urban science

MDPI

Article

Towards Environmental Sustainability: Wastewater Management and Sewer Networks for Protecting Groundwater in Rural Settlements

Tamás Mester [1,*], György Szabó [1], Emőke Kiss [1] and Dániel Balla [2]

[1] Department of Landscape Protection and Environmental Geography, Institute of Earth Sciences, Faculty of Science and Technology, University of Debrecen, 4032 Debrecen, Hungary; szabo.gyorgy@science.unideb.hu (G.S.); kiss.emoke@science.unideb.hu (E.K.)
[2] Department of Data Science and Visualization, Faculty of Informatics, University of Debrecen, 4023 Debrecen, Hungary; balla.daniel@inf.unideb.hu
* Correspondence: mester.tamas@science.unideb.hu

Abstract: Sewer networks are essential in supporting the sustainable development of rural settlements. However, many municipalities face difficulties due to inadequate or missing sanitation systems. Thus, the contamination of municipal water supplies has become a pressing issue. In the present study, the process of the sewer network establishment and its impacts on groundwater was assessed in the case of a Hungarian settlement. It was found that, following the realization of wastewater agglomeration in 2015, 85% of households in the municipality were connected by 2023. Results indicate that uninsulated septic tanks used before the sewer system resulted in a high rate of sewage leakage. 3D models using RockWorks software show a groundwater dome of more than 1 m in the vicinity of the septic tank. The discharge had a significant impact on groundwater quality; high NH_4^+ concentrations (>90 mg/L) within the vicinity of the tank and above the limit value (0.5 mg/L) in the total area were detected. Na^+ and NO_3^- concentrations above the contamination limit also reflect the severe impact of wastewater discharge. Significant positive changes in groundwater quality have been detected following sewerage. Our results highlight the importance of similar investments and draw attention to the positive changes that can be achieved. However, a very significant decrease in water levels was detected both in the vicinity of the septic tank and at the municipal level, which, in addition to precipitation patterns, is mainly attributable to the cessation of sewage outflow. Between 2013 and 2022, the average groundwater level declined by 3.8 m in the settlement. Therefore, long-term monitoring of the investment is essential.

Keywords: sustainable rural development; sewer network; septic tanks; groundwater quality; environmental pollution; settlement infrastructure; water level

Academic Editors: Qiyang Liu, Zhengying Liu and Mengqiu Cao

Received: 21 January 2025
Revised: 28 February 2025
Accepted: 10 March 2025
Published: 12 March 2025

Citation: Mester, T.; Szabó, G.; Kiss, E.; Balla, D. Towards Environmental Sustainability: Wastewater Management and Sewer Networks for Protecting Groundwater in Rural Settlements. *Urban Sci.* **2025**, *9*, 80. https://doi.org/10.3390/urbansci9030080

1. Introduction

Sustainable development of rural settlements requires adequate water resource protection [1–3]. Groundwater is a crucial resource for rural communities, providing a significant share of drinking water, irrigation, and industrial activities [4]. However, the degradation of groundwater quality due to inadequate sanitation, agricultural, and industrial activities has become a pressing environmental problem, especially in rural communities [5,6]. Kim et al. (2024) used a numerical model to simulate the transport of N species derived from personal sewage treatment facilities (PSTF) in Jeju Island, South Korea [7]. Results on elevated NO_3^- and Cl^- concentrations indicated anthropogenic influence; moreover, agricultural

N source greatly contributed to NO_3^- pollution. As reported by the WHO in 2024, over 1.5 billion people worldwide do not have access to basic sanitation services [8]. The lack of adequate sanitation systems in these areas often leads to the uncontrolled discharge of domestic, agricultural, and industrial wastewater directly into the environment, resulting in the contamination of groundwater resources with nutrients, pathogens, and hazardous chemicals [9,10]. Abanyie et al. (2022) assessed sanitation practices in the peri-urban areas of Doba and Nayagenia in Ghana and stated the presence of total coliform and *E. coli*, indicating pollution by human sewage or animal droppings [11].

According to UN Habitat and WHO data (2021), 44% of the household wastewater generated globally was discharged without safe treatment [12]. A major challenge in rural areas without centralized sewage systems is the leakage of wastewater from septic tanks [13]. When septic tanks are poorly constructed or not properly maintained, untreated, or partially treated wastewater can seep into the surrounding soil. This leakage can contaminate shallow aquifers resulting in elevated levels of NO_3^-, which is linked to serious health conditions such as methemoglobinemia [14,15]. Sanitation services are therefore crucial for protecting both public health and the environment, especially in urban areas. Shaban et al. (2023) carried out a health risk assessment of nitrate contamination in drinking water and vegetables for infants in the northern Gaza Strip, and found that methemoglobinemia was present in 32.2% of infant samples in the study area [14].

tions such as methemoglobinemia.esultiInnovative and decentralized wastewater treatment technologies are emerging as potential solutions to overcoming these challenges [16,17]. Constructed wetlands, anaerobic digesters, and community-based sewage systems are among the approaches gaining traction due to their cost-effectiveness, adaptability to local conditions, and minimal environmental footprint [18,19]. Furthermore, these systems can facilitate the reuse of treated wastewater for irrigation, thereby reducing the demand on freshwater resources [20,21]. Bui et al. (2024) found that integrated fixed-film activated sludge (IFAS) technology significantly improves nitrogen removal efficiency, increasing treatment capacity and nitrification efficiency ranges from 89.2% to 98.8%. Concentrations of N-NO_3^- after treatment ranged between 27–45 N-NO_3^- mg/L, which were significantly lower than the Vietnamese effluent discharge limit of 60 mg/L [22].

The Sustainable Development Goals (SDGs), particularly Goal 6 on clean water and sanitation, play a crucial role in the context of wastewater management and sewerage network construction [23,24]. To achieve the SDGs, it is essential to ensure access to adequate sanitation facilities, reduce water pollution, and improve water quality through safe treatment and reuse [25,26]. In rural settlements, implementing these goals requires developing sanitation infrastructure that prevents groundwater contamination [27,28].

However, rural municipalities often face specific challenges in implementing effective wastewater management strategies. Limited financial resources, inadequate infrastructure, and lack of technical expertise contribute to the reliance of municipalities on inappropriate or non-existent sewerage networks [29]. The problem is further exacerbated by a lack of regulatory control and a lack of awareness among residents about the proper maintenance of septic tanks [30]. Studies has also highlighted that homeowners had difficulty in maintaining their septic systems, leading to overflows and further groundwater contamination [31,32]. Several studies have examined the attitudes of the population; Brzusek et al. (2023) conducted a willingness-to-accept (WTA) and willingness-to-pay (WTP) survey, with results showing significant level of acceptance and involvement of the local population of the Zagrody settlement in Poland in sustaining improved sanitation [33]. Leaky sewer systems pose significant risk to the environment as well [34,35]. Addressing this issue requires not only technical interventions, such as better septic tank design and the use of leak detection technologies, but also the education of communities and a strong regulatory framework to ensure proper maintenance and waste disposal practices [36].

The Urban Wastewater Treatment Directive (UWWTD) plays a crucial role in European communities, with populations exceeding 2000 population equivalents (PE). It mandates the collection and treatment of wastewater to prevent environmental pollution. For rural settlements with more than 2000 inhabitants, the UWWTD has facilitated substantial infrastructure investments, including the establishment of centralized treatment plants and the implementation of advanced technologies. These efforts have led to improvements in water quality and public health [37–39].

In Hungary, the implementation of the UWWTD has led to significant advancements in wastewater collection and treatment infrastructure. Centralized sewerage systems have been constructed in many settlements, and ongoing projects aim to extend these systems to cover even more rural areas [40]. Accordingly, the proportion of households connected to the sewer system increased to 88.4% by 2023 [41]. These efforts have greatly improved wastewater management practices, reducing the pollution of natural water bodies and protecting groundwater resources [42]. However, ensuring full compliance and maintaining the infrastructure remains a particular challenge, requiring continued investment and technical support [43].

The aim of the present study is to investigate the impacts of municipal sanitation infrastructure development and to explore the effects of septic tank elimination on groundwater. The novelty of the study lies in the fact that few studies have addressed the long-term effects of environmental investments in rural municipalities. According to the hypothesis formulated before the investment, the disappearance of the sewage discharge positively alters the quality of the municipality's groundwater resources.

2. Materials and Methods

2.1. Location of the Study Area

The municipality—Báránd—under study is situated in the Nagy–Sárrét microregion, which is part of the Great Hungarian Plain (Figure 1). The lowland area (altitude 85–89 m) is part of the alluvial deposit of the Sebes-Körös River, categorized as a flat plain [44]. The sample area covering 3 km^2 is part of the Kaba–Báránd–Tetétlen wastewater agglomeration and located in a nitrate-sensitive area according to The Nitrate Directive (91/676/EEC) of the European Union.

