Ambiente & Água - An Interdisciplinary Journal of Applied Science
ISSN 1980-993X – doi:10.4136/1980-993X
www.ambi-agua.net
E-mail: ambi.agua@gmail.com

Assessment of sediment grain size and hydraulic interactions in urban drainage systems: a case study from Juliaca, Peru

ARTICLES doi:10.4136/ambi-agua.3063

Received: 15 Feb. 2025; Accepted: 14 May 2025

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Editor-in-Chief: Nelson Wellausen Dias

ABSTRACT

Urban drainage systems are essential for the sustainability of cities, significantly impacting water management, pollution control, and urban planning. The city of Juliaca is characterized by a predominantly low slope, ranging from 0.0003 to 0.001 m m^{-1}, making it particularly susceptible to sedimentation processes within the existing drainage network. The objective of the research was to characterize the sediments in the stormwater drains and to assess the relationship between the granulometric properties and the hydraulic parameters of the drainage system. To achieve this, 12 sediment samples were collected from Zone D of Juliaca at the end of the rainy season and analyzed in the laboratory to determine the granulometric distributions and physical properties. Spearman's correlation coefficient was employed to establish the relationships between sediment characteristics and hydraulic parameters. The results revealed that the granulometric curves exhibited multimodal distributions. Sand was the predominant component in the samples, with an average content of 72.74%, followed by gravel at 21.36%, and silt and clay at 5.90%. The average particle size ranged from 0.159 to 2.132 mm. The drainage system was found to possess considerable hydraulic cross-sectional dimensions, with slope values ranging from 0.0004 to 0.031 m m^{-1}. The correlation analysis found both positive and negative relationships between particle-size distribution, sediment composition, and slope. However, these correlations were not entirely consistent with established sediment transport principles. This inconsistency is likely attributed to the influx of sediments into the drainage network from unpaved roads, driven by wash-off processes and surface erosion, among other contributing factors.

Keywords: critical velocity, granulometry, hydraulic parameters, unpaved roads, Urban drainage system

Avaliação do tamanho dos grãos de sedimentos e das interações hidráulicas em sistemas de drenagem urbana: um estudo de caso de Juliaca, Peru

RESUMO

Os sistemas de drenagem urbana são essenciais para a sustentabilidade das cidades, impactando significativamente a gestão da água, o controle da poluição e o planejamento urbano. A cidade de Juliaca é caracterizada por uma declividade predominantemente baixa, variando de 0,0003 a 0,001 m m^{-1}, tornando-a particularmente suscetível a processos de sedimentação dentro da rede de drenagem existente. O objetivo da pesquisa foi caracterizar os sedimentos nos drenos de águas pluviais e avaliar a relação entre as propriedades granulométricas e os parâmetros hidráulicos do sistema de drenagem. Para isso, 12 amostras de sedimentos foram coletadas da Zona D de Juliaca no final da estação chuvosa e analisadas em laboratório para determinar as distribuições granulométricas e propriedades físicas. O coeficiente de correlação de Spearman foi empregado para estabelecer as relações entre as características dos sedimentos e os parâmetros hidráulicos. Os resultados revelaram que as curvas granulométricas exibiram distribuições multimodais. A areia foi o componente predominante nas amostras, com um teor médio de 72,74%, seguido por cascalho com 21,36% e silte e argila com 5,90%. O tamanho médio das partículas variou de 0,159 a 2,132 mm. O sistema de drenagem apresentou dimensões transversais hidráulicas consideráveis, com valores de declive variando de 0,0004 a 0,031 m m^{-1}. A análise de correlação mostrou relações positivas e negativas entre distribuição do tamanho das partículas, composição do sedimento e declive. No entanto, essas correlações não foram totalmente consistentes com os princípios estabelecidos de transporte de sedimentos. Essa inconsistência é provavelmente atribuída ao influxo de sedimentos na rede de drenagem de estradas não pavimentadas, impulsionado por processos de lavagem e erosão da superfície, entre outros fatores contribuintes.

Palavras-chave: estradas não pavimentadas, granulometria, parâmetros hidráulicos, sistema de drenagem urbana, velocidade crítica.

1. INTRODUCTION

Urban drainage systems play a key role in ensuring the sustainability and flood resilience of cities (Zuñiga-Igarza, 2018; De Oliveira *et al.*, 2022). As fundamental components of urban infrastructure, these systems influence stormwater management, flood mitigation, and water quality preservation (Haarstrick and Sharma, 2024; Li *et al.*, 2019; McGrane, 2016). Efectiveness is largely dictated by the hydraulic characteristics within urban drains, which are influenced by various factors, including drainage network design, the physical properties of the drainage materials, and the surrounding environment conditions (Ghani *et al.*, 2008; Karamouz, 2021).

Urban drainage research encompasses diverse aspects, such as drainage system design and performance, stormwater runoff management, urban flood mitigation (Parkinson *et al.*, 2010), and sediment transport in drainage network (Ghani *et al.*, 2000; Koç and Yilmaz, 2014; López De la Rosa *et al.*, 2015; Marsalek *et al.*, 1993). Recent studies have highlighted the complex interactions between the physical, chemical, and biological properties of sediments within urban drainage systems and their impact on hydraulic behavior Pouyat *et al.* (2015). Additionally, urbanization has been shown to significantly affect drainage performance, reinforcing the necessity of sustainable urban planning and resilient drainage design (La Rosa and Pappalardo, 2020). This underscores the importance of employing hydrological modeling and management tools to address urban drainage challenges under evolving environmental conditions (Griffiths and Singh, 2019).

The analysis of sediment properties in urban drainage systems is essential for identifying sediment sources, characterizing sediment composition, and assessing their effects on the hydraulic performance and long-term sustainability of drainage networks. The spatial distribution of suspended and bed sediments is strongly influenced by geological, land-use, and climatic factors (Khan, 2024; 2018; Panwar *et al.*, 2016). In particular, the presence of unpaved roads has been shown to significantly contribute to the generation of suspended sediments (Guzman *et al.*, 2017). The increasing sedimentation in urban drainage networks necessitates a more comprehensive analysis of sediment properties and their relationship with hydraulic, social, economic and environmental factors. A detailed understanding of these interactions is essential for sustainable management of urban drainage systems (García-Haba *et al.*, 2023).

