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STEPGRAD
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FROM WASTE TO RESOURCE: BIOGAS PRODUCTION FROM BLACKWATER THROUGH DECENTRALIZED URBAN PLANNING MODELS

Abstract:

Blackwater, the wastewater stream with the highest sanitary and energy load, is increasingly seen as a resource within circular urban systems. This paper explores its valorization through anaerobic digestion and decentralized planning. Using Banja Luka as a case study, key energy, economic, and spatial thresholds for local treatment feasibility are defined. GIS-based analysis and a university campus pilot confirm that building aggregation enables functional clusters. Results show that demographically balanced, spatially compact zones hold the greatest potential. The cluster model proves optimal for integrating blackwater into sustainable urban systems. This reframes blackwater as a resource linking sanitation, energy, and planning.

Keywords: blackwater, anaerobic digestion, GIS analysis, urban infrastructure, clusters

ЕНЕРГЕТСКИ ПОТЕНЦИЈАЛ ЦРНЕ ВОДЕ: МОГУЋНОСТИ ЛОКАЛНЕ ПРОИЗВОДЊЕ БИОГАСА КРОЗ ДЕЦЕНТРАЛИЗОВАНЕ КЛАСТЕРЕ

Сажетак:

Црна вода, ток отпадних вода са највећим санитарним и енергетским оптерећењем, све више се препознаје као ресурс у оквиру кружних урбаних система. Овај рад истражује њену валоризацију кроз анаеробну дигестију и децентрализоване приступе у управљању. На примјеру Бање Луке дефинишу се кључни енергетски, економски и просторни прагови изводљивости локалне обраде. ГИС анализа и пилот-студија универзитетског кампуса показују да обједињавање објеката омогућава формирање функционалних кластера. Резултати указују да највећи потенцијал имају демографски уједначене и просторно компактне зоне. Кластер модел се потврђује као оптималан за интеграцију црне воде у одрживе урбане системе. На тај начин црна вода се редефинише као ресурс који повезује санитарну инфраструктуру, енергетику и урбано планирање.

Кључне ријечи: црна вода, анаеробна дигестија, ГИС анализа, урбана инфраструктура, кластери

1. INTRODUCTION

Research in the field of sustainable urbanism has shown that the green structure of a city is not merely an aesthetic or recreational element, but a crucial regulator of climate conditions and a carrier of long-term ecological processes [1]. This opens up space for rethinking the city and architecture through broader ecosystem dimensions, where natural flows become active shaping and functional factors [2]. Within this framework, water is recognized as an element whose presence and transformation have multiple spatial, ecological, and energy implications [3]. The concept of wastewater as a resource gains particular significance, shifting the focus from traditional approaches of removal and neutralization toward its reintegration into the cycles of matter and energy [4]. The central research question thus arises: under what conditions does wastewater cease to be waste and become a resource?

The answers to this question can be traced through different flows. Stormwater (rainwater) demonstrates its value at the architectural level, shaping space and materiality through retention and infiltration systems [5]. Greywater (tap/shower water) creates a direct link between a building and the geobiological characteristics of the site, since local biological treatment requires consideration of soil and vegetation capacities [6]. Blackwater (fecal wastewater), unlike these flows, carries the highest sanitary risk, but also the greatest potential. Blackwater (toilet wastewater) differs from greywater (kitchen and bathroom water without feces) in both chemical composition and its potential for energy conversion [7], [8].

This paper therefore positions blackwater as a specific flow which, although not a primary energy source, achieves measurable and renewable energy potential through anaerobic digestion. Its analysis goes beyond the scale of individual buildings and their immediate surroundings, requiring planning at the block or neighborhood level, within clusters. Using QGIS tools, the study analyzes how population density, spatial scope, and system size influence the sustainability of local blackwater treatment. In this way, blackwater is not seen as an end-product, but as a starting point for designing decentralized and sustainable urban networks.

2. REFRAMING BLACKWATER: FROM WASTE TO RESOURCE

2.1. BLACKWATER AS A WASTE

The dominant model of wastewater management in cities is based on a linear disposal principle: collection, conveyance, and discharge. In contrast, contemporary approaches rooted in circular economy principles and renewable resources recognize blackwater as a local resource with energy potential. The wastewater disposal system in Banja Luka faces significant infrastructural and environmental challenges. As shown on the accompanying map (Figure 1), watercourses and numerous discharge points (marked in red) clearly indicate a high level of untreated wastewater being released into receiving bodies. According to data from Vodovod A.D. Banja Luka, only about 60% of the population is connected to an organized wastewater collection system, while a significant portion of households remains unconnected to the central sewer network [9]. This points to highly uneven service coverage, creating spatial and social inequalities in access to basic communal infrastructure. Moreover, the city lacks a centralized wastewater treatment facility that processes the entire wastewater flow, and there is no pre-treatment of industrial effluents by commercial entities.

The sewer network in Banja Luka is predominantly constructed as a combined system, meaning that both fecal and stormwater flows are conveyed through the same infrastructure. In urban areas, such systems often lead to overload during heavy rainfall events, causing large volumes of mixed water to overflow without any treatment. This results in elevated concentrations of suspended solids, nutrients (nitrogen, phosphorus), and microbial pollutants in rivers and streams, with direct negative impacts on surface water quality, biodiversity, and public health [10], [11].

The map of wastewater discharge points clearly illustrates the spatial logic of the existing sewer system. The central area corresponds to the city's dense urban fabric, while numerous discharge points of the combined system are located along the periphery, near watercourses. This distribution confirms that the city's system was primarily designed to rapidly divert wastewater away from central zones, effectively relocating the pollution problem rather than solving it. The urban core is thus relieved of immediate burden, while downstream ecosystems absorb the cumulative impact. This creates a stark imbalance: the city becomes drained and dehydrated, while natural systems downstream are exposed to intense ecological pressure. This pattern reflects the classic infrastructural logic of combined sewer systems, a linear network that collects all flows and channels them toward the nearest recipients without prior separation or treatment.

