in unoccupied dwellings and the demographic decline of the resident population.

Finally, when examining the contribution of economic activities, those that are more "water-demanding" are considered, meaning activities that use water in their production cycle and return it to the environment with modified qualitative characteristics compared to the initial state (Barbiero, 2003). Enterprises with more than six employees are excluded from the calculation because, in most cases, they do not use the public sewer system and have their own treatment systems. Specifically, for each municipality, the number of employees, distinguished by economic activity, was obtained from the Asia Archive of local units for 2020, and the relevant IRSA-CNR coefficient was applied[2]. These coefficients consider one equivalent inhabitant to be the amount of organic substance present in the daily domestic discharge, equivalent to 54 g of BOD_5 per person, while current regulations state that an equivalent inhabitant produces 60 g of BOD_5 per day. Therefore, a re-proportioning coefficient of 54/60 = 0.9 was applied. Additionally, to account for

[2] IRSA's Notebook 119 (ISSN 0390-6329), "The method of zonal coefficients for assessing potential industrial pollutant load in different territorial aggregations," was consulted, in which the "national" coefficients for converting inhabitant equivalent/addicted for hydro-demanding economic activities are given. The "zonal" coefficients are also reported in the notebook, but since some years have passed since the calculation of these coefficients, it was deemed more appropriate to use the national ones, which are valid from the point of view of their applicability throughout the country, considering Italy a homogeneous area from the economic point of view (Barbiero, 2003).

preliminary treatments before discharge into the public sewer system, a multiplicative coefficient of 0.2 was used, considering an 80% reduction in the pollutant load by the producers.

For a more detailed territorial analysis, the calculation of TUEI (Total Urban Equivalent Inhabitants) was also developed for census sections. Information on residents is provided by ISTAT for census sections, while all other factors were estimated for census sections with weights determined by the resident population. For the population present in private homes, weights were determined using data on unoccupied dwellings from the 2011 Census.

Table 1 - *Summary of the methodology adopted for the calculation of TUEI.*

COMPONENT	SOURCE (YEAR)	METHOD	COEFFICIENTS
Resident Population	Population Census (2021)		1 inhabitant = 1 E.I.
Present population but not resident	Population Census (2021)	Linear regression model between resident and present population in 2011.	1 inhabitant = 1 E.I.
Commuter population	Commuting Matrix (2011)		8/24 for work 6/24 for students
Potential population present in hotel facilities	Capacity of collective accommodation establishment (2021)	Beds in hotel facilities (excluding cottages and lodges).	Tourism vocation = 1 No-tourist = 0,9
Potential population present for tourism or holidays in private dwellings	Population Census (2011-2021)	Unoccupied dwelling, multiplied by the average number of people in the occupied dwelling.	Variation population 2021/11 • >0%= 0,7 •<0 >-10% =0,5 •<-10% = 0,3
Population equivalents related to restaurant and bar service activities	Business Register (ASIA, 2021)	1 employee = 12 place settings (Restaurant). 1 employee = 50 customers (Bar). Restaurants = E.I. for every 3 place and 3 employees. Bar = E.I. every 7 customers and 7 employees.	Tourism vocation = 1 No-tourist = 0,9
I.E to the most water-intensive micro-enterprises with less than six employees	Business Register (ASIA, 2020)	Employees in local industrial unit by IRSA CNR coefficients (with adjustment).	Reductions of pollutant load by producers = 80%