Sedimentation in urban drainage networks is a complex process influenced by multiple factors. Flow velocity is a primary determinant, with low velocities being particularly conducive to sediment deposition (Wu *et al.*, 2024). The presence of various sediments types, such as gravels, sands, silts, and clays, further complicates drainage performance, as sediment accumulation can reduce hydraulic capacity and drainage functionality (Charters *et al.*, 2015; Tang, 2016).

The design of urban storm drainage systems involves multiple stages, including defining design objectives, collecting input data, calculating design flows, and determining the appropriate size and configuration of drainage elements (Marsalek *et al.*, 1993; Abd-Elhamid *et al.*, 2020). A critical aspect of drainage design is the incorporation of self-cleaning mechanisms, which prevent excessive sediment accumulation and maintain drainage Soler Martín (2021).

Sediments in urban drains originate from multiple sources. Erosion from higher elevations, influenced by local topography, is a significant contributor (Russell *et al.*, 2018). Additionally, sediment accumulation on road surfaces is linked to the duration of dry periods, which affects particle-size distribution (Zafra *et al.*, 2008). Previous research has also demonstrated that fine clay particles exhibit adhesive and rolling behaviors at the tired-road interface. During friction tests, fine particles tend to remain trapped in tire cavities, whereas coarser particles are more readily expelled (Changarnier *et al.*, 2018). This phenomenon highlights the role of vehicular activity in redistributing sediment across urban environments. The relationship between the granulometric characteristics of sediments and the hydraulic properties of urban drainage systems remains an understudied topic, with a significant knowledge gap in this area. Previous studies (Ghani *et al.*, 2008; Karamouz, 2021) have analyzed the particle-size distribution of sediments and its relationship with hydraulic properties such as flow velocity. However, these studies have not explicitly established correlations between sediment characteristics and hydraulic properties of drainage systems.

In the context of Juliaca, Peru, sediment and flow characterization in urban drainage networks is particularly relevant. Situated in the Andean highlands, the city experiences unique climatic conditions that pose distinct challenges for stormwater management. The flat topography, combined with a predominantly commercial urban watershed, complicates drainage efficiency. Furthermore, an extensive network of unpaved and poorly maintained roads exacerbates sediment transport and accumulation issues MPSR (Juliaca, 2016). The combined effects of these factors significantly influence hydraulic conditions within the city's drainage network, necessitating a thorough investigation of sedimentation processes. These factors collectively alter the hydraulic behavior of the drainage system, particularly during and after the rainy season, when the influx of loose materials from unpaved surfaces intensifies sediment loading.

This study presents a novel contribution by relating the particle-size distribution of sediments to key hydraulic parameters, based on empirical measurements from a real-world case study in an urban setting characterized by low topographic gradients. While sediment transport processes have been extensively studied in natural riverine environments and engineered systems, limited research has addressed sedimentation phenomena within stormwater networks of rapidly urbanizing cities in developing regions such as Juliaca. Consequently, this research fills an important knowledge gap and provides essential insights to support the development of sustainable urban drainage and sediment management strategies.

The primary objective of this study was to conduct a comprehensive assessment of sediment grain-size distribution and to analyze its interactions with hydraulic parameters within the urban drainage network of Juliaca, Peru, thereby contributing to the understanding of sediment dynamics and supporting strategies for improving drainage performance and mitigation long-term environmental impacts.

2. MATERIAL AND METHODS

2.1. Study area

Juliaca is a city located in the Peruvian highlands covering a total area of 93.45 km^2, with a population of 443,189 inhabitants, making it the most populous district in the department of Puno. For the study, the city was divided into four drainage zones (Figure 1). Zones A, B, C and D correspond to individual storm drainage systems that exhibit distinct characteristics due to the city's commercial nature and informal urban expansion. Zone D was selected as the study area because it includes a natural drainage system, the Torococha River, and is primarily influenced by commercial and domestic activities, making it a representative sample of the city. This area receives significant sediment and solid waste inputs from various sources (Figure 3b and 3c). Rainwater flows from road surfaces into the drainage system and the Torococha River, which subsequently discharges into the Coata River, ultimately reaching Lake Titicaca approximately 25 km downstream (Figure 1). The total annual precipitation recorded at the Juliaca meteorological station, managed by the National Meteorological and Hydrological Service of Peru (SENAMHI), averages 607 mm year^{-1}. The precipitation regime is characterized by two well-defined seasons: the wet season, from November to April, and the dry season, from May to October. More than 85% of the total annual precipitation occurs during the wet period, primarily influenced by the South American Monsoon, which generates convective storms due to easterly moisture {laden winds from the Amazon Torres-Batlló and Martí-Cardona (2020). The average annual temperature ranges from 4.5 to 10.6°C, with the lowest temperatures recorded during winter (June to August) and the highest during summer (December to February).

2.2. Geological characterization

The city of Juliaca exhibits a diverse geological framework, characterized by lithological units of sedimentary, volcanic, and Quaternary origin. Prominent geological formations within the area include the Azangaro formation, composed predominantly of low cohesion lacustrine sands and silts, and the Huancane formation, which consists of fine to medium-grained quartz sandstones. Additionally, sequences from the Puno group are present, comprising feldspathic sandstones and polymictic conglomerates interbedded with vulcanoclastic rocks. The predominant surface deposits are alluvial in nature, classified into three primary types: rounded gravels, subangular gravels, and sandy matrix gravels. Bofedal deposits, characterized by silts and clays with a high organic matter content, are also notable in the region. Volcanic units, particularly those belonging to the Tacaza group, are represented by andesitic lava flows and breccias, indicative of historical magmatic activity. Furthermore, carbonate formations such as the Ayabacas formation, comprising micritic limestones and cherts, are interbedded with the gray shales of the Cabanillas group. The contemporary fluvial systems in the area are influenced by unconsolidated sediments present in riverbeds and lacustrine environments. Meanwhile, urban expansion is progressively altering the surface geology through dynamic land-use changes (Figure 2).