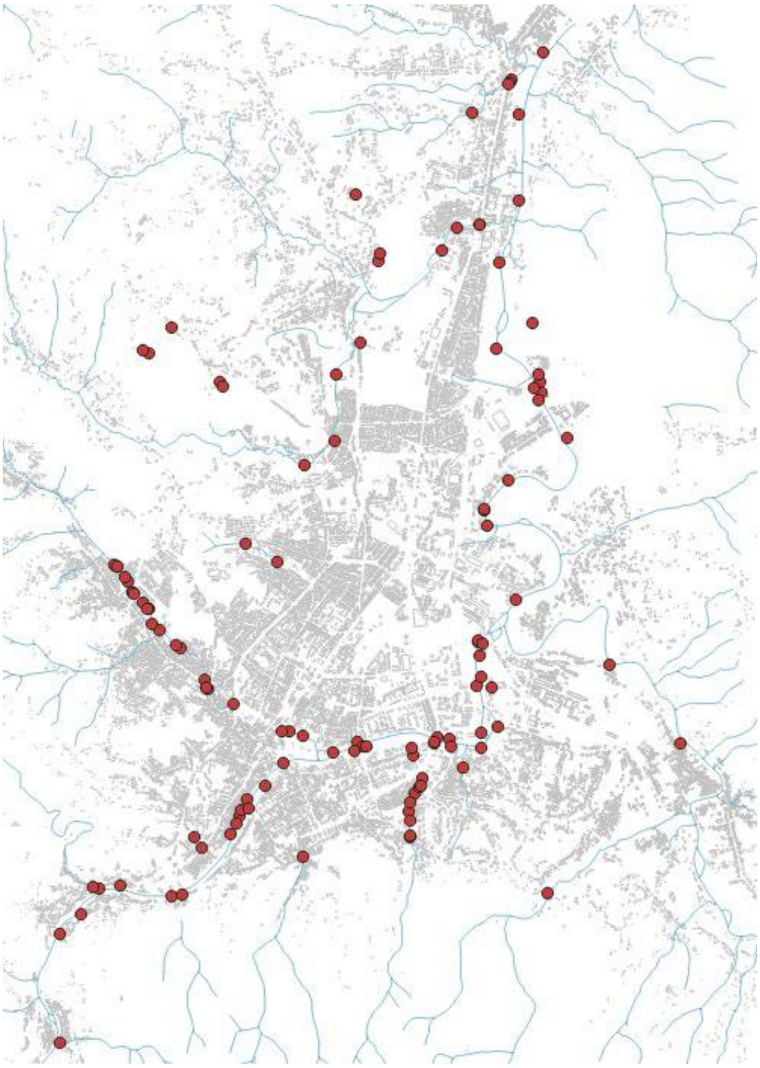


Figure 1. Existing system with direct wastewater discharges into watercourses (red dots = discharge points). Source: authors' elaboration using GIS spatial analysis in QGIS.

The result is continuous strain on aquatic ecosystems along the city's edges, raising critical questions about the sustainability of such a model under contemporary environmental protection demands [10], [12]. Such spatial dispersion poses a particular challenge for centralized treatment: fragmented flows require additional infrastructure for collection, aggregation, and transport, significantly increasing costs and energy demand. Simultaneously, the dispersion leads to uneven ecological impacts, as different discharge points receive varying concentrations of organic pollutants and nutrients. In this regard, the current combined sewer model is not only environmentally risky but spatially inefficient, complicating future centralized interventions and highlighting the need for alternative, adaptive wastewater management solutions [11].

The only existing treatment facility, located in the Zeleni Vir neighborhood, has a capacity of just 500 population equivalents (PE), which is negligible compared to the city's needs, with over 200,000 residents [9]. With such minimal coverage, the system remains fundamentally linear, managing waste without achieving energy efficiency or resource recovery.

Therefore, the existing system in Banja Luka can be described as underdeveloped in infrastructure, environmentally hazardous, and misaligned with regulatory standards. Instead of a functional and integrated wastewater management system, the city currently operates on a model of partial coverage and dispersed direct discharges. This foundation presents significant challenges for sustainable urban development, especially in light of modern insights that recognize wastewater not only as a burden to be managed, but as a resource to be valorized. Consequently, the following chapters focus on blackwater as a distinct flow whose potential opens opportunities for rethinking planning and design approaches to urban resource management.

2.2. BLACKWATER AS A RESOURCE

Previous research has shown that architectural planning based on resource circulation cannot rely on a single linear wastewater flow, but must instead differentiate between streams according to their composition and reuse potential. Stormwater, when collected using appropriate coefficients and spatial integration, has proven to be a renewable source of technical water. Greywater, due to its lower organic and microbial load, allows for localized biological filtration and recycling within closed cycles. In this way, even at the scale of individual buildings or parcels, it is possible to significantly relieve infrastructure systems and reduce potable water consumption for non-hygienic purposes. In this scenario of separation, blackwater remains as the flow with the highest sanitary, nutrient, and energy load. It consists of a mixture of fecal matter and toilet flush water, with a chemical oxygen demand (COD) ranging from 4,000 to 8,000 mg/L, several times higher than that of combined sewer systems [7]. This high organic matter concentration makes blackwater particularly suitable for energy recovery through microbial degradation in anaerobic conditions.