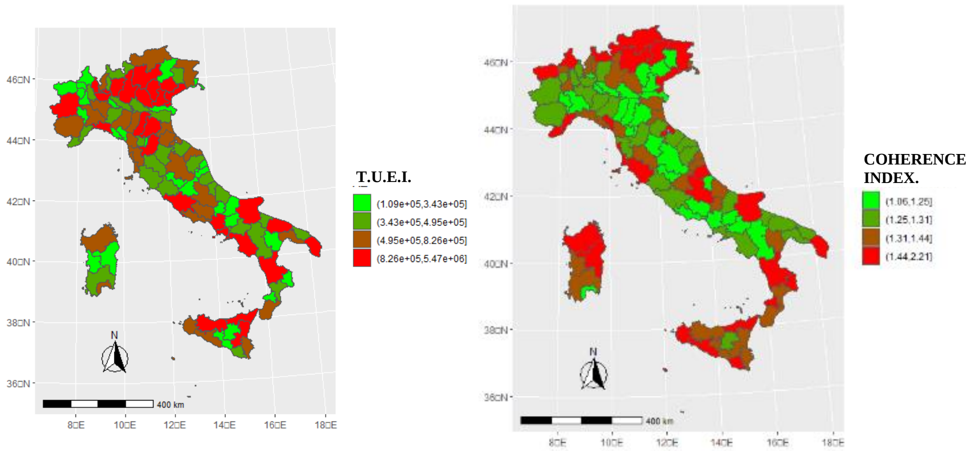
Once the TUEI for each census section was calculated, based on the sum of the previous variables, the density of TUEI per square kilometer for each census section was determined. It was decided not to include in the calculation of total urban equivalent inhabitants at the municipal level those sections where pollutant loads are not normally conveyed into the public sewer system, those with a TUEI/km² density of less than 1000.

3. Result: Descriptive analysis of TUEI and service coverage

In this section, a descriptive analysis is made of the results obtained from the estimation of TUEI considering the different components used. Next, the results of the TUEI at the provincial level are examined. In conclusion, a comparison is made between the actual purification capacities of plants at the regional level (Ramberti et al., 2022) and the maximum potential pollutant load estimated through the proposed methodology.

Figure 1 - *Provincial distribution of TUEI in absolute values (left) and consistency index (right). Colors refer to quartiles of the distributions.*

a) b)



As we can see in figure 1.a), there is a non-homogeneous distribution of the potential pollutant load of urban wastewater across the national territory. The areas with the highest presence of TUEI in absolute terms are, as expected, the metropolitan cities and the most populated provinces, but also provinces with historically significant tourism development and attractive capacities, such as coastal areas. Conversely, the inland areas of our peninsula, particularly the Apennine region and the Sardinian hinterland, which are less involved in major tourist routes and have fewer water-intensive industries, show a lower presence of equivalent inhabitants (E.I.).

In order to better assess the impact of the various components in the calculation of TUEI, particularly concerning the most significant component, the resident population, a consistency index was defined as follows:

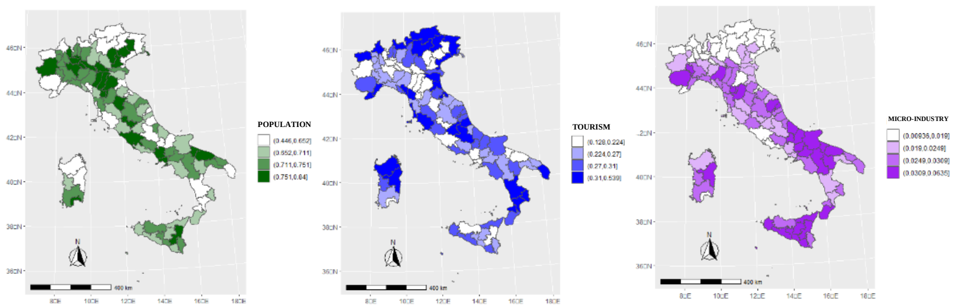
$$\textit{Coherence Index} = \frac{TUEI}{resident\ population}$$

This indicator always takes values greater than 1 since the estimate of TUEI is, in all cases, higher or at most equal to that of the resident population. The closer the indicator is to 1, the greater the coherence between TUEI and the resident population; the further the indicator is from 1, the greater the impact of the non-resident population or the presence of economic, tourism, and commuting activities. The territories that report the greatest distances (Figure 1.b) seem to refer to the main tourist areas of our country such as the Ligurian coast, much of the Alpine chain, the Romagna riviera, the Versilia coast, the center of the Adriatic coast, the Calabrian coast and much of the insular territories of Italy. From this perspective, although it seem an obvious result, the proposed analysis thus confirms its robustness and validity.

As shown in the following graphs (Figure 2), the weight of the "population" component is less pronounced in the aforementioned provinces, which fall in the lower quartiles of the distribution, with an incidence between 44% and 71%. Conversely, these areas are shown in darker colors, indicating a higher percentage of the tourism component, which ranges between approximately 27% and 54%.