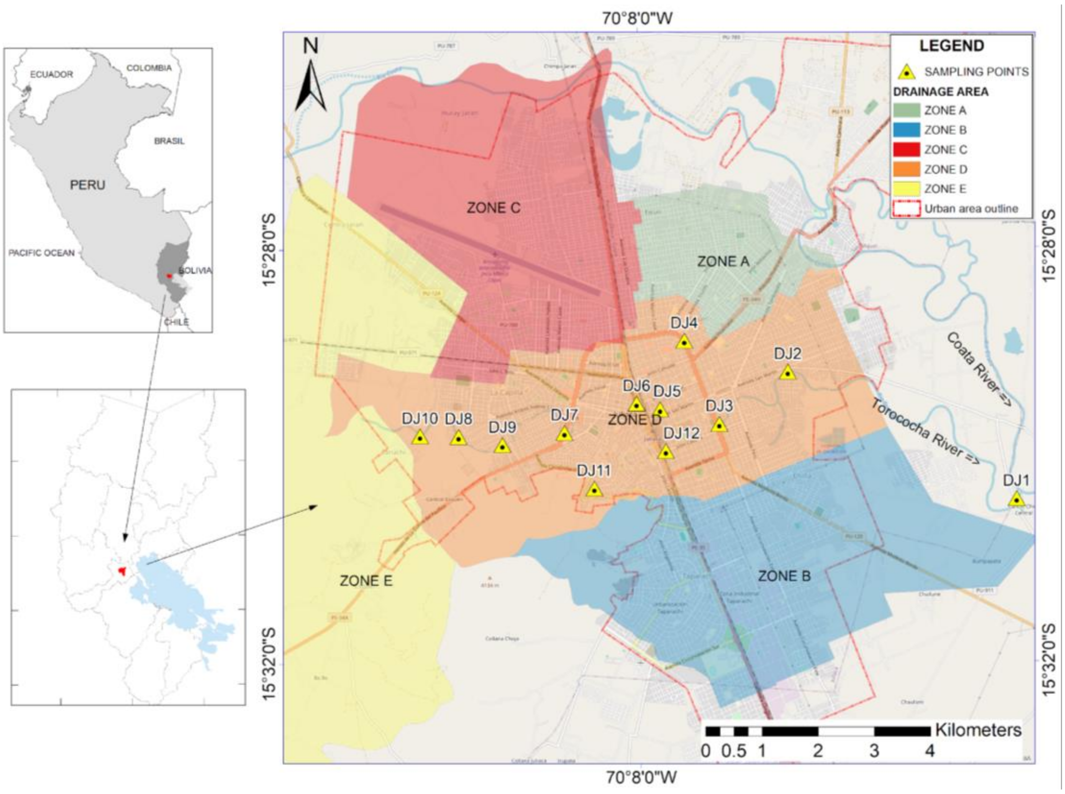

Figure 1. Location of the study area in the city of Juliaca.

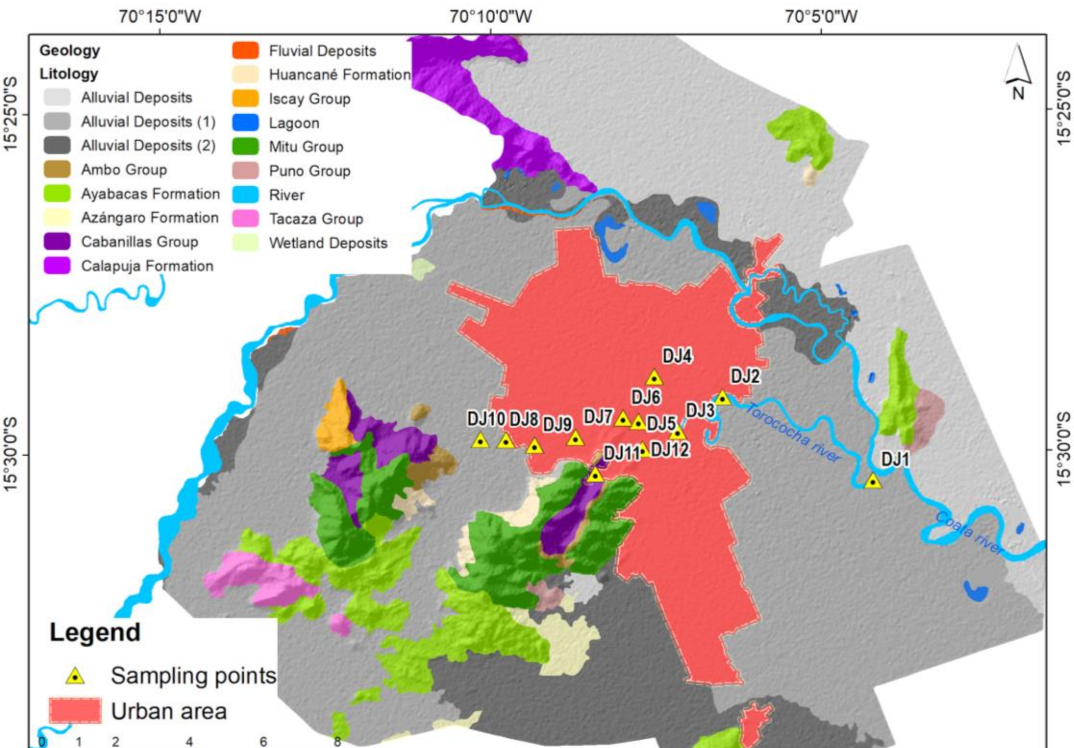

Figure 2. Geological composition of the city of Juliaca and surrounding areas.

A critical factor influencing the study area is the impact of exogenous processes. Quarrying and weathering processes mobilize and amalgamate sediments, leading to the formation of new composite materials that accumulate on roadways and within urban environments. This natural sediment production is compounded by the generation of anthropogenic materials, originating from human activities, such as artificial fills, construction debris, and soils modified by vehicular traffic. These materials alter the original lithological composition of the Surface layer. The interplay between natural geomorphic processes and anthropogenic interventions results in a dynamic and continuously evolving geological landscape, with significant implications for soil stability, urban infrastructure, and the spatial development of the city.