Unlike other renewable energy sources, whose availability depends on weather conditions (e.g., solar or wind energy), blackwater provides a stable and predictable yield because it is directly linked to daily human activities and population size. Its valorization has dual significance: untreated, it poses a serious pollution threat; treated, it becomes a source of energy and nutrients [4], [13]. Despite this potential, blackwater valorization requires specific infrastructural and technical conditions. Chief among them is the separation of blackwater from other flows (greywater and stormwater). This can be achieved through separate sewer networks, vacuum or low-flush toilet systems, and urine-separating toilets. These technologies help preserve the concentration of organic matter and reduce water volume, thereby significantly improving digestion efficiency [7], [8]. In practice, blackwater is processed using various types of digesters, selected based on the amount of available substrate, number of users, and technical-spatial conditions. Technologies range from large centralized reactors to decentralized solutions located at the block, parcel, or building level. Moreover, in cases of low daily inflow or when a higher energy yield is desired, blackwater can be co-digested with other organic waste streams such as food, kitchen, or green waste [14], [15]. In addition to biogas, anaerobic digestion produces digestate, a stabilized by-product rich in nitrogen and phosphorus, which can be used as fertilizer in agriculture or as a soil amendment in urban green infrastructure [10], [11], [12], [16]. This closes the loop between water, energy, and soil, transforming blackwater treatment from a technical process into a component of integrated urban metabolism. Such an approach demands that blackwater no longer be treated merely as a disposal issue, but rather as an input into the renewable resource system. However, to make this valorization feasible in practice, it is necessary to define the operational thresholds and boundary conditions under which digesters can function effectively. These thresholds (energy, economic, and spatial) form the foundation for the following chapter.

2.3. STANDARDS AND EFFICIENCY THRESHOLDS

The use of blackwater as a resource is regulated by both international and national standards. The European Union, through the Urban Wastewater Treatment Directive (91/271/EEC, revised in 2022), sets stricter requirements for treatment and reduction of direct discharges into receiving waters [12]. The U.S. Environmental Protection Agency (EPA), through its guidelines for large-capacity septic systems, defines minimum sanitary and energy criteria [11], while ISO 30500 establishes technical and hygiene standards for decentralized sanitation systems not connected to a public sewer network. Based on the literature, three key thresholds can be identified: energy, economic, and spatial, where the spatial threshold is a spatial manifestation of the first two.

The energy threshold represents the minimum amount of blackwater required for the stable and efficient operation of anaerobic digesters, typically expressed as daily blackwater inflow per person [17]. According to the literature, the technical lower limit for sustainable digester operation ranges from 15 to 20 liters of blackwater per person per day, which corresponds to an annual inflow of 5,500 to 7,300 m^3 for a system serving 1,000 population equivalents (PE). Below these values, the digestion process becomes sensitive to fluctuations in substrate quantity and composition, leading to the accumulation of volatile fatty acids, reduced methane yield, and a drop in overall energy efficiency [18], [19].

To maintain process stability under different spatial and demographic conditions, various digester types are used, with capacities defined by the daily blackwater inflow and the number of users. In large, centralized facilities, Continuous Stirred Tank Reactors (CSTR) are commonly used, operating optimally with daily inflows of 30–50 m^3 of blackwater, which corresponds to a load of 1,500–2,500 PE [17]. In decentralized systems and smaller zones, Upflow Anaerobic Sludge Blanket (UASB) reactors are used, with capacities of 10–30 m^3/day, or 500–1,500 PE, offering lower energy consumption and compact construction [20], [21]. In systems with lower blackwater inflows, dry digestion technologies are increasingly applied, combining blackwater with biodegradable waste (e.g., food, kitchen, or green waste), allowing stable operation and higher energy yield with typical combined capacities of 15–40 m³/day [14], [15].

The average energy content of biogas produced from blackwater digestion ranges from 8 to 20 kWh/m³, depending on substrate composition, temperature, and degree of stabilization [8]. These values form the basis for assessing energy production potential in relation to digester capacity and population served. Systems with lower inflows must often be supplemented by co-digestion to ensure stability and adequate methane production [15].

The economic threshold refers to the cost-effectiveness of investing in relation to the number of users and amount of available resource. According to the literature, the financial viability of anaerobic digesters strongly depends on scale. Some sources indicate that systems can become economically feasible at a population equivalent of 5,000–10,000, especially in rural or semi-urban contexts where transport and infrastructure costs are lower [20]. In urban settings, however, this threshold is significantly higher due to more complex investment and operational costs. In such cases, literature suggests stable and positive returns are achieved only at scales of 10,000–15,000 PE [17], [20], [21].

According to WHO (2006) and EPA (2012) guidelines, blackwater collection zones should not exceed a distance of 200–500 meters from the furthest building to the collection system to reduce loss and leakage risks. In the eco-sanitation literature, Jönsson et al. (2005) emphasize that decentralized clusters should consist of small spatial units (blocks or building groups) to ensure inflow stability and substrate quality. Conversely, Metcalf & Eddy (2014) report that blackwater transport via pipelines becomes significantly more expensive beyond 1–2 km, setting this as the upper economic limit of the collection area. Research in semi-urban areas by Hernández-Chover et al. (2025) defines optimal cluster sizes as 5,000–10,000 PE, which in practice corresponds to a collection area of several hundred meters up to 1 km², depending on residential density.

Based on these sources, the optimal cluster distance ranges between 200 meters and 1 km, while the optimal spatial coverage depends on context: smaller clusters (blocks or building groups) are appropriate in dense urban zones, whereas in lower-density areas, clusters may span up to 1–2 km². As shown in Table 1, there is no fixed universal value, cluster sizing is determined through a balance between energy content, transport limitations, inflow stability, and investment cost-efficiency.