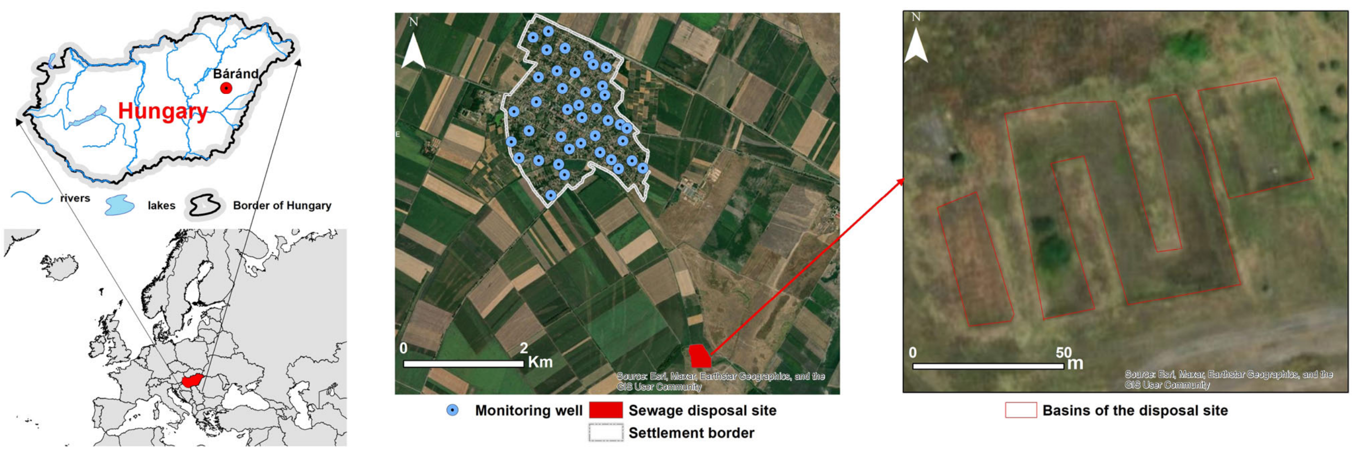

Figure 1. Location of the study area and the monitoring wells in the settlement. Location and satellite image of the municipal sewage disposal site under operation between 1990 and 2010.

Before the establishment of wastewater agglomeration, municipal wastewater was transported to a liquid waste landfill located about 1.5 km southeast of the municipality, which was in operation between 1994 and 2010 (Figure 1). The basins of the disposal site can be seen on satellite images as shown in Figure 1.

Soil formation in the region is significantly influenced by shallow groundwater, which fluctuates between 1 and 3 m below the surface leading to the dominance of Vertisol, Solonetz, Chernozem, and Kastanozem soil types, as classified by the World Reference Base for Soil Resources (WRB) [45]. Saline soils make up 36% of the microregion, while meadow Chernozem soils, which are not directly impacted by groundwater, cover 16% of the area. The prevailing soil texture in the study area consists of loam and clay loam. The region receives an average annual precipitation of 520–540 mm and is characterized by a moderately warm and dry climate (Cfb) [44].

2.2. Wastewater Agglomeration

The Council Directive 91/271/EEC concerning urban wastewater treatment (UWWTD), has established the framework for the development of wastewater treatment systems across Europe. The UWWTD requires all agglomerations with a population equivalent (PE) above 2000 people to undergo a secondary (mechanical/physical and biological) wastewater treatment [37]. According to this, the Kaba–Báránd–Tetétlen wastewater agglomeration in Hungary was with the development project initiated in 2012 and completed in 2015 (Figure 2). The agglomeration serves the municipalities of Kaba, Báránd, and Tetétlen, with a total population equivalent (PE) of approximately 13,855. The annual volume of wastewater generated in the agglomeration is approximated at 151,100 m^3. Situated within a nitrate-sensitive area, this agglomeration is subject to enhanced nutrient management measures as outlined in Directive 91/676/EEC (Nitrates Directive). The treatment plant employs advanced biological processes to reduce nitrogen and phosphorus loads, ensuring compliance with EU water quality standards.

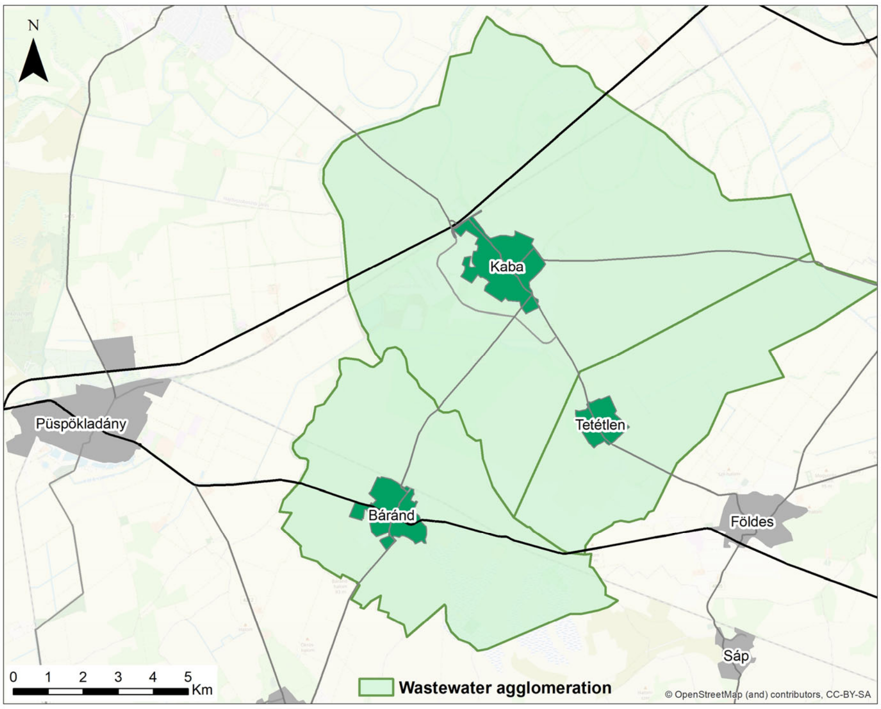

Figure 2. The Kaba–Báránd–Tetétlen wastewater agglomeration with a total population equivalent (PE) of approximately 13,855.

2.3. Impacts of Uninsulated Septic Tanks on Groundwater

To assess the impact of septic tank effluent on groundwater, 10 monitoring wells were installed around an uninsulated septic tank at a depth of 3 m (Figure 3). The BA1 and BA6 wells were situated 1 m from the tank, while the BA5 and BA10 wells were located 25 m away, allowing the assessment of contamination spread over different distances. The wells were constructed with a filtered section in the lower 1 m part of the PVC pipes (Ø 50 mm). Water samples were collected between 2012 and 2019, following the extraction of three times the well volume, in accordance with the MSZ ISO 5667-11:2012. standard.

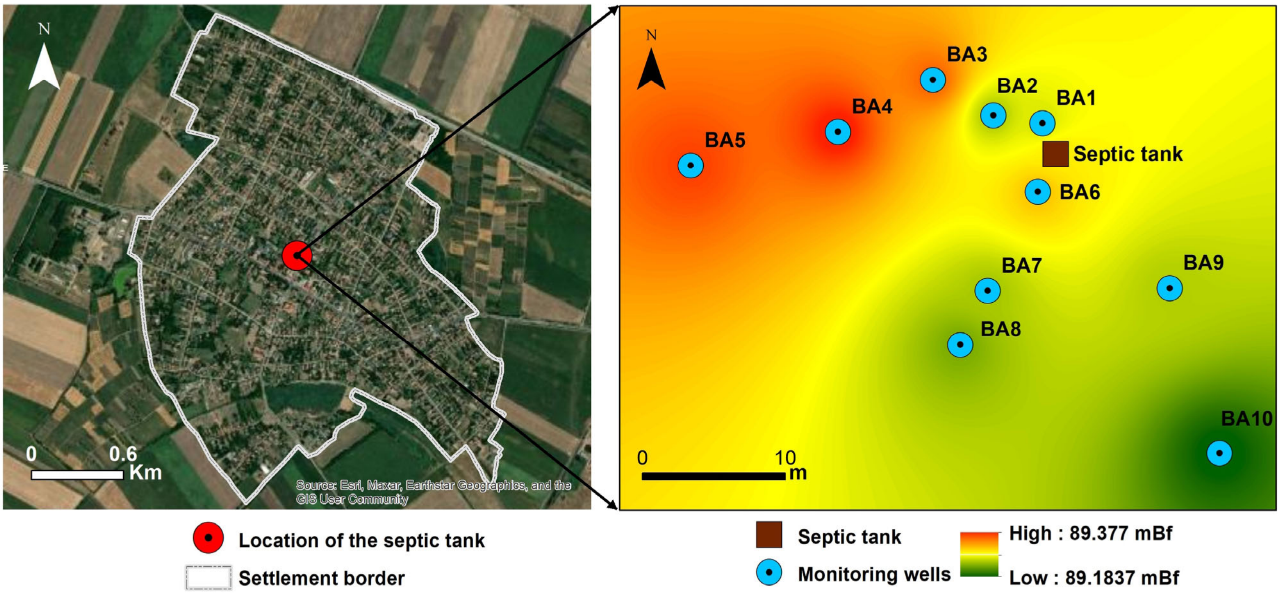

Figure 3. Location of the uninsulated septic tank and the monitoring wells around it. The digital elevation of the area was determined using high precision Trimble S9 GPS device.