2.3. Granulometric characteristics of sediments in drains

Sediment samples were collected at the end of the wet season (May 2023) at 12 sites within Zone D of the Juliaca drainage system (Torococha River). These samples are considered representative as they correspond to sediments accumulated during the wet season. The decision to conduct only one sediment sampling campaign at the end of the wet season is justified by its representativeness of the deposited sediments during this period. Additionally, the number of sampling campaigns was constrained by the seasonal variability of precipitation and the availability of resources (García-Haba *et al.*, 2023). This study corresponds to a preliminary assessment of drainage systems in the Peruvian Altiplano corresponding to the rainy season. Therefore, future research should incorporate a larger number of samples and extend the sampling to different hydrological periods to enhance the reliability and comprehensiveness of the findings.

The selection of sampling points was determined based on land use and anthropogenic activities. The sampling sites encompassed locations upstream of the urbanized area (DJ4 to DJ12), within the commercial sector (DJ4, DJ5, DJ6, DJ7, DJ12) and in zones distal to the city (DJ1, DJ2, DJ3, DJ10, DJ11). Sediment collection in open channels without concrete lining was conducted using a manual shovel, ensuring that the samples corresponded to deposited sediments rather than the channel bed. This distinction was made based on the degree of material consolidation. For covered and unlined drainage channels, an auger-hole drill was utilized. This device was inserted through small access openings in the drainage covers to extract sediment samples (Figure 3a y 3b) Peru (2014).

Figure 3. a) Sediment sampling at point DJ3; b) closed-duct sampling; c) laboratory analysis of samples; and d) direct measurement of geometric characteristics of drains.

At each site, sediment samples were collected and subsequently analyzed through laboratory testing. Granulometric analysis was conducted to determine characteristic particle size parameters, including the mean particle diameter (d_{50}) and the percentage of soil passing through the #200 sieve, in accordance with ASTM D6913 (Das and Sobhan, 2017) (Figure 3c).

The geometric standard deviation was calculated using Equation 1, where values less than 3 indicate a uniform granulometric distribution or poorly graded material Chanson (2004).

$$\sigma_g = \left(\frac{d_{84}}{d_{16}}\right)^{1/2} \quad (1)$$

Where: σ_g= geometric standard deviation, d_{84}; d_{16}= characteristic diameter (mm)

The gradation coefficient was also used using Equation 2.

$$G_r = \frac{1}{2}\left[\frac{d_{50}}{d_{16}} + \frac{d_{84}}{d_{50}}\right] \quad (2)$$

Where: G_r= gradation coefficient, d_{84}; d_{50}; d_{16} = characteristic diameter (mm)

The gradation coefficient increases with non-uniformity, and high gradation coefficients describe well-graded mixtures.

The presence of solid waste, mainly plastics, was characterized by direct observation at the different sampling points (Figure 4).

Figure 4. a) Solid waste and construction debris near sampling point DJ10; b) private vehicle on unpaved road adjacent to DJ3; c) unpaved road near DJ6 and DJ7; and d) presence of solid waste in sediment samples.

2.4. Characteristics of drainage systems

The geometric characteristics of the drainage system were determined through direct field measurements (Figure 3d). The channel slopes were obtained using topographic equipment, existing design plans from the Provincial Municipality of San Roman Salazar Jaime and MPSR (2014), and analytical formulas for calculating the geometric properties of drainage channels (Akan and Iyer, 2021) for the cross-sections analyzed.

Figure 5 illustrates the drainage network of the city of Juliaca, specifically corresponding to Zone D. The Storm Water Management Model (SWMM) was employed solely for the topological representation of the drainage system on the map, as it is commonly used for visualizing this type of infrastructure (Cortes Zambrano *et al.*, 2022; Liu *et al.*, 2022; Niazi *et al.*, 2017). However, no hydrodynamic modeling of the drainage system was conducted, as it was beyond the scope of this study. The drainage system in Zone D consists of 171 conduits of varying dimensions, including rectangular and trapezoidal cross-sections, as well as covered and uncovered segments. The network primarily comprises concrete-lined drains, with a smaller proportion of unlined earthen channels. Additionally, the drainage system in this sector includes 163 manholes and three discharge points for stormwater outflow into the Torococha River. Constructed in 2014, the drainage system was designed based on a return period of 25 years for the major drainage system and between 5 and 10 years for the minor drainage system, in accordance with the Peruvian Technical Standard for storm drainage MVCS (Peru, 2021).