Table 1. Technical and Spatial Parameters for Blackwater Digester Planning

Parameter	Value	Source
Minimum blackwater quantity	15–20 L/person/day (~5,500–7,300 m³/year for 1,000 PE)	Jönsson et al. (2005); Jia et al. (2023)
Energy content of biogas	8–20 kWh/m³	Hamawand et al. (2023)
CSTR capacity (medium to large clusters)	30–50 m³/day (>5,000 PE)	Metcalf & Eddy (2014)
UASB capacity (decentralized, small to medium zones)	10–30 m³/day (≈500–1,500 PE)	Hernández-Chover et al. (2025)
Dry digestion (co-digestion)	15–40 m³/day (combined with biodegradable waste)	Guo (2014); Wen et al. (2022)
Economic feasibility (rural context)	5,000–10,000 PE	Hernández-Chover et al. (2025)
Economic feasibility (urban context)	10,000–15,000 PE	Metcalf & Eddy (2014)
Recommended collection distance	200–500 m (max. 1–2 km)	WHO (2006); EPA (2012); Metcalf & Eddy (2014)
Optimal spatial coverage (clusters)	Block / urban quarter (up to 1 km²)	Jönsson et al. (2005); Metcalf & Eddy (2014)

While energy and economic thresholds are clearly grounded in existing literature and standards, the spatial threshold remains insufficiently defined. If blackwater is perceived as waste, planning is focused on its rapid removal and neutralization. However, if blackwater is recognized as a resource, the entire system must be designed differently: spatial dimensions, infrastructure coverage, and the logic of urban development must all be shaped by the boundaries of its resource potential.

This implies that blackwater is no longer a by-product to be removed, but a flow that generates new collection centers, new networks, and new relationships among urban built zones. In this way, blackwater thresholds become not only indicators of energy or economic feasibility but criteria for shaping the city as a metabolic system.

This raises a crucial question: What do planning and design look like when wastewater becomes the starting point, not the leftover, of urban development?

2.4. METHODOLOGICAL FRAMEWORK

developed that quantifies and spatially models the production of this flow based on demographic structure and the physical characteristics of space. Instead of treating wastewater as an end-product to be disposed of, the method relies on identifying sustainability energy, economic, and spatial thresholds and applying them as criteria for planning. In doing so, it establishes a link between human activity, spatial organization, and the feasibility of localized treatment, thus opening space for rethinking infrastructure and planning decisions.

The starting point of the research is population size and residential density, as spatial users represent the primary source of blackwater generation. Unlike stormwater or greywater, whose quantities may vary with climate conditions or building function, blackwater is produced independently of land use and is directly proportional to the number of users. This places the demographic component as the key parameter of resource potential, in order to examine the spatial conditions and dependencies that determine whether a flow remains fragmented or becomes consolidated enough to function as a resource.

The methodology then defines three core threshold categories: energy, economic, and spatial. To test these thresholds in a spatial context, the methodology includes multi-scalar analysis at the levels of individual buildings, pilot clusters, and the city (via GIS analysis). Finally, the results are synthesized through visualization and interpretation, enabling an understanding of the conditions under which blackwater ceases to be waste and becomes a planning resource for sustainable system design.

The methodology is based on a combination of quantitative and spatial analyses, following these steps:

- User identification, determining the number of users in buildings and zones (using statistical data).
- Blackwater production calculation, applying predefined coefficients and correction factors.
- Threshold comparison, evaluating whether individual buildings, pilot clusters, and city zones reach the previously defined thresholds.
- GIS analysis, mapping the spatial distribution of blackwater and connecting it to administrative, infrastructural, and construction boundaries.
- Spatial threshold evaluation, analyzing the relationship between user density and coverage size (building – campus – city).

This sequential approach enables the progressive construction of an analytical framework, in which quantitative data on blackwater production is translated into spatial insights via GIS. The results of each step are interrelated and lead toward defining sustainability thresholds, building an integrated model for assessing the spatial potential of localized treatment systems. The following diagram (Figure 2) illustrates the methodological flow of the research, from input data to interpretation of results across different spatial scales.

In the context of contemporary theories on urban metabolism and circular resource management, the diagram presents a methodological structure that connects quantitative indicators with the spatial dimensions of planning. This methodology thus provides a systematic framework for transitioning from theoretical values to spatial scenarios, clearly identifying the conditions under which blackwater ceases to be waste and becomes a resource. It enables not only the evaluation of existing urban conditions, but also the planning of future interventions aligned with sustainability principles. At the same time, this approach facilitates the integration of sanitary, spatial, and energy parameters into a unified analytical model tailored to the complex demands of contemporary urban planning.

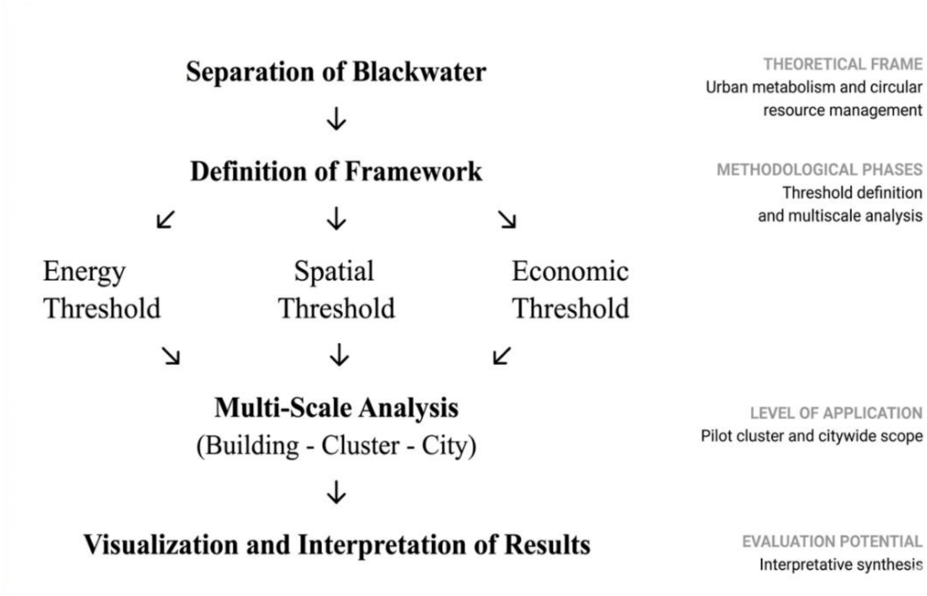


Figure 2. Methodological Framework of the Study. Quantification of Blackwater and Definition of Spatial Conditions through Multi-Scale Analysis. Source: authors' conceptual diagram.