In the years following the cessation of sewage outflow, groundwater levels exhibited a steady decline, gradually decreasing from an initial depth of 1–2 m to below 3 m by 2020, leading to a lack of data beyond that point. To enable continued long-term monitoring, the authors intend to install deeper monitoring wells in the near future.

2.4. Field Measurements and Laboratory Analysis

Field measurement data collected using a Trimble S9 dual-frequency, high-precision GPS device were utilized to generate a digital elevation model of the study area and to determine the absolute elevation of groundwater levels. Groundwater level measurements were carried out from 40 monitoring wells in the municipality every summer from 2013 onwards (Figure 1).

Laboratory measurement of NH_4^+, NO_2^-, NO_3^-, and PO_4^{3-} were conducted in accordance with Hungarian Standards (HS ISO 7150-1:1992; HS 1484-13:2009). The results were assessed based on the contamination limits specified in Joint Regulation KvVM-EüM-FVM No 6/2009 (IV. 14) [46].

2.5. Data Processing

The results were visualized using SPSS 26 and ArcGIS 10.4.1 software, the spatial distribution of the groundwater levels was created by using Kriging interpolation in Surfer 19 software. A static 3D model of the septic tank area was generated using Kriging interpolation with RockWorks 2025 software. RockWorks is a powerful geospatial and geostatistical software designed for modeling subsurface geological and environmental data. The models were constructed using voxel-based representations and 3D interpolation techniques, allowing for a high-resolution spatial analysis of the contaminant distribution within the saturated zone, while allowing 3D visualization of the groundwater levels as well. A voxel (volumetric pixel) is the fundamental building block of 3D models, representing a discrete unit of space within the modeled volume. In this study, voxel modeling was employed to simulate the spatial distribution of groundwater levels and contamination. The initial model was calibrated by integrating groundwater level measurements and contaminant concentration data from 10 monitoring wells. As the soil texture in the study area is dominantly loam, a pore space of 45% was applied. In order to develop the 3D model of the spatial distribution of the contamination (**M**), the following formula was applied:

$$M\ (mg) = V_{voxel}\sum_{i=1}^{n} n_{0i}c_i$$

where: $\mathbf{V_{voxel}}$ is the volume of the voxel (m^3), $\mathbf{n_{0i}}$ is the degree of effective porosity, and $\mathbf{c_i}$ is the concentration value (mg/L) measured at the given location.

3. Results and Discussion

3.1. Sewer Network Establishment in the Municipality

Considering the number of households connected to the sewerage network in the municipality, 63% of households were connected in 2016, which represents 710 connections (Figure 4).

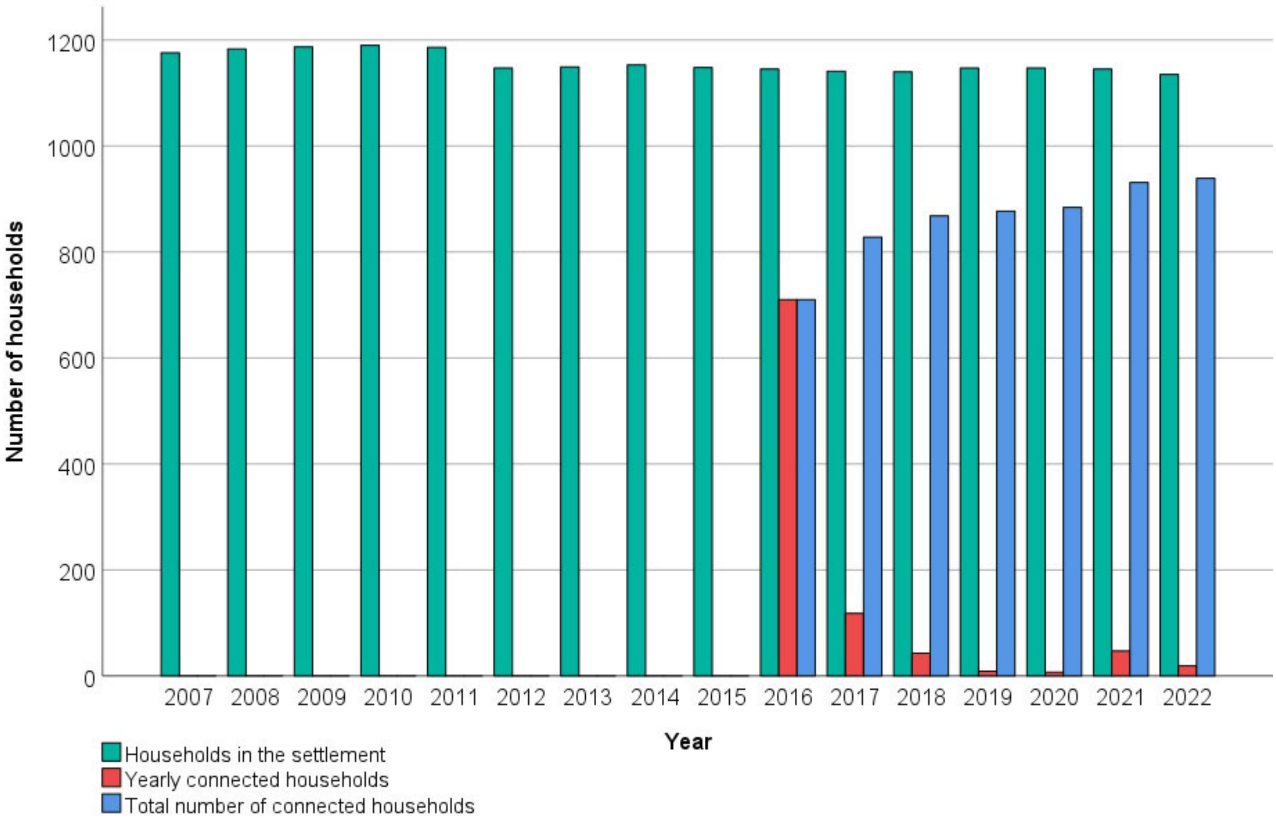

Figure 4. Number of households of the settlement, and the yearly connection numbers to the sewer system.

In 2017, the following year, there was another large increase in connections, with 118 households connected, while in the following years the number of new connections remained below 50. A major constraint is that households have to connect to the street pipeline on their own using their own resources, which is a major financial burden for many people. It is therefore essential to involve additional state support. It is also important to raise the environmental awareness of the local population.

Figure 5 shows the sewer network pipelines in the village. This shows that the sewerage network has been completed in all streets of the municipality so that all households have access to the service.

Figure 5. Map of the sewerage network of the municipality.

3.2. Impacts of Uninsulated Septic Tanks on Groundwater and Sewer Network Construction

As a result of high wastewater transport costs, municipal inhabitants have built their residential septic tanks with impermeable concrete or brick walls (uninsulated septic tanks), which allow sewage to leach easily into the subsurface, resulting in soil and groundwater pollution (Figure 6). The issue was exacerbated by the fact that the groundwater level in the municipality under study fluctuated between 1 and 3 m during the operation of the septic tanks, resulting in direct mixing of the wastewater with groundwater. Furthermore, the pollution caused by these modified septic tanks is significantly higher than that caused by septic tanks, as they emit raw, untreated wastewater into the aquifer, consequently representing the main source of groundwater contamination in settlements without sanitation.

As shown in Figure 3, monitoring wells were established around one of these wells, allowing regular groundwater level water quality measurements. After the high-precision determination of the surface elevation and groundwater levels, a 3D model of the saturated zone was created. Figure 6 presents the static level of the saturated zone in spring 2013 with 10× vertical exaggeration for better interpretation. In the area, the groundwater dome is clearly defined as a result of sewage discharge from the uninsulated septic tank. A difference of more than 1 m in water level compared to the water level in the more distant wells was observed throughout the operational phase of the septic tank.

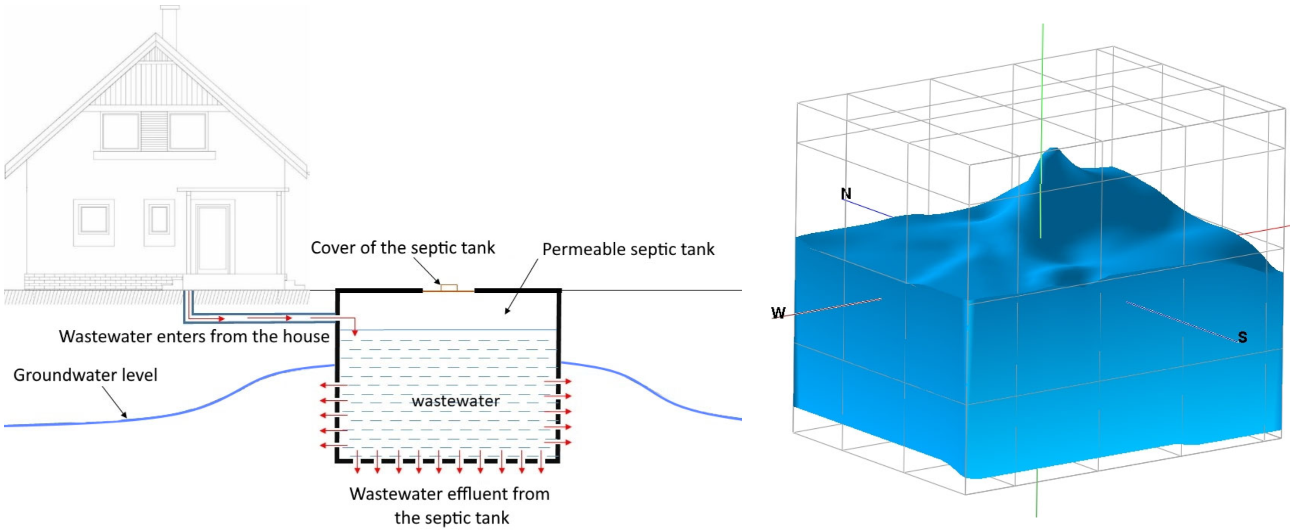

Figure 6. Schematic illustration of uninsulated septic tanks and 3D model of the saturated zone down to a depth of 3 m from the surface around the investigated leaky septic tank, based on the groundwater level data in spring 2013, with 10× vertical exaggeration.