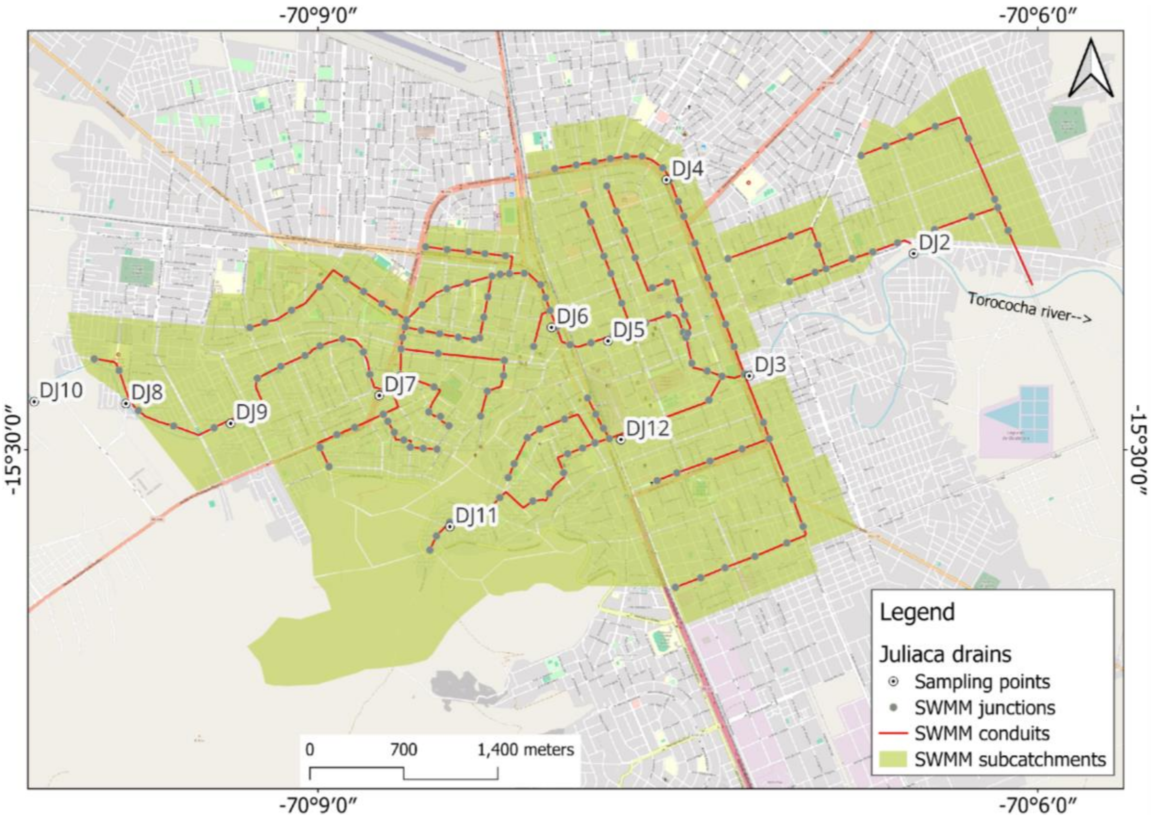

Figure 5. Topology of the urban drainage network of the city of Juliaca - Zone D.

2.5. Relationship between granulometric and hydraulic characteristics of the drainage network.

To evaluate the relationship between sediment characteristics and the hydraulic properties of the drainage system, the normality of both datasets was first assessed using Shapiro-Wilk tests (Shapiro and Wilk, 1965) y D'Agostino's K-squared (D'Agostino and Pearson, 1973). Given the results, Spearman's rank correlation coefficient (r_s) was employed, as it is a non-parametric (distribution-free) statistical measure that quantifies the strength and direction of the association between the rankings of two variables. Although the Spearman correlation between two variables X and Y is mathematically equivalent to the Pearson correlation applied to the rank-transformed values R(X) and R(Y), it does not specifically measure a linear relationship. Instead, Spearman's coefficient evaluates how well an arbitrary monotonic function (whether linear or nonlinear) describes the relationship between the two variables (Ahmadi *et al.*, 2024).

Equation 3 defines the computation of r_s, which ranges between -1 and 1.

$$\rho_{R(X),R(Y)} = \frac{COV(R(X),R(Y))}{\sigma_{R(X)}\sigma_{R(Y)}} \quad (3)$$

Where cov(R(X), R(Y)) is the covariance of two variables and $\sigma_{R(X)}$ and $\sigma_{R(Y)}$ are the standard deviations of X and Y, respectively. The corrplot package in R was used to calculate Spearman's correlation.

3. RESULTS AND DISCUSSION

3.1. Granulometric characteristics of the drainage sediments

The particle-size characteristics of bottom and suspended sediments are critical to the dynamic of urban drainage systems. This study specifically analyzed bottom sediments. Figure 6 illustrates the particle-size distribution of the sediments collected from 12 sampling sites within Zone D of the drainage system. The results reveal that all samples exhibited multimodal distribution patterns. Table 1 summarizes the granulometric properties of the collected sediments. In nearly all cases, with the exception of sample DJ9, sand constituted the predominant fraction, ranging from 44.73% to 94.32% with an average content of 72.74%. Gravel content varied between 2.52% and 51.33%, with a mean of 21.36%. Silt and clay represented the least abundant fractions, except in sample DJ11, ranging from 0.47% to 13.57%, with an average of 5.90%. Moreover, a significant presence of solid waste materials, such as, glass, plastics, wood, construction debris, was observed in the sediment samples (Figure 4a y 4d).

The mean particle diameter (d_{50}) ranged from 0.159 mm to 2.132 mm, with an overall mean of 0.783 mm. The largest mean particle diameters were recorded at sampling sites DJ3, DJ8, and DJ9, whereas the smallest value was observed at site DJ11. The d_{16} and d_{84} particle diameters ranged between 0.081 mm and 0.344 mm, and between 0.712 mm and 8.543 mm, respectively, following a similar spatial pattern to that of d_{50}. Sediment moisture content varied significantly, ranging from 21.1% to 189.2%, with particularly high values recorded at DJ1 (169.1%), DJ2 (189.2%), and DJ3 (161.2%). The geometric standard deviation ranged from 2.54 mm to 5.68 mm, while the coefficient of gradation varied between 2.63 mm and 6.03 mm.