3. UNIVERSITY CAMPUS AS A PILOT CLUSTER

spatial conditions, a university campus was selected as a pilot cluster. The campus represents a spatially well-defined unit with a high concentration of educational and administrative buildings, a homogeneous user structure, and stable daily occupancy patterns. This configuration allows for a realistic assessment of blackwater generation and its potential for energy valorization, in comparison with literature-defined thresholds that determine the feasibility of localized treatment systems.

Thus, the campus is viewed not merely as a collection of individual buildings but as an integrated unit, a functional cluster in which resource aggregation can provide the critical mass required for stable anaerobic digestion.

For this model, the quantity of blackwater is estimated based on the assumed number of toilet uses during working hours. While some standards (e.g., WHO, EPA) indicate that an individual uses the toilet 4–7 times within 24 hours, a conservative assumption of 3 uses per person per day was adopted for the working hours context of a university campus. With a standard flush volume of 6 liters per use and 215 working days per year, the annual blackwater production per person is calculated as follows:

$$V_{person}=3\times6\times215=3{,}870 \text{ L/year}\approx3.87 \text{ m3/year} \quad (1)$$

This results in an average daily blackwater production of 18 L/person/day, which is more realistic for public and university buildings than the commonly used abstract value of 40 L/person/day. This estimate reflects actual time spent in the building and is considered a conservative model. Moreover, these figures would be even lower if low-flush toilets (e.g., 4–4.5 L per flush) were applied, in line with current recommendations. Thus, the resulting energy and water balances provide a conservative baseline, while the adoption of modern sanitary technologies would further reduce overall blackwater volume and improve system sustainability.

However, these calculations represent only the theoretical potential based on the volume of blackwater produced. In practice, the actual yield of anaerobic digestion depends significantly on the organic matter concentration. Diluted blackwater, resulting from higher flushing volumes, reduces the chemical and biological loading of the digester, leading to weaker and less efficient biogas production. In contrast, low-flush toilets, although reducing total volume, produce a more concentrated blackwater stream, enabling more stable operation and higher yield per unit volume.

As such, the overall energy potential does not decrease in direct proportion to blackwater volume. Based on the average number of users per building and the adopted standard model, the annual quantity of blackwater produced was calculated. The results are presented in Table 2.

Table 2. Quantification of Blackwater in University Campus Buildings. Annual Production and Average Daily Inflow

No.	Building	Number of Users (Staff + Students)	Blackwater Production (m^3/year)	Daily Inflow (m^3/day)
1	Rectorate	109	421.83	1.16
2	Academy of Arts	567	2194.26	6.01
3	Faculty of Architecture, Civil Engineering and Geodesy	726	2809.52	7.70
4	Faculty of Medicine – Main Building	527	2039.49	5.59
5	Faculty of Agriculture	255	986.55	2.70
6	Faculty of Physical Education and Sport	394	1523.18	4.17
7	Faculty of Philosophy	517	1993.83	5.46
8	Faculty of Forestry	561	2173.47	5.96
9	Faculty of Philology	575	2227.65	6.10
10	Faculty of Natural Sciences and Mathematics	570	2207.37	6.05
	TOTAL	4803.00	18,587.61	50.92

Note: Number of users per building for 2024 provided by the University of Banja Luka.

The results show that none of the analyzed buildings individually reaches the minimum blackwater volume required for the stable operation of a digester. The largest facility (AGGF) produces approximately 2,800 m^3/year (7.7 m^3/day), which is significantly below the lower technical threshold. This confirms that the individual-building approach is unsustainable in the observed context, and that spatial aggregation into a larger unit is necessary. When considered collectively, the university campus produces around 18,600 m^3/year (≈ 51 m^3/day), exceeding the minimum and approaching the upper operational threshold. This provides a solid basis for forming a functional pilot cluster.

Although blackwater holds significant energy potential, its full capacity is rarely harnessed in practice. The efficiency of anaerobic digestion typically ranges between 60–80% of the theoretical maximum, depending on technical and biological parameters such as temperature, pH, retention time, and organic matter concentration [7], [8]. Additionally, the use of standard toilet systems with 6 L flush volumes dilutes the blackwater stream, reducing the concentration of useful matter. However, this can be mitigated with modern separation systems that retain highly concentrated blackwater, better suited for digestion. Based on the pilot location data and using a conservative estimate of 10 kWh/m^3 energy content and 60% digestion efficiency, the total thermal energy potential (prior to conversion) of raw biogas is calculated as:

$$50.92 m^3/day \times 10 kWh/m^3 \times 0.6 = 305.5 kWh/day \quad (2)$$

Annually, this equals approximately 111,500 kWh, representing the gross energy potential of raw biogas prior to its conversion into usable forms. The final energy form (thermal, electrical, or combined) depends on user needs and system efficiency. This result confirms that, even under conservative conditions, the pilot cluster possesses measurable capacity to support the energy self-sufficiency of at least one infrastructure segment of the campus. To support this inflow (≈ 51 m^3/day), a digester would require a working volume of 500–800 m^3 based on a hydraulic retention time (HRT) of 10–15 days. This fits within the UASB reactor range for medium-sized systems [20]. Moreover, the compactness of the campus ensures a collection radius under 500 m, satisfying WHO and EPA guidelines for sanitary and technical feasibility [11], [16].

The system also shows operational resilience during non-working days, as reduced inflows could be stabilized via co-digestion with biowaste from the campus landscape. According to the Maintenance Rulebook of the Protected Area of the University of Banja Luka (2021), regular activities include lawn mowing, pruning, leaf collection, and biowaste management [22]. This confirms the presence of a continuous source of organic waste within the campus, strengthening the cluster's capacity for co-digestion and ensuring operational stability even during lower blackwater production periods. The performance indicators presented in Table 3 confirm that the pilot cluster exceeds the energy threshold, while also meeting spatial and economic criteria defined by existing standards. Therefore, the university campus can be considered a representative model for testing decentralized blackwater management systems in urban conditions.