3.3. Groundwater Contamination Around the Septic Tank and Changes After Its Elimination

The average values of the water chemistry parameters of the 10 monitoring wells around the septic tank for the pre- and post- sewerage periods are shown in Table 1.

Table 1. Average values for the assessed parameters measured in monitoring wells before and after sewerage.

Well ID	Distance from the Septic Tank (meter)	Prior Sewerage				After Sewerage			
		NH_4^+ mg/L	NO_2^- mg/L	NO_3^- mg/L	Na^+ mg/L	NH_4^+ mg/L	NO_2^- mg/L	NO_3^- mg/L	Na^+ mg/L
BA1	1 m	107.55	0.12	2.19	414.49	55.06	0.09	9.02	309.34
BA2	5 m	1.85	0.42	72.80	375.63	0.62	0.05	50.45	362.55
BA3	9 m	0.59	0.06	4.45	276.67	3.27	0.14	25.73	271.40
BA4	15 m	0.62	0.06	32.35	261.40	0.74	0.04	8.80	145.39
BA5	15 m	0.56	0.05	15.74	243.55	0.39	0.05	5.80	261.80
BA6	1 m	63.17	1.13	19.56	414.32	36.16	5.88	523.59	433.32
BA7	8 m	0.81	0.10	97.09	361.41	0.34	0.08	96.18	402.47
BA8	13 m	0.69	0.05	81.90	229.81	0.56	0.04	35.97	243.26
BA9	10 m	0.64	0.06	38.49	172.79	0.55	0.13	18.47	127.04
BA10	25 m	0.67	0.10	300.94	161.23	0.78	0.13	78.25	107.33

To reveal the spatial evolution of the pollutants discharged from the septic tank, 3D kriging interpolation was used to model the pollutants in the saturated zone based on water quality data from the monitoring wells. All models are framed from the surface to a depth of 3 m below the bottom of the well (Figures 7–10). This range is represented by rectangles. For better visibility, the unsaturated zone is not colored above the saturated zone. The models were prepared for 2013, 2016, and 2019. The last full year of operation of the septic tank was 2013.

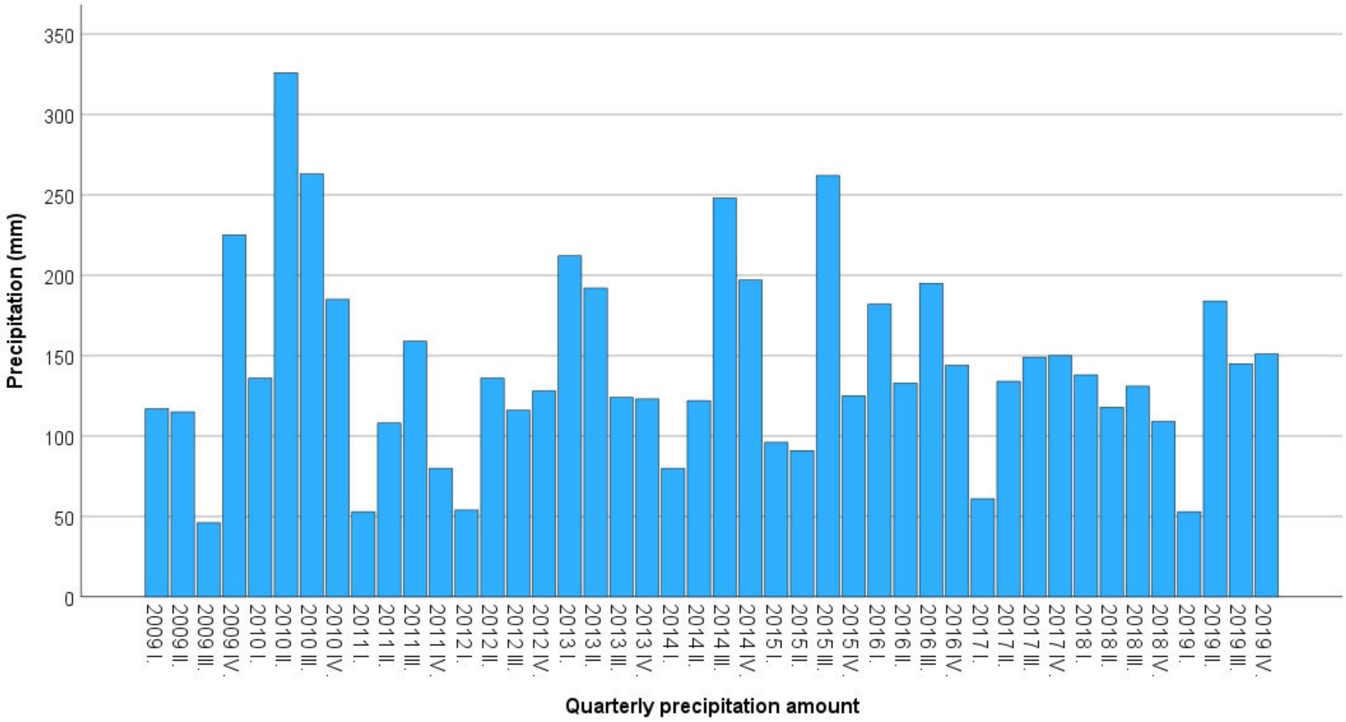

Figure 7. Quarterly precipitation trends between 2009 and 2019.

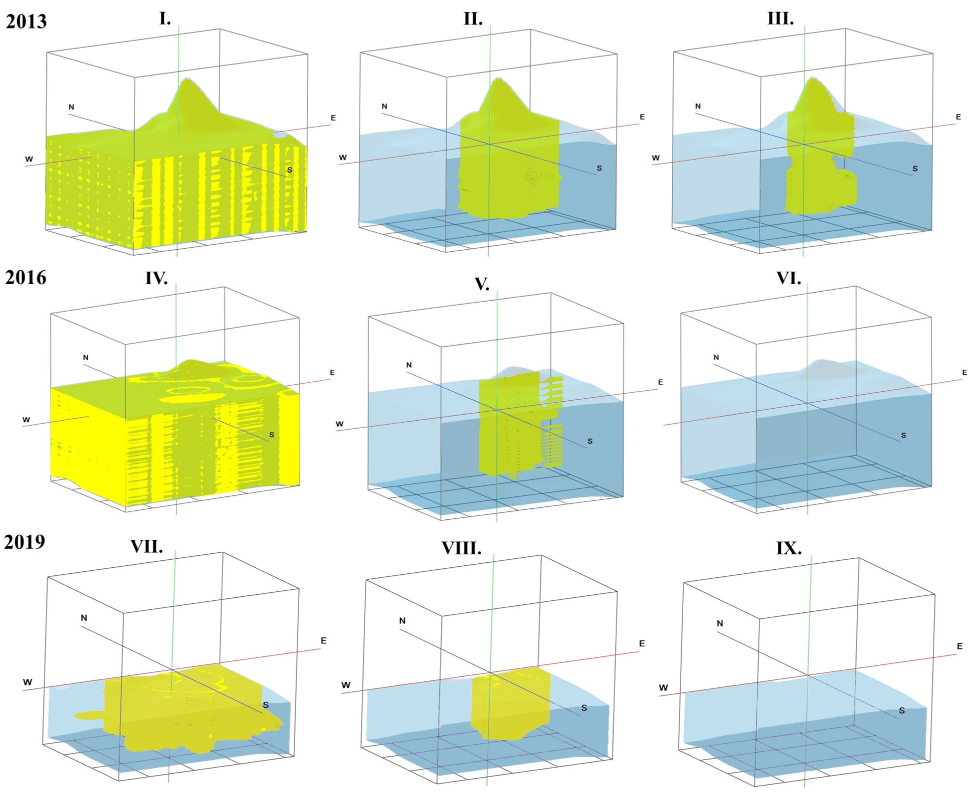

Figure 8. Spatial distribution of NH_4^+ pollution down to a depth of 3 m from the soil surface. Extent of water bodies with varying NH_4^+ levels indicated in yellow (I, IV, VII > 0.5 mg/L; II, V, VIII: >30 mg/L; III, VI, IX: >90 mg/L).