Figure 2 - *Provincial distribution of the population component (left), tourism component (center) and micro-industry component (right) in percentage values. Colors refer to quartiles of the distributions.*

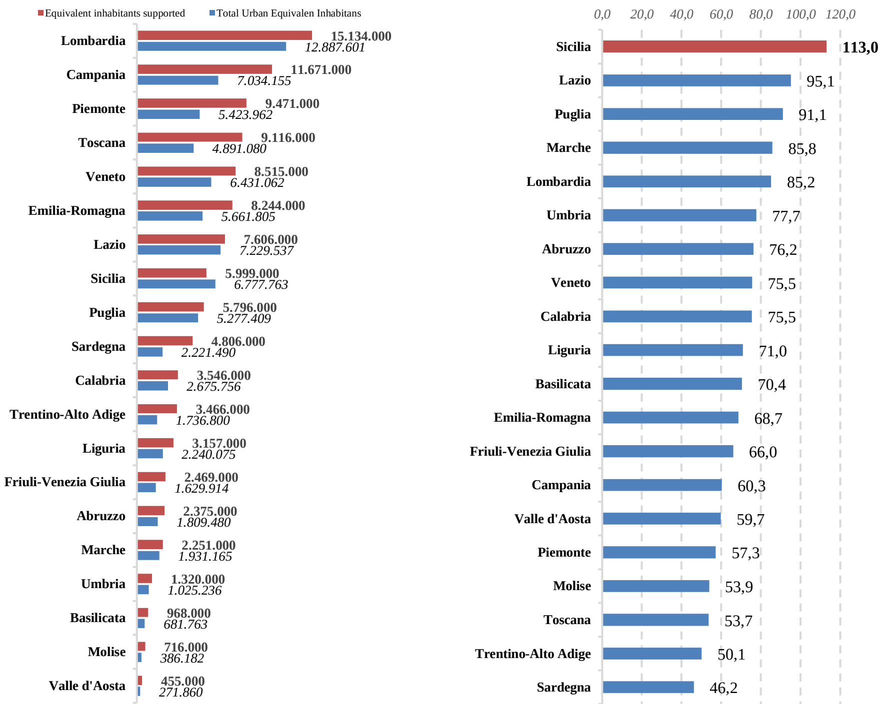
a) b) c)



An interesting aspect that emerged from the analysis is that in many provinces of Southern Italy (particularly in the regions of Puglia, Calabria, and Sicilia), there is a higher percentage incidence of the industrial component compared to the northern regions (Fig. 2.c). This finding may be linked to the fact that industrial activities are present in territories with a smaller population compared to the north, thus increasing the percentage of this component on the total TUEI. However, it should be noted that the percentage values are still marginal, not exceeding 6.4%. Turning finally to the comparison between the actual purification capacities of the plants at the regional scale, (information obtained from the ISTAT survey "Urban Water Census - Year 2020") and the maximum potential pollutant load estimated through the proposed methodology (Fig.3a) the region where the discrepancy (Fig. 3.b) is greatest is Sardegna, with a percentage difference of 46.2%. This means that, overall, Sardinian regional plants are capable of treating wastewater from a number of equivalent inhabitants more than double that potentially present in the territory (TUEI).

Figure 3 - *Regional distribution of maximum loads supported by plants in absolute values (left) and percentage of load generated in TUEI according to the proposed methodology on maximum supported load (right).*

a) b)



In most regions, the total pollutant load that can be purified by municipal wastewater treatment plants is greater than the potential TUEI present in the territory. The most problematic situation is observed in the region of Sicily, where the estimated number of equivalent inhabitants during the period of maximum load exceeds the maximum capacity of the plants present in the region. According to the data from the Urban Water Census, the Sicilian region has a treatment plant capacity of about 6 million equivalent inhabitants, while the estimated total load generated in the territory is over than 6.7 million TUEI, highlighting a significant purification deficit. A condition that deserves more attention and supervision is that of Lazio and Puglia, which show a smaller discrepancy: the TUEI present within their jurisdiction represents over 90% of their plants' capacity.