Table 3. Summary Indicators and Calculated Metrics for Spatial Analysis

Indicator	**Value**
Cluster Area	27 ha
Number of Users	4,803
Total Blackwater Generation	18,587.61 m^3/year
Average Daily Inflow	50.92 m^3/day
Blackwater Generation per Hectare	688 m^3/ha/year
User Density	178 users/ha
Collection Distance	< 500 m

The analysis of the pilot cluster served as a testing unit for validating the previously defined thresholds: energy, economic, and spatial distribution. Within a clearly defined area characterized by high user density and infrastructural connectivity, these thresholds were tested and brought into functional correlation. The pilot cluster analysis confirmed three key aspects outlined in the earlier methodological framework:

- The energy threshold was exceeded due to a stable daily inflow per user and per building;
- The economic threshold, defined by collection distance, was met as the distance between buildings was less than 500 meters;
- The spatial threshold was validated through user density and the homogenous structure of the site.

Although functioning under ideal conditions, this model is not proposed for direct scaling, but rather to highlight the resource potential that remains invisible within the existing linear system. In conventional combined sewer systems, blackwater is treated solely as waste; however, the cluster analysis shows that, when spatially and infrastructurally integrated, it becomes a quantifiable resource. Based on these findings, the next phase of research shifts to the broader urban context, aiming to identify zones where similar conditions already occur spontaneously, even though they are neither recognized as coherent units nor valorized as resources under the current system.

4. PRODUCTION THRESHOLDS IN URBAN CLUSTERS

The previous chapters defined the energy, spatial, and economic thresholds and validated their operational relevance through the pilot cluster analysis. This chapter shifts focus to a spatial model of blackwater potential across urban planning zones, aiming to identify clusters as functional spatial units where blackwater production reaches the thresholds at which valorization becomes feasible, yet remains unrecognized within the current linear infrastructure system.

The analysis is based on combined spatial and demographic datasets from the following sources:

- Population density data obtained from the WorldPop (2025) high-resolution raster dataset;
- Building zones and watercourses provided by the City Administration of Banja Luka, based on current urban planning documentation;
- Sewer network and settlement data supplied by the Republic Administration for Geodetic and Property Affairs (RUGIPP).

This combination of data sources enabled the integration of demographic, spatial-functional, and infrastructural parameters into a unified model for estimating blackwater distribution and potential by urban zone.

A threshold of 6,000 m^3/year per cluster was established as the lower limit for selecting zones with a realistic capacity for energy valorization. This volume corresponds proportionally to a cluster of approximately 900 population equivalents (PE), in line with literature citing a technical minimum of 5,500–7,300 m^3/year for 1,000 PE as necessary for stable digester operation. Therefore, the 6,000 m^3/year threshold is validated as a functional criterion, equivalent to a daily blackwater output of approximately 18.3 liters per person, within the recommended range of 15–20 L/day/PE.

Blackwater potential was quantified by combining demographic and spatial data within a GIS environment using two complementary analytical approaches:

- Zonal analysis, based on interpolating the number of residents within officially defined building zones, was used to estimate the total annual blackwater production per zone. This method allowed for the calculation of the total number of potential clusters, based on the defined 6,000 m^3/year threshold.

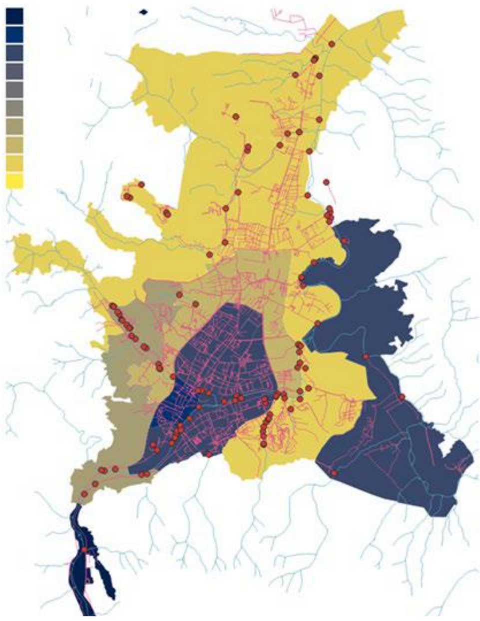
- Grid-based (network) analysis, in which spatial units were formed as polygons based on a target of 900 residents per unit, the minimum required for a sustainable digester system. Depending on the surface area within which this population was reached, the units were categorized into three size groups: up to 1 km², less than 2 km², and greater than 2 km². This gradation enabled the spatial threshold to be assessed not only quantitatively but also in terms of territorial compactness and infrastructural feasibility.

Through this dual approach, the zonal analysis provides insight into cumulative capacities and the total number of eligible clusters, while the network analysis delivers information about spatial distribution and unit classification based on density and area. Together, these methods further reinforce the applicability of the model at the urban scale.

4.1. ZONAL ANALYSIS DISCUSSION

The cartographic representation shows that the quantity of blackwater, as an energy potential, is not evenly distributed across space, but depends on a combination of population density and the surface area of building zones. It is important to emphasize that the number of discharge points into watercourses (red dots on the map) does not necessarily indicate greater quantities of available resources. In the inner city area, where population density is highest, the amount of blackwater is relatively lower because the zones themselves are small in size. In contrast, Zone 2 covers a larger area and therefore accumulates much greater quantities of resources, not due to higher population density, but due to the size of the territory it covers. Zones with larger surface areas achieve significantly higher total values, even though their population densities are lower. This confirms that the area of a zone and the number of users within its boundaries are the key parameters determining the overall energy potential.

To understand the territorial distribution of blackwater potential in the urban area of Banja Luka, spatial mapping of annual blackwater production and the estimated number of potential energy clusters per building zone was conducted. The results are presented in combination, through a cartographic visualization and a tabular overview (Figure 3), where each zone is represented by several parameters: total annual blackwater production, estimated number of clusters, zone area (in hectares), and production intensity expressed in m³/year/ha.