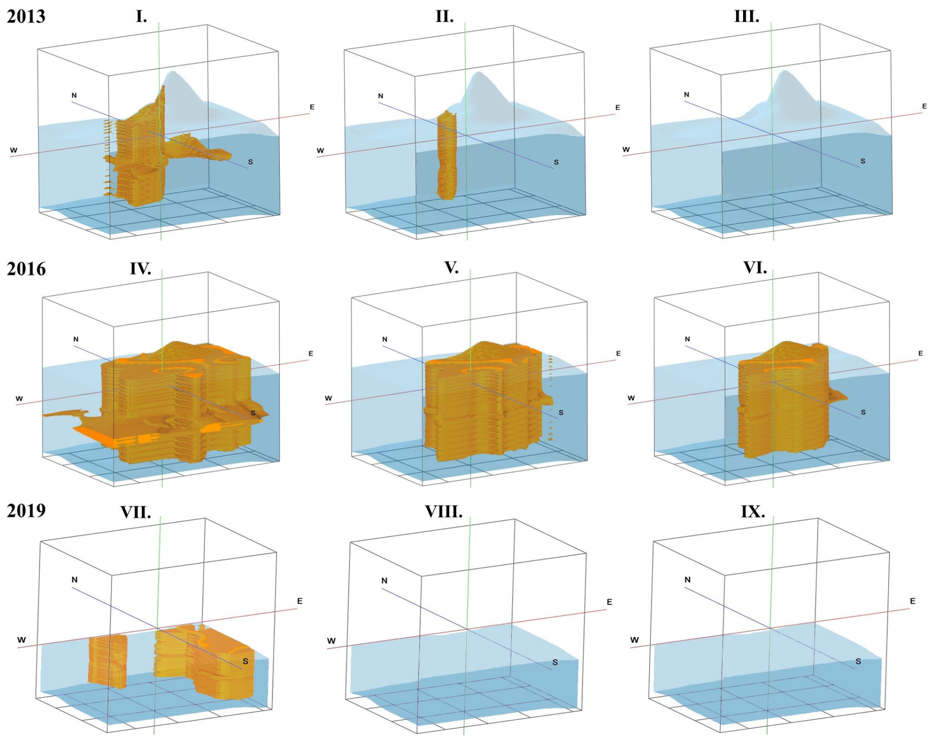

Figure 9. Spatial distribution of NO_2^- pollution down to a depth of 3 m from the soil surface. Extent of water bodies with varying NO_2^- levels indicated in orange (I, IV, VII: >0.1 mg/L; II, V, VIII: >0.5 mg/L; III, VI, IX: >1 mg/L).

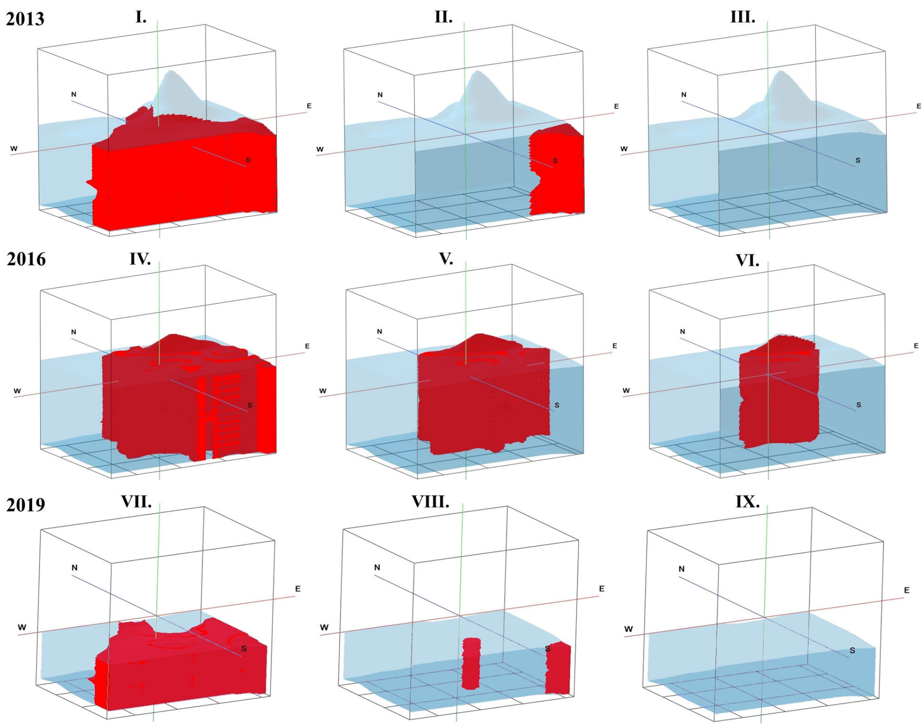

Figure 10. Spatial distribution of NO_3^- pollution down to a depth of 3 m from the soil surface. Extent of water bodies with varying NO_3^- levels indicated in red (I, IV, VII: >50 mg/L; II, V, VIII: >150 mg/L; III, VI, IX: >500 mg/L).

Examining the evolution of the elevation of the saturated zone, it can be seen that the groundwater dome, which initially exhibited a 1.2 m difference between the lowest and highest groundwater levels measured in the monitoring wells in 2013, was still very pronounced in the last year of the septic tank operation, having significantly decreased to 30 cm by 2016, one and a half years after the cessation (Figure 6). Five years after the cessation, a significant decrease in groundwater level occurred and the steady water level typical of lowland areas has been restored, with a water level difference of only 2 cm in the wells. The decline in water levels continued in the following years and dropped to under 3 m below the bottom of the wells, so no data were available for subsequent years.

The precipitation data for the period 2009–2019, presented in Figure 7, indicate that no significant decline in precipitation was observed during this timeframe. This suggests that the reduction in groundwater levels until 2019 was primarily attributed to the construction of the sewerage system rather than changes in precipitation patterns.

The effluent from the septic tank contains significant amounts of organic matter, including organic nitrogen, which in the first step of the decomposition produce NH_4^+.

In 2013 and 2016, concentrations above 90 mg/L were found in the vicinity of the septic tank, which is typical for raw sewage (Figure 8(III)). However, the highly contaminated area decreased in 2016 (Figure 8(VI)). Five years after closure, concentrations of 90 mg/L or higher cannot be detected in the saturated zone, indicating that the effluent discharge has ceased (Figure 8(IX)). Due to the high organic carbon content, the formation of nitrite (NO_2^-) and nitrate (NO_3^-) from NH_4^+ is limited, as the ammonifying bacteria responsible for the chemical transformation cannot multiply in this environment. Conditions for nitrification improve as the organic carbon content decreases away from the septic tank. Therefore, the concentration of ammonium decreases rapidly, moving away from the tank (Figure 8(I,II)) to a concentration close to the pollution limit of 0.5 mg/L at a distance of 15–20 m. While in 2013 and 2016, the concentration of ammonium in the saturated zone was above 0.5 mg/L in the entire area (Figure 8(I,IV)), in 2019, the concentration in the most remote areas from the mine was reduced to below 0.5 mg/L (Figure 8(VII)).

As continuous discharge inhibits nitrification, NO_2^- concentration above 1 mg/L were not measured in the vicinity of the septic tank during operation (Figure 9(III)). Since nitrite does not accumulate under natural conditions, no values above 0.5 mg/L were measured 5 years after cessation (Figure 9(VIII,IX)). In 2016, however, nitrite concentrations increased significantly over the entire area, due to the cessation of sewage outflow and the start of nitrification in the effluent, while the oxygen needed for its transformation into nitrate was no longer available (Figure 9(IV,V,VI)). In 2019, the concentration in the total sample area was below the contamination limit (0.5 mg/L).

The concentration of nitrate during the period of operation of the mine was the opposite of ammonium. In the vicinity of the mine, it ranged around only 2–3 mg/L and exceeded the 50 mg/L contamination limit when moving away (Figure 10(I)). Shortly after the end of the effluent discharge, large amounts of ammonium were oxidised to nitrate, resulting in a very significant increase in concentration. High concentrations of over 500 mg/L were detected over a large area, and concentrations of over 1000 mg/L were found in the immediate vicinity of the septic tank (Figure 10(VI)). Large parts of the area are still considered as contaminated 5 years after the closure, which highlights the slow decontamination process (Figure 10(VII)).

Sodium (Na^+) is present at high levels in municipal wastewater and can also be an indicator of leaking sewage. Concentrations in the vicinity of the mine exceeded 400 mg/L in both 2013 and 2016 (Figure 11(III,VI)), above the limit value of 200 mg/L. By 2019, however, values above 400 mg/L were no longer measured (Figure 11(IX)). Although the proportion of water bodies above 300 mg/L has decreased, concentrations above 200 mg/L are still prevalent in a significant part of the area. However, this may be attributed to natural factors, as soils in the area have typically higher salinity.