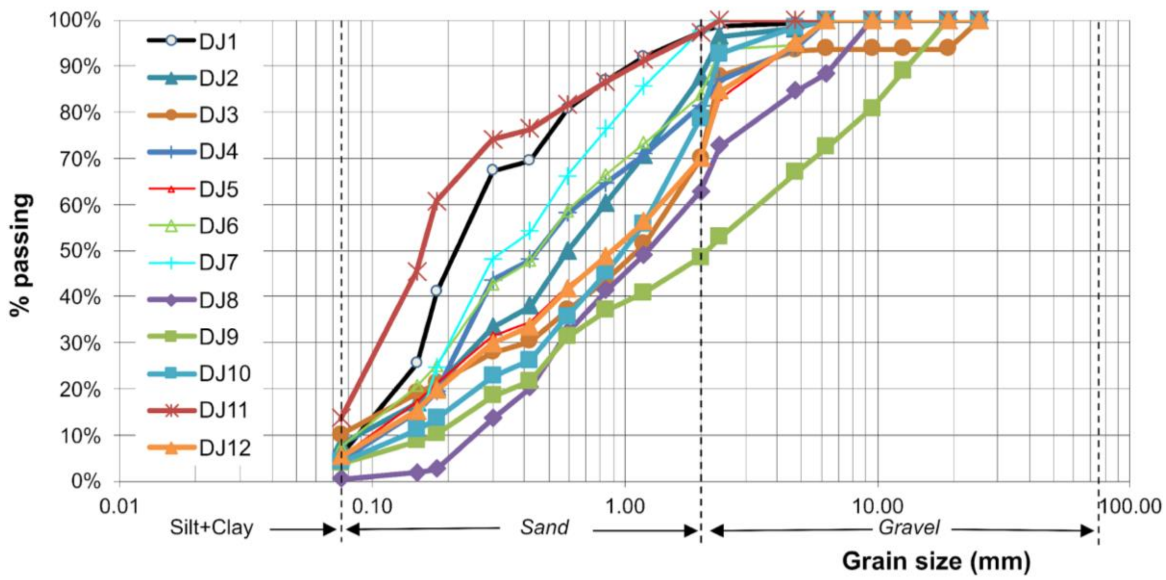

Figure 6. Cumulative particle distribution curves of sediment samples collected from the drainage system of Juliaca city.

Table 1. Summary of the granulometric characteristics of sediment particles in samples DJ1 to DJ12 from the drainage system of Juliaca.

Location	Code	Soil moisture (%)	d_{16} (mm)	d_{50} (mm)	d_{84} (mm)	Gravel (%)	Sand (%)	Silt + Clay (%)	σ_g (mm)	G_r (mm)
Residential	DJ1	169.1	0.114	0.221	0.732	2.67	91.53	5.80	2.54	2.63
Residential	DJ2	189.2	0.142	0.454	1.406	12.46	79.69	7.85	3.14	3.14
Residential	DJ3	161.2	0.124	1.133	2.300	30.03	59.94	10.03	4.30	5.57
Commercial	DJ4	35.4	0.157	0.455	2.174	18.57	77.04	4.38	3.73	3.84
Commercial	DJ5	23.8	0.144	0.902	2.569	30.67	64.07	5.26	4.23	4.57
Commercial	DJ6	65.5	0.124	0.457	2.013	16.34	76.44	7.22	4.03	4.04
Commercial	DJ7	87.0	0.160	0.338	1.129	2.52	94.32	3.16	2.65	2.72
Residential	DJ8	23.4	0.344	1.243	4.647	37.17	62.36	0.47	3.67	3.67
Residential	DJ9	24.7	0.265	2.132	8.543	51.53	44.73	3.74	5.68	6.03
Residential	DJ10	34.2	0.212	0.997	2.146	21.40	74.58	4.01	3.18	3.43
Residential	DJ11	21.1	0.081	0.159	0.712	2.83	83.60	13.57	2.97	3.22
Residential	DJ12	29.3	0.156	0.900	2.366	30.08	64.57	5.35	3.90	4.21
Mean		72.0	0.169	0.783	2.561	21.36	72.74	5.90	3.67	3.92

The composition of the sediments in the Juliaca drainage system is characterized by a predominance of sand and exhibits multimodal distribution patterns. This distribution can be attributed to the various sources of sediment input, influenced by the varying land use patterns and anthropogenic activities, particularly construction, which increases the susceptibility of the area to soil erosion and sediment deposition within drainage channels (Grimm *et al.*, 2024; Rowlands, 2019). Therefore, It is essential to implement measures aimed at managing erosion and preventing the transfer disturbed soil into drainage networks and downstream systems (Ashley *et al.*, 2000; Towsif Khan *et al.*, 2025). Furthermore, this finding can be explained by the urbanization patterns observed in Juliaca, where rapid and unplanned urban development contributes to a complex sediment regime, as corroborated in other urban areas worldwide (Halder and Majed, 2023; Russell *et al.*, 2019).

The range of mean sediment sizes (d_{50}) and associated particle-size parameters (d_{16} and d_{84}) observed recorded in this study are consistent with those reported in other urban drainage contexts, indicating commonalities in sediment behavior across diverse urban landscapes (Bong *et al.*, 2014; Ghani *et al.*, 2000; 2008). No significant differences were found in the mean particle diameter (d_{50}) between residential and industrial areas, aligning with the findings of Yan *et al.* (2024).

The frequent presence of solid waste materials such as plastics and glass further supports observations from previous studies on urban drainage systems, where these materials are commonly linked to inadequate waste management practices and human behavior (De Barros *et al.*, 2014). The accumulation of such debris can contribute to drainage blockages and exacerbate urban flooding issues (Sarmah and Das, 2018).

3.2. Hydraulic characteristics of the drainage system

Table 2 presents a summary of the hydraulic characteristics of the drainage system in the city of Juliaca at the locations corresponding to the sediment sampling points. The drainage network comprises both rectangular and trapezoidal cross-sections, with some sections consisting of closed conduits. The base width of the drainage channels ranges from 0.88 m to 4.00 m, while hydraulic depth varies between 0.70 m and 1.50 m. For the sampling points DJ7 to DJ9, the slope (z) remains constant at 0.5. The cross-sectional area of the drainage system spans from 0.70 m^2 and 6.00 m^2, and the wetted perimeter varies between 2.40 m to 7.00 m. The hydraulic radius ranges from 0.29 m to 0.86m, while the longitudinal slope values fluctuate between 0.0004 m m^{-1} to 0.031 m m^{-1}.

Table 2. Hydraulic characteristics of drainage systems at sampling points.

Code	Cross section	B (m)	Y (m)	z	Area (m^2)	Perimeter (m)	hydraulic radius (m)	Slope (m m^{-1})
DJ4	R*	0.88	1.05		0.92	2.98	0.31	0.00090
DJ5	R*	4.00	1.40		5.60	6.80	0.82	0.00052
DJ6	R*	4.00	1.50		6.00	7.00	0.86	0.00052
DJ7	T	4.00	1.20	0.5	5.52	6.68	0.83	0.00040
DJ8	T	4.00	1.20	0.5	5.52	6.68	0.83	0.00040
DJ9	T	4.00	1.20	0.5	5.52	6.68	0.83	0.00040
DJ11	R	1.00	0.70		0.70	2.40	0.29	0.03100
DJ12	R*	2.00	1.50		3.00	5.00	0.60	0.00175

R is rectangular, T is trapezoidal, B is the base, y is the brace, z is the slope, * corresponds to a closed and concrete-lined conduit.