Zone (ID)	Blackwater production (m³/year)	Number of clusters	Zone area (ha)	Intensity of BW production m³/year/ha	LEGEND
4	312,08	0,05	1,416	220,4	
4	5.715,90	0,95	216,279	26,4	
1	12.926,48	2,15	69,308	186,5	
0	31.284,15	5,21	169,452	184,6	
1	32.620,05	5,44	177,494	183,8	
2	35.335,65	5,89	244,889	144,3	
4	40.586,18	6,76	1079,282	37,6	
3	45.590,33	7,60	481,932	94,6	
2	77.564,33	12,93	505,686	153,4	
3	102.524,85	17,09	1054,461	97,2	
4	103.351,58	17,23	1776,206	58,2	

Figure 3. GIS-Based Cartographic Visualization and Tabular Representation of Blackwater Potential by Number of Possible Clusters. Source: authors' elaboration using GIS spatial analysis in QGIS.

The table on the right side of the figure provides a systematic overview of key parameters for each analyzed zone: total blackwater production, number of potential clusters (based on the 6,000 m³/year threshold), zone area, and production intensity per unit area (m³/year/ha). Based on the presented results, several important conclusions can be drawn:

- The zones with the highest total blackwater production are part of Zone 4 (103,351.58 m³/year) and part of Zone 3 (102,524.85 m³/year), enabling the formation of the largest number of clusters, up to 17.23 and 17.09. These values confirm that in these areas, a sufficiently high and stable inflow is achieved for energy valorization of wastewater through anaerobic digestion. However, the per-hectare intensity in these zones (58.2 and 97.2 m^3/year/ha) indicates that they are spatially extensive areas with moderate user density, implying the potential need for a more extensive collection infrastructure.

- In contrast, the highest resource intensity per unit area was achieved in small and compact zones: part of Zone 4 (220.4 m^3/year/ha) and Zone 1 (186.5 m^3/year/ha). Although the total volumes of blackwater in these zones are not dominant, the high population density in a small area indicates extremely favorable conditions for localized collection and valorization, with minimal need for spatial expansion of infrastructure. These cases confirm the importance of spatial compactness as one of the key factors for achieving the economic threshold.
- Mid-sized and medium-density zones (e.g., Zones 2 and 0) achieve balanced values, in terms of both total volume and intensity. This balance makes them especially suitable for planning modular systems that can combine infrastructure efficiency with stable inflow.
- The lowest production is found in a small part of Zone 4, with an area of less than 1.5 ha and only 312 m^3/year, which is nowhere near sufficient for forming a self-sustaining cluster. This confirms that small and isolated zones without significant population density do not represent rational units for energy utilization of blackwater, unless combined with a larger area.

Graphical representation (left side of the image) visually reinforces these findings. The color indicates the number of possible clusters, the lighter the color, the higher the number of clusters, and thus the greater the total quantity of blackwater. This results in an intuitive map for identifying priority areas for the development of decentralized systems.

Based on the analysis shown in the table and map, a clear conclusion can be drawn regarding the relationship between zone area, total blackwater production, and the number of possible clusters.

Zones with larger surface areas (especially above 1,000 ha) generally accumulate greater total amounts of blackwater, not necessarily due to high population density, but because of the spatial coverage where the resource is accumulated in a dispersed manner. This is precisely why the largest quantities of blackwater and the highest number of potential clusters were recorded in zones 2, 3, and 4, where coverage exceeds 500 ha, and in some cases, over 1,000 ha. However, these zones also record lower values per hectare, meaning the user concentration is lower, but the spatial availability allows for resource aggregation and energy valorization.

In contrast, smaller zones with areas under 100 ha (e.g., zone 1) may have high population density and therefore higher energy potential per unit area (expressed in m^3/year/ha), but they do not reach the thresholds for a stable cluster without additional aggregation with the surroundings. Larger areas compensate for lower density, while compact urban units make up for small size through high resource concentration. In this sense, the analysis of zone areas confirms that forming functional clusters does not depend on a single factor (e.g., number of users), but on their combination with spatial coverage. Such combinations enable more flexible system planning, especially in cities with spatially uneven population structures.

4.2. GRID-BASED (NETWORK) ANALYSIS DISCUSSION

After the analysis based on building zones and total blackwater production within them, clusters were identified based on population density, without relying on administrative or infrastructure boundaries. In this way, it is possible to independently identify functionally aggregatable spaces, starting from the basic demographic criterion, the number of 900 users, which represents the minimum needed for stable digester operation, according to previously defined energy thresholds.

For further analysis, areas were classified based on whether the 900 inhabitants are located within a surface area of:

- less than 1 km^2,
- between 1–2 km^2, or
- more than 2 km^2.

This allows a more precise examination of economic viability as a relationship between population density and the potential to form clusters, where high density can compensate for limited space, and broader territorial coverage can offset a lower number of users per hectare. This approach enables the identification of both compact urban areas with high density and more spacious but sparsely populated areas, where the threshold is nonetheless cumulatively met. The method thus overcomes the limitations of administrative boundaries and offers a more flexible model for determining clusters, aligned with the functional logic of urban metabolism. Therefore, to further validate the results and test spatial conditions for forming functional clusters, an analysis was conducted based on population density, independently from administrative and infrastructure divisions. This method made it possible to identify potential clusters exclusively based on the number of users per unit of area, eliminating the limitations associated with formal boundaries and providing a more realistic insight into the spatial distribution of resources. In Figure 4, two key steps of the analysis are shown. On the left, the existing discharge points into watercourses are mapped, serving as indicators of the problem of dispersed pollution and spatial fragmentation of waste streams. On the right, the modeled distribution of potential clusters based on population density is presented.