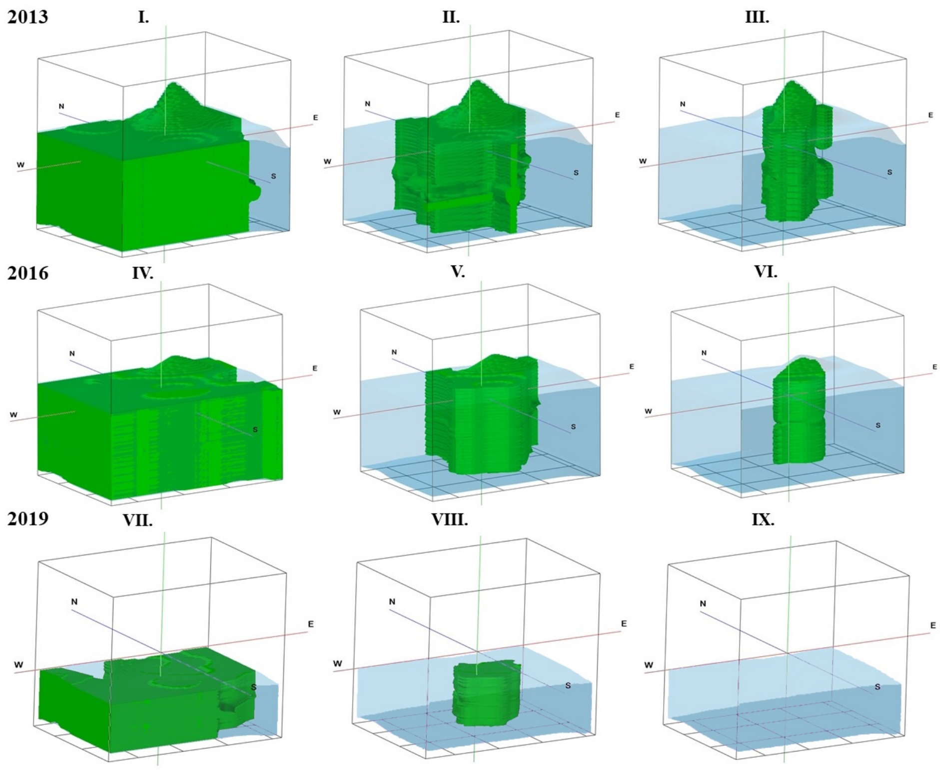

Figure 11. Spatial distribution of Na^+ pollution down to a depth of 3 m from the soil surface. Extent of water bodies with varying Na^+ levels indicated in green (I, IV, VII: >200 mg/L; II, V, VIII: >300 mg/L; III, VI, IX: >400 mg/L).

3.4. Groundwater Level Changes in the Municipality After the Sewer Network Construction

In 2013, prior to the construction of the sewer network, the absolute height (amsl) groundwater levels ranged between 88.51 and 86.98 m. The highest levels were observed in the central area of the municipality, while the lowest were recorded in the southern region. The local groundwater flow predominantly moved southward (Figure 12).

Following the establishment of the sewer network, marked changes occurred as wastewater outflow ceased. Groundwater levels significantly declined, dropping from an average of 87.82 m in 2013 to 86.09 m in 2017 (Figure 11). In 2017, groundwater levels remained highest in the central parts of the municipality and lowest in the south and south-western areas.

This decline has been further intensified by global climate change. The summer of 2022, which was the driest in the last century, led to an additional decrease in groundwater levels, substantially dropping to an average of 84.63 m (Figure 11). This sharp decline of approx. 3.8 m has resulted in several groundwater wells drying up, causing widespread public concern.

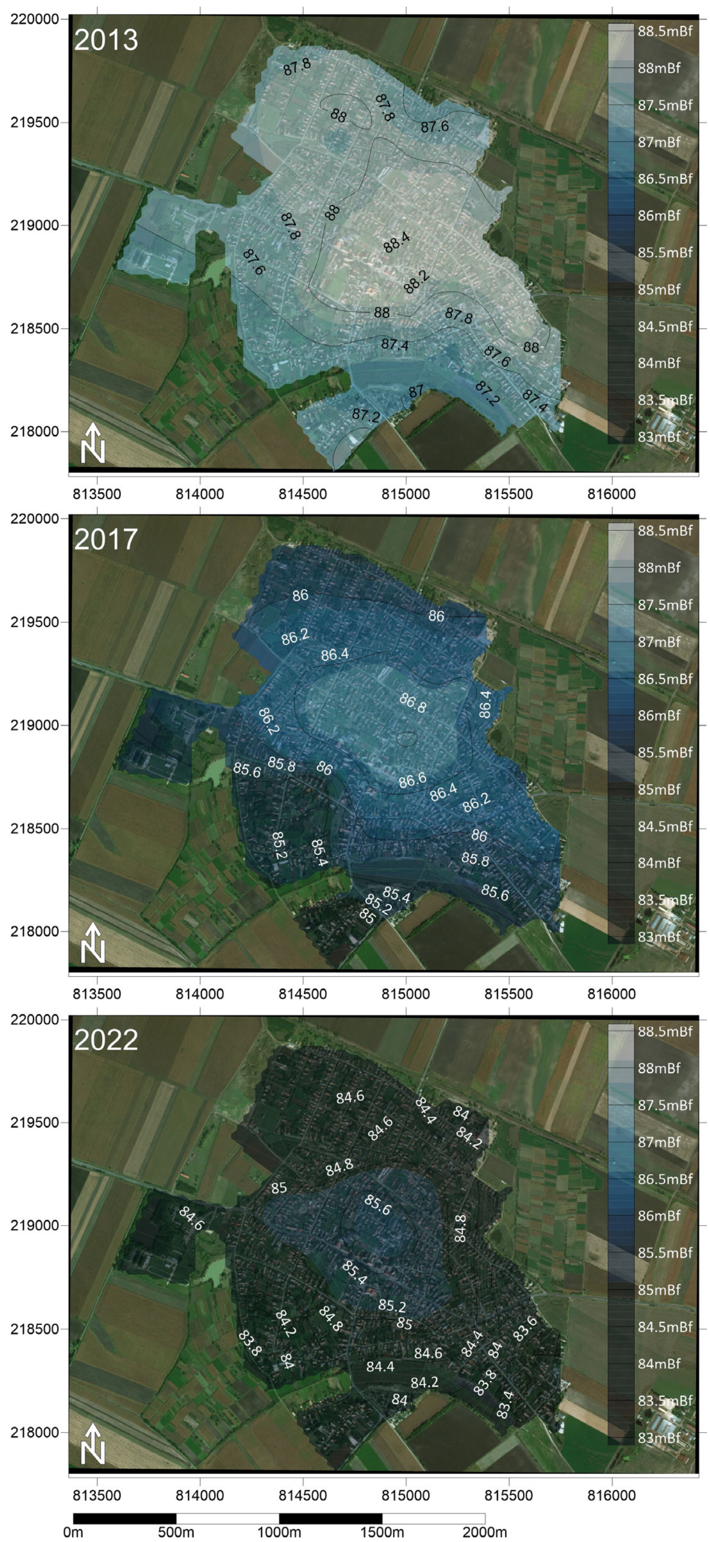

Figure 12. Groundwater level fluctuation in the settlement.

4. Discussion

In the present study, the transition from uninsulated septic tanks to central sewer systems was assessed from an environmental perspective. The results concluded that similar investments in rural municipalities have significant environmental benefits. Leaking septic tanks have been shown to significantly contaminate groundwater supplies, which is in line with other similar international studies. Several studies emphasize that poorly managed septic tanks are a major source of nutrient pollution of groundwater, especially in areas with high groundwater levels [46,47]. The observed reductions in groundwater contamination, especially in ammonium (NH_4^+) and nitrate (NO_3^-) levels, are in accordance with the results of international studies [48]. Other studies reported that advanced wastewater treatment systems effectively reduced nutrient and microplastic leaching into aquifers [49,50].

A significant reduction in groundwater levels has been detected in the post-sewerage period, indicating reduced wastewater discharges. The restoration of groundwater levels to natural conditions aligns with observations of other studies [48]. Similar trends have been reported internationally, where the reduction in groundwater recharge due to improved wastewater management led to lower water tables, albeit with significant environmental benefits in water quality. Additionally, studies highlighted that the decommissioning of septic tanks in favor of centralized sewer systems reduced aquifer recharge but led to improved water quality and compliance with environmental regulations [51].

While improved wastewater management enhances water quality, reduced infiltration from leaking systems contributes to a decline in groundwater levels, potentially affecting local wells and ecosystems. Therefore, the development of mitigation strategies becomes necessary, which, based on the natural characteristics of the settlement, can alleviate the decline in groundwater levels and contribute to sustainable water management. These should include managed aquifer recharge (MAR) through controlled infiltration basins, promoting water-efficient agricultural practices, and rethinking urban drainage strategies [52]. Instead of canalizing precipitation as in previous decades, efforts should focus on collecting and storing rainwater in the soil through permeable surfaces, retention basins, and infiltration trenches. However, several studies also identified challenges in achieving full connectivity to the sewer network due to financial constraints, a common issue highlighted in global rural sanitation projects. Alam et al. (2020) found in Bangladesh similar difficulties, where high connection costs and lack of governmental subsidies limit household participation in centralized systems [53]. Sachet and Bilotta (2020) analyzed the connection rates of municipalities in Paraná, and found that no projects achieved 100% of household connections; total connections were less than 80% in 40% of the projects [54].