4. Conclusions: limitations and further development

In line with the initial goals set, the work succeeded in developing a uniform and nationally shared estimation method capable of quantifying the pollutant potential produced by territories in the week of maximum plant load.
This methodology also reported realistic results, with a good degree of reliability and certainly more usable than the variety of calculation methods adopted to date. The analysis also made it possible to highlight regional areas where greater attention is needed regarding plant capacities to prevent potential critical situations.

On the other hand, it is necessary to point out the inherent limitations of established system. A first major point of criticism concerns the use of outdated sources.

The proposed estimates have tried to circumvent this obstacle, however, pointing out this criticality also allows us to remark a greater statistical attention on the issue and to urge a greater collection of quality and up-to-date data, information and analysis from all the stakeholders involved.

The work presented represents a possible starting point for new and more in-depth studies on the topic. Future research paths could aim, for instance, to adapt the methodology to the new, more stringent regulations currently under approval or to refine the calculations for new census polygons in development. Further applications of the TUEI calculation with the new methodology applied in this work could involve comparisons with calculations made by regions at the municipal level. This would allow for an assessment of the actual capacity of the urban wastewater system and existing agglomerations at a level of detail never previously investigated.

References

BARBIERO G. 2003. *Il metodo dei coefficienti "zonali" per la valutazione del carico inquinante potenziale industriale nelle diverse aggregazioni territoriali*. Roma: CNR Istituto di Ricerca sulle Acque IRSA.

CONSIGLIO DELLE COMUNITA’ EUROPEE. Direttiva 91/271/CEE del Consiglio, del 21 maggio 1991, concernente il trattamento delle acque reflue urbane. Bruxelles. Gazzetta Ufficiale delle Comunità Europee, N. L 135/40 del 30/05/1991.

EUROPEAN ENVIRONMENT AGENCY. 2019. *Urban wastewater treatment for 21st century challenges*. https://www.eea.europa.eu/publications/urban-waste-water-treatmentfor/urban-waste-water-treatment

HALLEUX V. 2023. Urban wastewater treatment. *Updating EU rules*. European Parliamentary Research Service.
ISTITUTO NAZIONALE DI STATISTICA. 2009. Stima del carico inquinante delle acque reflue in termini di abitanti equivalenti - Nota metodologica.
ISTITUTO NAZIONALE DI STATISTICA. 2011. Matrici di pendolarismo – Tavole di dati. Matrice origine-destinazione degli spostamenti per motivi di lavoro o di studio rilevata al 15° Censimento generale della popolazione (data di riferimento: 9 ottobre 2011). https://www.istat.it/non-categorizzato/matrici-di-contiguita-distanza-e-pendolarismo/
ISTITUTO NAZIONALE DI STATISTICA. 2021. Capacità degli esercizi ricettivi. https://www.istat.it/scheda-qualita/capacita-degli-esercizi-ricettivi-2/
ISTITUTO NAZIONALE DI STATISTICA. 2022. Classificazione dei Comuni in base alla densità turistica come indicato dalla Legge 17 luglio 2020, n. 77, art. 182- Nota metodologica e tavole di dati. https://www.istat.it/classificazione/classificazione-dei-comuni-in-base-alla-densita-turistica/
ISTITUTO NAZIONALE DI STATISTICA. 2023. Popolazione presente in "Glossario Statistico" in https://www.istat.it/classificazioni-e-strumenti/glossario/
RAMBERTI S., BALDONI T., TERSIGNI S. 2022. Censimento delle acque per uso civile 2020 – Tavole di dati. Istat 29 dicembre 2022. https://www.istat.it/tavole-di-dati/censimento-delle-acque-per-uso-civile-anno-2020/#:~:text=Il%20volume%20di%20acqua%20prelevato,modesta%20(%2D0%2C4%25).
UNESCO. 2024. The United Nations World Water Development Report 2024: water for prosperity and peace. Paris. https://unesdoc.unesco.org/ark:/48223/pf0000388948

Stefano TERSIGNI, Istat, tersigni@istat.it
Valerio ADOLINI, Istat, adolini@istat.it
Francesco ISIDORI, Istat, isidori@istat.it