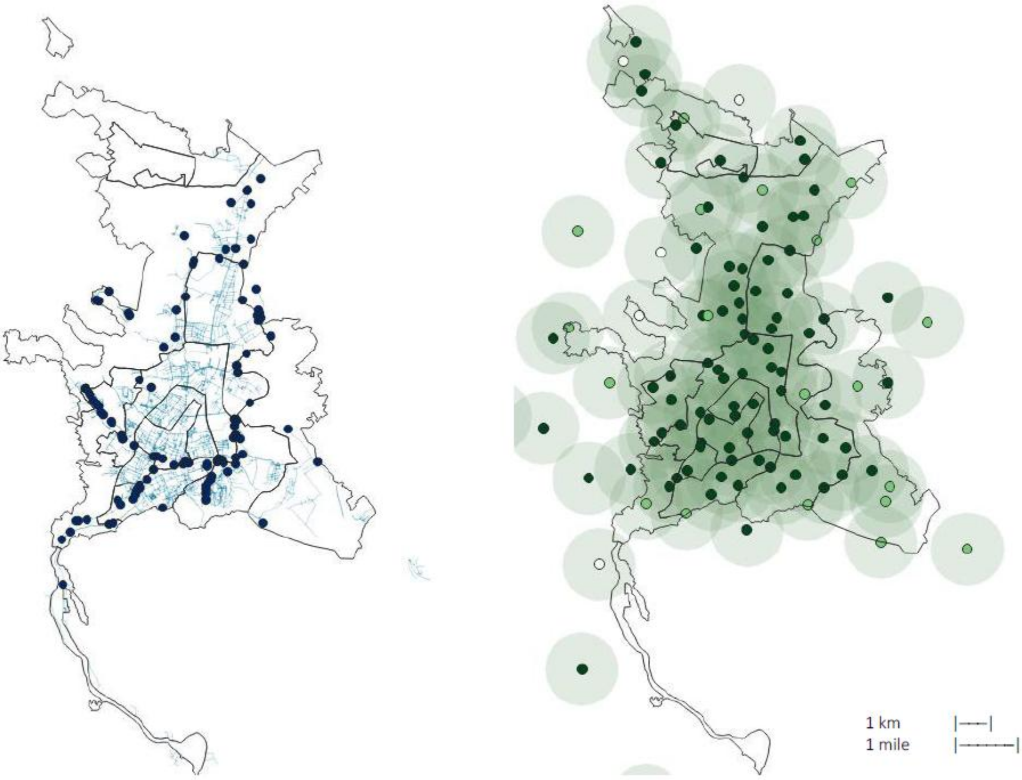


Figure 4. Spatial distribution of direct wastewater discharges into watercourses and sewer networks in Banja Luka (left). Spatial analysis of blackwater potential and catchment zones, decentralized cluster model (right). Source: authors' elaboration using GIS spatial analysis in QGIS.

Cluster centroids are represented in three classes according to their blackwater production potential relative to the minimum energy threshold. Dark green points indicate centroids where production exceeds the threshold, light green points denote units operating at the threshold level, while white points mark sub-threshold locations with insufficient resource concentration for independent system functioning. The larger semi-transparent circles illustrate the spatial catchment radius of each centroid, representing the potential collection distance and revealing areas of overlap where aggregation of neighbouring clusters may occur.

The spatial distribution clearly shows that many functional clusters correspond to densely populated zones, while additional potentials also emerge in peripheral parts of the city. These areas remained unrecognized in the previous method due to their position outside the public sewer network and the initially analysed building zones. By removing administrative and infrastructural boundaries, the analysis enables the identification of previously overlooked resource concentrations and emphasizes the importance of planning approaches based on user density and spatial functionality.

Beyond the identification of individual clusters based on the minimum energy threshold (≈6,000 m^3/year for 900 PE), the results also reveal the spatial occurrence of multiple cluster points within the inner urban core. Within a radius of up to 1 km^2, two or three centroids may occur in close proximity, creating opportunities for their integration into larger functional units with increased energy capacity, comparable to the pilot campus model (≈18,600 m^3/year).

Such spatial aggregation enhances flexibility in infrastructure planning and supports the rationalization of decentralized treatment systems through shared resource use. The findings suggest that the functional logic of circular wastewater management does not necessarily follow formal planning divisions, but can instead be structured around actual patterns of user concentration and resource availability. In this way, the analysis establishes a spatial basis for rethinking wastewater flows as an organizing component of urban metabolic systems.

5. CONCLUSION

This study demonstrates that blackwater, long treated solely as sanitary waste, possesses significant untapped potential to become a valuable energy and planning resource within the framework of contemporary urban metabolism. Through spatial analysis and quantitative modeling, a methodological framework was developed that enables the identification of functional clusters suitable for localized anaerobic digestion systems, offering an alternative to existing linear wastewater management models.

The established thresholds (energy, spatial, and economic) allowed for a multilayered evaluation of potential. The pilot cluster, based on a university campus example, validated all thresholds under real spatial conditions, even during periods of reduced flow, thanks to the possibility of co-digestion with bio-waste from the campus' green areas. This confirmed that high user density, stable daily inflow, and compact territorial organization are the foundation for technically and economically viable systems.

In the next phase, spatial analysis based on building zones and population density further confirmed locations with the capacity to form functional clusters. The dual method, based on zones and on density, produced a similar number of clusters, but the density-based method enabled the identification of additional potential beyond the existing sewer network.

Typical spatial planning parameters, population density and distance, already define the logic of city development: traffic flows, infrastructure layout, and access to public services. This study shows that these same factors become crucial in designing circular blackwater management. When density and distance are seen as metabolic rather than merely planning parameters, the flow of blackwater stops being a byproduct of the system and becomes an organizing principle for a new, decentralized infrastructure.

In conclusion, planning based on resource flows, rather than solely on administrative boundaries and existing linear infrastructure, opens up opportunities for regeneration, circular infrastructure, and localized production. These findings contribute to contemporary discussions on circular urban metabolism and localized energy production. This research focuses on spatial and energy feasibility conditions, while detailed techno-economic assessment and infrastructure implementation strategies remain subjects for future investigation.

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