5. Conclusions

The study investigated the effects of leaking septic tanks and the construction of a sewer network in a Hungarian lowland municipality in light of the baseline situation. To achieve this, 10 monitoring wells were installed around a leaking septic tank and groundwater levels and quality were measured from 2013 onwards, following the closure of the septic tank in 2014. The 3D interpolated models created using RockWorks software provided a detailed overview of the spatial evolution of pollution. The effluent discharged has polluted the local environment to a very high degree; the concentration of NH_4^+ near the tank exceeded 90 mg/L and was above the contamination limit (0.5 mg/L) of the total investigated area. Na^+ and NO_3^- concentrations above the contamination limit also reflected the impact of wastewater discharge. A reduction in pollution levels was found after the elimination of the septic tank, but the results also highlight the slow rate of decontamination processes.

The seepage had formed a pronounced groundwater dome of over 1 m in height 25 m from the septic tank. This was significantly decreased by 2016, and 5 years after the remediation, the difference in water levels in the area was reduced to 2 cm. The annual discharge of tens of millions of liters of wastewater also had an impact at the municipal level, and water level data from the 40 groundwater wells examined in the municipality have also shown a significant water level reduction. The average groundwater level dropped by

3.8 m between 2013 and 2022, with further declines exacerbated by climatic factors, such as the extreme drought of 2022.

Due to recurrent inland flooding issues in previous decades, an extensive network of drainage canals was constructed across the municipality's inner areas to drain excess water. However, a paradigm shift from drainage-focused infrastructure to water retention strategies is crucial to enhance local water balance and mitigate groundwater depletion.

The study also revealed challenges associated with incomplete household connections to sewer infrastructure in rural areas due to high costs and low environmental awareness among the population. In order to ensure high connection rates, it is crucial to provide continued governmental subsidies, enhance community awareness, and implement stricter regulatory measures. The results confirm that sanitation investments contribute significantly to achieving the Sustainable Development Goals (SDGs), particularly those related to clean water and sanitation, and support the sustainable development of rural communities.

Author Contributions: Conceptualization. T.M., G.S., E.K. and D.B.; methodology. T.M., software. T.M. and D.B.; validation. T.M., G.S., E.K. and D.B.; formal analysis. T.M.; investigation. T.M., G.S. and D.B.; resources. T.M. and G.S.; data curation. T.M. and D.B.; writing—original draft preparation. T.M. and D.B.; writing—review and editing. T.M., G.S., E.K. and D.B.; visualization. T.M. and D.B.; supervision. T.M. All authors have read and agreed to the published version of the manuscript.

Funding: Project no. TKP2021-NKTA-32 has been implemented with the support provided from the National Research Development and Innovation Fund of Hungary. Financed under the TKP2021-NKTA funding scheme. Supported by the University of Debrecen Scientific Research Bridging Fund (DETKA).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The work of Dániel Balla was supported by the EKÖP-24-4-II-DE-89 University Research Scholarship Program of the Ministry for Culture and Innovation from the source of the National Research, Development, and Innovation Fund.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Sharma, K.; Rajan, S.; Nayak, S.K. Chapter 1—Water Pollution: Primary Sources and Associated Human Health Hazards with Special Emphasis on Rural Areas. In *Water Resources Management for Rural Development*; Madhav, S., Srivastav, A.L., Chibueze Izah, S., van Hullebusch, E., Eds.; Elsevier: Amsterdam, The Netherlands, 2024; pp. 3–14, ISBN 978-0-443-18778-0.
2. Zuniga-Teran, A.A.; Mussetta, P.C.; Lutz Ley, A.N.; Díaz-Caravantes, R.E.; Gerlak, A.K. Analyzing Water Policy Impacts on Vulnerability: Cases across the Rural-Urban Continuum in the Arid Americas. *Environ. Dev.* **2021**, *38*, 100552. [CrossRef]
3. Makanda, K.; Nzama, S.; Kanyerere, T. Assessing the Role of Water Resources Protection Practice for Sustainable Water Resources Management: A Review. *Water* **2022**, *14*, 3153. [CrossRef]
4. Sun, Q.; Yang, K.; Li, C.; Li, C.; Ling, X.; Yang, D. Analysis on the Chemical Characteristics and Genesis of Drinking Groundwater in Rural Areas of Suihua City, Northeast China. *Environ. Forensics* **2024**, *25*, 614–625. [CrossRef]
5. Guo, W.; Li, P.; Du, Q.; Zhou, Y.; Xu, D.; Zhang, Z. Hydrogeochemical Processes Regulating the Groundwater Geochemistry and Human Health Risk of Groundwater in the Rural Areas of the Wei River Basin, China. *Expo. Health* **2024**, *16*, 291–306. [CrossRef]
6. Sun, Q.; Guo, L.; Hu, C.; Liu, T.; Sun, J.; Zhou, L. Health Risk Assessment of Drinking Groundwater in Rural Areas of Ru Village and Surrounding Areas in Wutai County, China. *J. Water Health* **2023**, *22*, 183–196. [CrossRef]
7. Kim, M.; Koh, E.-H.; Kim, J. Field Study and Numerical Modeling to Assess the Impact of On-Site Septic Systems on Groundwater Quality of Jeju Island, South Korea. *Hydrology* **2024**, *11*, 146. [CrossRef]
8. WHO. Sanitation. Available online: https://www.who.int/news-room/fact-sheets/detail/sanitation (accessed on 21 January 2025).
9. Alam, S.M.K.; Li, P.; Fida, M. Groundwater Nitrate Pollution Due to Excessive Use of N-Fertilizers in Rural Areas of Bangladesh: Pollution Status, Health Risk, Source Contribution, and Future Impacts. *Expo. Health* **2024**, *16*, 159–182. [CrossRef]

10. Mester, T.; Szabó, G.; Kiss, E.; Balla, D. Long-Term Spatiotemporal Changes in Nitrate Contamination of Municipal Groundwater Resources after Sewerage Network Construction in the Hungarian Great Plain. *Environ. Sci. Pollut. Res.* **2024**, *31*, 61114–61137. [CrossRef]
11. Abanyie, S.K.; Amuah, E.E.Y.; Douti, N.B.; Antwi, M.N.; Fei-Baffoe, B.; Amadu, C.C. Sanitation and Waste Management Practices and Possible Implications on Groundwater Quality in Peri-urban Areas, Doba and Nayagenia, Northeastern Ghana. *Environ. Chall.* **2022**, *8*, 100546. [CrossRef]
12. UN Habitat; WHO. *Progress on Wastewater Treatment—Global Status and Acceleration Needs for SDG Indicator 6.3.1*; United Nations Human Settlements Programme (UN-Habitat) and World Health Organization (WHO): Geneva, Switzerland, 2021.
13. Mester, T.; Szabó, G.; Sajtos, Z.; Baranyai, E.; Kiss, E.; Balla, D. Assessment of Groundwater Decontamination Processes around a Dismantled Septic Tank Using GIS and Statistical Analysis. *Water* **2023**, *15*, 884. [CrossRef]
14. Shaban, J.; Al-Najar, H.; Kocadal, K.; Almghari, K.; Saygi, S. The Effect of Nitrate-Contaminated Drinking Water and Vegetables on the Prevalence of Acquired Methemoglobinemia in Beit Lahia City in Palestine. *Water* **2023**, *15*, 1989. [CrossRef]
15. Nabi, A.; Garai, S.; Mondal, P.; Pal, F.; Ghosh, S.; Pal, P. Effect of Nitrate Contamination in Groundwater—A Worldwide Concern. *J. Surv. Fish. Sci.* **2023**, *10*, 6493–6497. [CrossRef]
16. Istenic, D.; Bodík, I.; Bulc, T. Status of Decentralised Wastewater Treatment Systems and Barriers for Implementation of Nature-Based Systems in Central and Eastern Europe. *Environ. Sci. Pollut. Res.* **2015**, *22*, 12879–12884. [CrossRef] [PubMed]
17. Vale, G.B.; Scalize, P.S.; Tonetti, A.L.; Ruggeri Junior, H.C. Cost-Effectiveness Study of Septic Tank Management in Rural Communities. *Int. J. Environ. Sci. Technol.* **2024**, *21*, 4599–4610. [CrossRef]
18. Samadi, M.T.; Asgari, G.; Leili, M.; Chavoshi, S. Integrated Modified Septic Tank and Constructed Wetland: An Alternative Green Technology for Phytoremediation of Highly Polluted Leachate. *Biomass Conv. Bioref.* **2024**, *14*, 23761–23773. [CrossRef]
19. Karczmarczyk, A.; Bus, A.; Baryła, A. Assessment of the Efficiency, Environmental and Economic Effects of Compact Type On-Site Wastewater Treatment Plants—Results from Random Testing. *Sustainability* **2021**, *13*, 982. [CrossRef]
20. Vazquez-Montiel, O.; Horan, N.J.; Mara, D.D. Management of Domestic Wastewater for Reuse in Irrigation. *Water Sci. Technol.* **1996**, *33*, 355–362. [CrossRef]
21. Gatto D'andrea, M.L.; Salas Barboza, A.G.J.; Garces, V.; Rodriguez Alvarez, M.S.; Iribarnegaray, M.A.; Liberal, V.I.; Fasciolo, G.E.; van Lier, J.B.; Seghezzo, L. The Use of (Treated) Domestic Wastewater for Irrigation: Current Situation and Future Challenges. *Int. J. Water Wastewater Treat.* **2015**, *1*, 1–10.
22. Bui, Q.C.; Phan, N.N.M.; Nguyen, T.V.; Yang, C.-C.; Chen, K.-F.; Tsai, Y.-P. Integrating Suspended Sludge and Fixed Film into a Biological Wastewater Treatment System to Enhance Nitrogen Removal. *Processes* **2024**, *12*, 2131. [CrossRef]
23. Garcia, C.; Pérez-Sánchez, M.; Ramos, H.M.; López-Jiménez, P.A.; Sánchez-Romero, F.-J. New Strategies in Wastewater Treatment Plants to Evaluate the Achievement of Sustainable Development Goals: A Case Study. *Urban Water J.* **2024**, *21*, 1201–1212. [CrossRef]
24. Kanchanamala Delanka-Pedige, H.M.; Munasinghe-Arachchige, S.P.; Abeysiriwardana-Arachchige, I.S.A.; Nirmalakhandan, N. Evaluating Wastewater Treatment Infrastructure Systems Based on UN Sustainable Development Goals and Targets. *J. Clean. Prod.* **2021**, *298*, 126795. [CrossRef]
25. Obaideen, K.; Shehata, N.; Sayed, E.T.; Abdelkareem, M.A.; Mahmoud, M.S.; Olabi, A.G. The Role of Wastewater Treatment in Achieving Sustainable Development Goals (SDGs) and Sustainability Guideline. *Energy Nexus* **2022**, *7*, 100112. [CrossRef]
26. Carrard, N. Reorienting Water and Sanitation Narratives towards Sustainability Transformations. *Nat. Water* **2024**, *2*, 2–3. [CrossRef]
27. Nchofoung, T.N.; Nkemgha, G.Z.; Fokam, D.N.D.T.; Kengdo, A.A.N. Achieving the Sustainable Development Goals Through Water and Sanitation: Do Information and Communication Technologies (ICTs) Matter for Africa? *J. Knowl. Econ.* **2024**, *15*, 4383–4407. [CrossRef]
28. Biswas, S.; Adhikary, M.; Alam, A.; Islam, N.; Roy, R. Disparities in Access to Water, Sanitation, and Hygiene (WASH) Services and the Status of SDG-6 Implementation across Districts and States in India. *Heliyon* **2024**, *10*, e37646. [CrossRef]
29. Hall, D.; Lobina, E. Public Policy Options for Financing Sewerage Systems. In *Water and Sanitation Services*; Routledge: London, UK, 2009; ISBN 978-1-84977-375-1.
30. Mela, A.; Alexakis, D.E.; Varelidis, G. Investigating Public Awareness towards Wastewater Management in a Small Community. *Glob. NEST J.* **2022**, *24*, 254–261. [CrossRef]
31. Kecil, J. *Homeowner Behavior Change Relating to Septic System Maintenance in Coastal South Carolina*; University of Michigan School for Environment and Sustainability: Ann Arbor, MI, USA, 2020.
32. Withers, P.J.; Jordan, P.; May, L.; Jarvie, H.P.; Deal, N.E. Do Septic Tank Systems Pose a Hidden Threat to Water Quality? *Front. Ecol. Environ.* **2014**, *12*, 123–130. [CrossRef]
33. Brzusek, A.; Widomski, M.K.; Musz-Pomorska, A. Socio-Economic Aspects of Centralized Wastewater System for Rural Settlement under Conditions of Eastern Poland. *Water* **2022**, *14*, 1667. [CrossRef]
34. Obradović, D.; Šperac, M.; Marenjak, S. Challenges in Sewer System Maintenance. *Encyclopedia* **2023**, *3*, 122–142. [CrossRef]