The drainage system of the city of Juliaca features sections with hydraulic areas of up to 6.00 m^2. Although these dimensions are generally adequate to evacuate runoff generated by precipitation events with a return period of twenty-five years, it is important to highlight that larger cross-sections require higher velocities to achieve self-cleansing. Observations revealed that the slopes at sampling points DJ8 and DJ9 are insufficient to meet the minimum self-cleansing velocity established by the Technical Standard for Urban Storm Drainage of Peru MVCS (Peru, 2021), set at 0.90 m s^{-1}. Therefore, it is crucial to ensure that adequate longitudinal slopes are incorporated during the design phase, as the slope exerts a greater influence on sediment transport capacity than either the unit discharge or the mean flow velocity (Ali *et al.*, 2012).

The low slopes observed across the drainage network lead to reduced flow velocities, promoting sedimentation processes and increasing the risk of overflow during high-intensity storm events due to diminished hydraulic capacity (Wu *et al.*, 2024). Specifically, the low slopes recorded at stations DJ7, DJ8 and DJ9 would generate velocities below the threshold required for self-cleaning, thereby exacerbating sediment deposition in the concrete-lined open drainage channels and compromising the long-term functionality of the system (Ghani *et al.*, 2000). Although the primary cause of these low is the natural topographic gradient, it is necessary to design drainage infrastructure capable of managing sediment dynamics effectively, which underscores the need to adopt updated self-cleaning design criteria (Vongvisessomjai *et al.*, 2010).

Given the limitations imposed by Juliaca's topography on the potential increase of slopes, it is recommended to implement Sustainable Drainage Systems (SuDS) (Chapman and Hall, 2022). These systems offer an effective strategy to mitigate urban flooding risks, particularly considering the compounded challenges of climate change and unplanned urban expansion, which significantly heighten the city's vulnerability.

Certain sediment management strategies, incorporated into urban planning and drainage design guidelines, such as sediment traps, forebays, and cross-sectional modifications to adapt to local flow and sedimentation conditions, include provisions for machinery Access to facilitate sediment removal and desilting operations (Ballard *et al.*, 2015). Furthermore, interdisciplinary research collaborations among municipal authorities, environmental organizations, and academic institutions are strongly encouraged to enhance the understanding of sediment dynamics in low-slope urban environments (Jamal *et al.*, 2025).

3.3. Relationship between granulometric and hydraulic characteristics of the urban drainage system

Figure 7 presents the correlation matrix between the granulometric and hydraulic characteristics of the drainage system in Juliaca city, showing the Spearman correlation coefficient for various sediment parameters, including particle diameters (d_{16}, d_{50}, d_{84}), gravel content (G), sand content (S) and silt and clay content (SC). The hydraulic parameters analyzed comprise channel width (B), flow depth (y), hydraulic area (A), wetted perimeter (P), hydraulic radius (R), and longitudinal slope (S.1). A strong positive correlation (0.83) was observed between the longitudinal slope (S.1) and the percentage of silt and clay content (SC). Furthermore, moderate positive correlations (ranging from 0.41 to 0.55) were found between the morphometric parameters of the channels (B, y, A, P, and R) and the mean sediment diameter (d_{50}).

The most notable negative correlation was detected between the longitudinal slope (S.1) and the fine particle diameter (d_{16}). In addition, moderate negative correlations (ranging from -0.36 to -0.54) were identified between S.1 and d_{50}, d_{84} and G, as well as between B and both sand content (S) and silt and clay content (SC). These findings highlight complex interrelations between sediment transport and deposition processes within the drainage network.

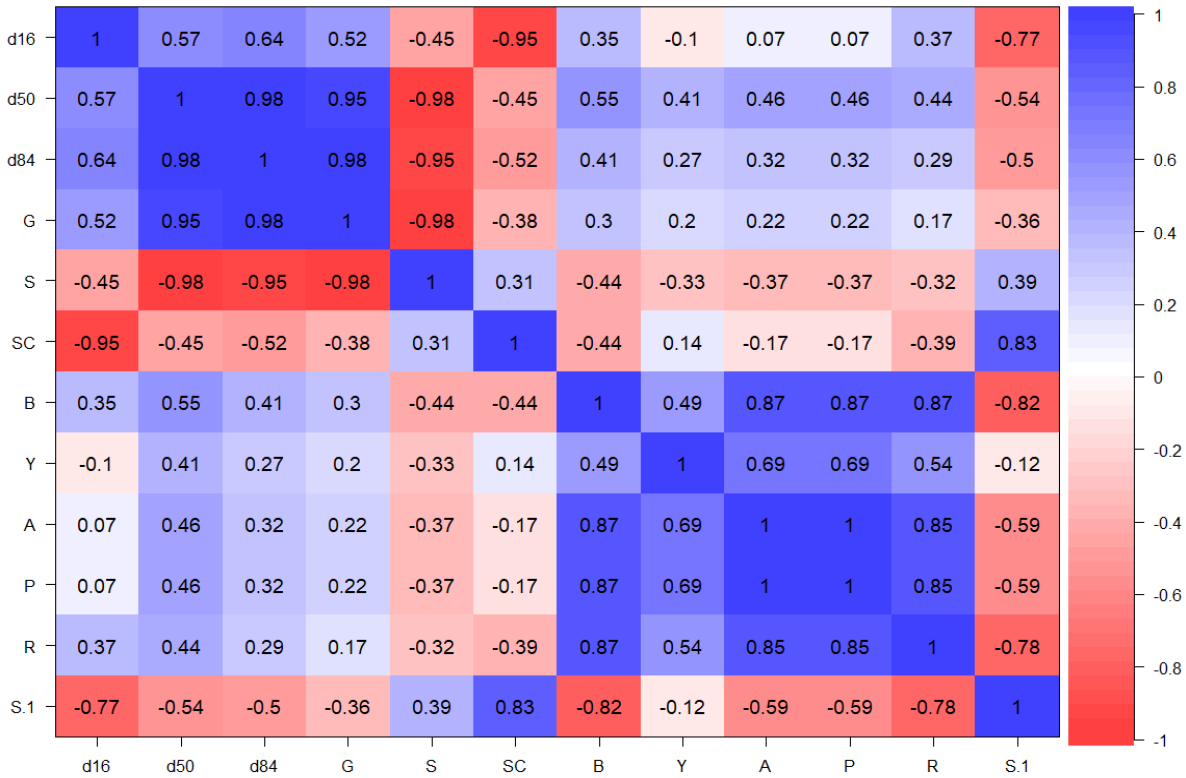

Figure 7. Correlation matrix between granulometric and hydraulic characteristics of the drainage system.

A significant to moderate negative correlation was identified between the longitudinal slope of the drainage network and the particle diameters of sediment deposited within the drainage channels. This relationship suggests that, as the longitudinal slope increases, the deposited sediment tends to exhibit smaller particle sizes. However, this pattern contradicts the classical principles of sediment transport, whereby steeper slopes (and consequently higher flow velocities) typically promote the transport of finer particles, leaving coarser materials to settle (Miller *et al.*, 2014). The observed discrepancy in the slope-diameter relationship may be explained by several factors including the seasonality of the sediment sampling, as samples were collected at the end of the rainy season, a period likely associated with sediment accumulation.

Moreover, the continuous influx of materials from unpaved roads into the drainage system through processes of wash-off and surface erosion, constitutes a significant source of sediments, pollutants, and other contaminants (Antonopoulos and Antonopoulos, 2017; Charters *et al.*, 2015; Russell *et al.*, 2019; Winston *et al.*, 2023). This phenomenon is particularly relevant in Juliaca, where a substantial proportion of the road network remains unpaved (Figure 3). Additional factors potentially influencing sediment grain-size distribution include precipitation intensity and season variability (Faisal *et al.*, 2024; Yan *et al.*, 2024), as well as the spatial scale of urban development (Seleznev *et al.*, 2024).

In Juliaca, there is also evidence of external sediment inputs, with some materials intentionally introduced by residents into the urban drainage systems. Nevertheless, it is important to acknowledge that the understanding of sediment sources in urban drainage environments remains limited (Russell *et al.*, 2019). Despite limitations related to sample size, sampling timing, and monitoring duration, the results of this study offer an initial insight into the relationship between sediment grain size and the hydraulic characteristics of urban drainage systems in the Peruvian Altiplano.

The significant positive correlations between the slope (S.1) and silt and clay content suggests that higher flow velocities are associated with an increased proportion of fine particles in sediments deposited at the sampling sites. This pattern is consistent with the trend identified in the slope-particle diameter relationship, indicating that similar factors, as previously discussed, may be influencing both relationships.

Although the correlation between downstream distance along the drainage network and the particle size was not directly analyzed in this study, it was noted that the mean particle (d_{50}) progressively increased downstream. This observation contrasts with the expected principles of sediment sorting described by Sternberg's law (Sternberg, 1875) and supported by subsequent studies (Attal and Lavé, 2009; Fedele and Paola, 2007; Miller *et al.*, 2014). This apparent anomaly could be attributed to the presence of open channels within the drainage network, which facilitate the direct discharge of various types of waste materials (Figure 3a, 3b and 3c). Such inputs can significantly alter the granulometric characteristics of sediments. Additionally, the low longitudinal characteristic of the drains may further influence sediment deposition and transport dynamics within the system.

4. CONCLUSIONS

The analysis demonstrated that the sediment samples from the Juliaca drainage system exhibited multimodal particle-size distributions. The mean sediment size (d_{50}) varied across the sampling locations, with a predominance of sand particles and significant contributions from gravel, while silt and clay fractions were less abundant. The variations suggest the presence of diverse sedimentary environments, shaped by both natural processes and anthropogenic activities associated with the urban sediment cycle.

The hydraulic characterization of the drainage network revealed that, despite the substantial hydraulic dimensions of certain sections, particularly at sites DJ8 and DJ9, the low longitudinal slopes resulted in insufficient low velocities under maximum capacity conditions to meet the minimum self-cleansing velocity requirements established by national design standards and prior research. Consequently, significant sediment accumulation is expected in these sections, potentially compromising the long-term functionality and resilience of the urban drainage system.

Statistical analysis identified significant positive and negative correlations between the granulometric properties of the sediment and the hydraulic characteristics of the drainage system. However, the observed relationship diverged from established sediment transport principles. Notably, finer particle sizes were found at location with steeper slopes, which contradicts theoretical expectations. Additionally, the mean sediment size (d_{50}) was observed to increase with downstream distance, contrary to Sternberg's law, which predicts a decrease in particle size during downstream transport. These anomalies are likely attributed to external sediment inputs from unpaved roads, facilitated by wash-off and erosion processes, coupled with the extensive presence of unpaved urban surfaces in Juliaca.

Overall, this study offers valuable initial insights into the interactions between sediment characteristics and hydraulic dynamics in the urban drainage systems of the Peruvian Altiplano. The findings underscore the need to develop more effective sediment management strategies to enhance the sustainability and resilience of drainage infrastructure under increasing environmental pressures.

Given the limitations associated with the sample size, sampling seasonality, and the monitoring duration in this study, future research should expand the spatial and temporal coverage of sediment sampling, including both wet and dry seasons. Additionally, integrating continuous hydraulic monitoring, tracer studies to track sediment sources, and the application of numerical modeling for sediment transport under urban conditions would further refine understanding and support the development of targeted sediment management interventions for Juliaca and similar urban environments.

5. ACKNOWLEDGMENTS

The authors would like to thank the Vice Rectorate of Research of the Universidad Nacional del Altiplano for funding of the research, and the students participating in the water and soil quality monitoring course of the Faculty of Agricultural Engineering for their support in the field work.

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