35. Wolf, L.; Held, I.; Eiswirth†, M.; Hötzl, H. Impact of Leaky Sewers on Groundwater Quality. *Acta Hydrochim. Hydrobiol.* **2004**, *32*, 361–373. [CrossRef]
36. Naughton, O.; Hynds, P.D. Public Awareness, Behaviours and Attitudes towards Domestic Wastewater Treatment Systems in the Republic of Ireland. *J. Hydrol.* **2014**, *518*, 108–119. [CrossRef]
37. Pistocchi, A.; Parravicini, V.; Langergraber, G.; Masi, F. How Many Small Agglomerations Do Exist in the European Union, and How Should We Treat Their Wastewater? *Water Air Soil Pollut.* **2022**, *233*, 431. [CrossRef]
38. Preisner, M.; Smol, M.; Szołdrowska, D. Trends, Insights and Effects of the Urban Wastewater Treatment Directive (91/271/EEC) Implementation in the Light of the Polish Coastal Zone Eutrophication. *Environ. Manag.* **2021**, *67*, 342–354. [CrossRef] [PubMed]
39. Farmer, A.M. Reducing Phosphate Discharges: The Role of the 1991 EC Urban Wastewater Treatment Directive. *Water Sci. Technol.* **2001**, *44*, 41–48. [CrossRef] [PubMed]
40. Mester, T.; Balla, D.; Szabó, G. Assessment of Groundwater Quality Changes in the Rural Environment of the Hungarian Great Plain Based on Selected Water Quality Indicators. *Water Air Soil Pollut.* **2020**, *231*, 536. [CrossRef]
41. Hungarian Central Statistical Office Dwellings Connected to the Sewer System. In Hungarian. Közműolló, Vármegye És Régió Szerint. Available online: https://www.ksh.hu/stadat_files/kor/hu/kor0067.html (accessed on 14 January 2025).
42. Balla, D.; Kiss, E.; Zichar, M.; Mester, T. Spatiotemporal Dynamics of Water Quality: Long-Term Assessment Using Water Quality Indices and GIS. *ISPRS Int. J. Geo-Inf.* **2024**, *13*, 408. [CrossRef]
43. Györki, G.; Szén, O.P.; Knisz, J. Impact of Maintenance on Domestic Wastewater Treatment Systems. *Pollack Period.* **2023**, *18*, 60–65. [CrossRef]
44. Dövényi, Z.; Ambrózy, P.; Juhász, Á.; Marosi, S.; Mezősi, G.; Michalkó, G.; Somogyi, S.; Szalai, Z.; Tiner, T. Magyarország Kistájainak Katasztere = Inventory of Microregions in Hungary. Available online: http://real.mtak.hu/1416/ (accessed on 23 January 2023).
45. Michéli, E.; Fuchs, M.; Hegymegi, P.; Stefanovits, P. Classification of the Major Soils of Hungary and Their Correlation with the World Reference Base for Soil Resources (WRB). *Agrokémia És Talajt.* **2006**, *55*, 19–28. [CrossRef]
46. Richards, S.; Paterson, E.; Withers, P.J.A.; Stutter, M. Septic Tank Discharges as Multi-Pollutant Hotspots in Catchments. *Sci. Total Environ.* **2016**, *542*, 854–863. [CrossRef]
47. Emeka, C.; Nweke, B.; Ihunwo, C.K.; Nta, S. Assessment of Groundwater Quality in Close Proximity to Septic Tanks and Potential Impact on Health. *Eur. J. Environ. Earth Sci.* **2021**, *2*, 8–10. [CrossRef]
48. Hashmi, S.; Kanwal, H.; Ghazal, L.; Arsalan, M. Spatial Distribution Analysis and Mapping of Groundwater Quality of Malir and Landhi Town, Karachi. *Pak. J. Sci. Ind. Res. Ser. A Phys. Sci.* **2023**, *66*, 169–179.
49. Krishnan, R.Y.; Manikandan, S.; Subbaiya, R.; Karmegam, N.; Kim, W.; Govarthanan, M. Recent Approaches and Advanced Wastewater Treatment Technologies for Mitigating Emerging Microplastics Contamination—A Critical Review. *Sci. Total Environ.* **2023**, *858*, 159681. [CrossRef] [PubMed]
50. Rout, P.R.; Shahid, M.K.; Dash, R.R.; Bhunia, P.; Liu, D.; Varjani, S.; Zhang, T.C.; Surampalli, R.Y. Nutrient Removal from Domestic Wastewater: A Comprehensive Review on Conventional and Advanced Technologies. *J. Environ. Manag.* **2021**, *296*, 113246. [CrossRef] [PubMed]
51. Nitka, A.L.; DeVita, W.M.; McGinley, P.M. Evaluating a Chemical Source-Tracing Suite for Septic System Nitrate in Household Wells. *Water Res.* **2019**, *148*, 438–445. [CrossRef]
52. Page, D.; Bekele, E.; Vanderzalm, J.; Sidhu, J. Managed Aquifer Recharge (MAR) in Sustainable Urban Water Management. *Water* **2018**, *10*, 239. [CrossRef]
53. Alam, M.-U.; Sharior, F.; Ferdous, S.; Ahsan, A.; Ahmed, T.; Afrin, A.; Sarker, S.; Akand, F.; Archie, R.J.; Hasan, K.; et al. Strategies to Connect Low-Income Communities with the Proposed Sewerage Network of the Dhaka Sanitation Improvement Project, Bangladesh: A Qualitative Assessment of the Perspectives of Stakeholders. *Int. J. Environ. Res. Public Health* **2020**, *17*, 7201. [CrossRef]
54. Sachet, M.A.D.C.; Bilotta, P. Sustainability Analysis of New Household Connections to the Municipal Sewage Collection Network in Paraná. *Rev. Ambient. Água* **2020**, *15*, e2419. [CrossRef]