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SEWAGE SYSTEMS INVESTMENT AND OPERATIONAL COSTS IN POLAND AND EUROPE IN 1950-2024

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ABSTRACT: This paper presents a historical and contemporary analysis of investment and operational costs associated with sewer networks in Poland and selected European countries from 1950 to 2024. The primary aim of the study is to identify long-term trends and cost dynamics resulting from changing legal frameworks, technological advancements, environmental standards, and urban development pressures. The hypothesis assumes that the costs of sewer infrastructure are not linear over time and are significantly influenced by external regulatory and economic drivers. The methodological approach combines historical data analysis with the use of descriptive statistics and time series models, based on data from national and EU statistics, technical archives, and financial reports. The results indicate several distinct cost phases: post-war reconstruction, expansion during industrialisation, stagnation in the 1990s, and sharp increases after EU accession and implementation of the Urban Waste Water Treatment Directive. The study concludes with a comparative overview of the cost profiles in different European regions, showing convergence of expenditures after 2004. These findings may support future investment planning and policy-making in sewer infrastructure.

KEYWORDS: investment costs, operational costs, sewage, rural areas

Introduction

Rural areas are characterised by unique wastewater management challenges. Scattered development, diverse site conditions and limited financial resources require flexible technological solutions. Since the late 20th and especially since the beginning of the 21st century, significant technological advances have been observed aimed at improving the efficiency, reducing costs and minimising the environmental impact of individual wastewater disposal systems (Bieker et al., 2010; Massoud et al., 2009; WHO, 2024).

Gravity sewers are based on the natural flow of wastewater under the influence of gravity in pipes with a suitable gradient. It is a traditional system that has been used for decades, especially in areas with favourable topography. It is characterised by high operational efficiency and the absence of the need for pumps, which significantly reduces operating costs (Tchobanoglous et al., 2004). Also of great importance is the life span of the system, about 30-50 years (EPA, 2020). In recent years, there has been a trend in the introduction of new pipe materials. There is a move away from traditional concrete pipes to more durable and lightweight materials such as PVC and PEHD. Their maintenance is facilitated by the use of new network inspection technologies: drones and robots. On the other hand, the system requires significant investment, especially in flat areas. In addition, ground conditions (water levels) need to be carefully identified, which can make construction difficult. An important constraint on investment is the dispersal of buildings in rural areas, which leads to the need to build long stretches of network and significantly increases costs (UN 2022).

Capital costs for gravity sewers include three main groups: construction costs (depending on topography, costs can reach €100-150/m) (Sikora-Fernandez 2019); material costs (PVC or PEHD pipes are more expensive, which reduces operating costs); and the need to construct inspection manholes and grease separators also increases costs. The main advantage of these systems is low maintenance costs. The lack of pumped storage systems means that operating costs are limited to monitoring and occasional inspections and are about €0.5-1 per inhabitant per month. Maintenance of pipes and inspection of manholes may only require repairs after 10-20 years of use. The high initial costs but low running costs make the system cost-effective in areas with favourable terrain (Płaszczyk & Pyziak-Szanficka, 1997).

A pressure system uses pumps to pump wastewater through a closed pipe system. It is particularly useful in areas with flat terrain or where distances between buildings are significant. This means that the system can be used regardless of the terrain, and modern modules allow the network to be easily extended (Wang et al., 2024). Compared to gravity systems, lower construction costs are incurred. The installation requires pipes with smaller diameters and embedment depths, which reduces the construction cost to €70-100 per running metre (Terryn et al., 2014). The system requires access to stable sources of electricity, which can be an issue in remote rural areas. Each farm requires the installation of a pump at a cost of €500-1500, depending on the model, which generates energy costs of €30-50 per year per farm, depending on the intensity of use (EPA, 2020). In contrast, the need to install central pumping stations for larger networks is a cost in the order of €20,000-50,000. However, pumps equipped with sensors and energy management systems have been introduced in recent years, which reduces power consumption, but the need for regular pump maintenance (replacement of parts, cleaning) increases operating costs to €2-4 per month per inhabitant. It should be kept in mind that pump failure can lead to system interruptions. Due to lower construction costs but higher operating expenses, pressure sewers are cost-effective in flat and dispersed areas.

Vacuum sewers use the generated vacuum to transport wastewater through a closed pipe system. It is a more advanced technology compared to traditional systems. The system is expensive to build, but its leak-free nature and low energy consumption make it advantageous in areas with difficult hydrological conditions. The effectiveness of a vacuum system depends on the tightness of the entire installation (Wang et al., 2024). Any damage to the pipes or valves can affect the performance of the system. The introduction of systems to monitor the operation of the system allows for rapid detection of malfunctions. Modern sealing materials provide greater durability and corrosion resistance. As a rule, systems must be leak-proof, which reduces the risk of groundwater contamination. In addition, the vacuum eliminates the problem of groundwater infiltration into the system. A vacuum sewer system requires precise design and installation, regular inspection and service, which increases capital costs (Sikora, 2021). It requires leak-proof, high-quality pipes and precise installation, increasing

costs to €120-200 per running metre. The key component of the system, vacuum collection stations, costs €50,000-100,000 depending on the size of the area being served. Modern monitoring and control systems add a cost of €5,000-15,000. During operation, vacuum generation at the collection stations generates energy costs of €1-2 per inhabitant per month. Regular inspection of valves and repair of faults in the system can increase operating costs to €2-5 per inhabitant per month. Due to the advanced technology, repairs are more costly than in other systems (UN 2022; Eurostat 2018).

Methods

This study employs a mixed-methods, interdisciplinary approach integrating historical infrastructure analysis, cost modelling, and macroeconomic evaluation to investigate the evolution of investment and operational costs of sewerage systems in Poland and Western Europe from 1950 to 2024. The central research hypothesis posits that shifts in capital investment patterns, progressive regulatory frameworks, and incremental technological modernisation have systematically reshaped expenditure dynamics in the sewerage sector – both in terms of infrastructure development and system maintenance. The central research hypothesis assumes that historical investment patterns, regulatory transformations, and technological modernisation have significantly influenced the dynamics of both capital and maintenance expenditures in the sewage sector.

The methodological design includes several stages. First, a broad literature review was conducted to contextualise policy, financial, and technical changes in sewerage networks. Sources included peer-reviewed journal articles, EU infrastructure development reports, national planning documents, and sector-specific publications. Key reference data were gathered from statistical databases such as the Central Statistical Office of Poland (GUS), the European Environment Agency (EEA), Eurostat, and the International Energy Agency (IEA).

The empirical data were stratified into three temporal phases: (i) post-war reconstruction and socialist development (1950–1990); (ii) post-transition and EU integration (1990–2024); and (iii) the most recent decade (2014–2024), marked by detailed national statistics and financial reports. These periods correspond to major institutional and economic shifts affecting infrastructure development, including pre- and post-accession to the EU, energy market liberalisation, and climate policy implementation.

Quantitative methods included time-series analysis, linear regression modelling, and inflation-adjusted cost trend forecasting. The models were developed using IBM SPSS Statistics v27 and Microsoft Excel with Solver for optimisation, enabling multivariate simulation of expenditure dynamics. Variables included CPI inflation, energy and fuel prices, labour costs, material prices, and utility service indexes. Comparative benchmarking was applied to distinguish trends across regions and between large and small urban systems.

In addition, scenario-based analysis was employed to assess the macroeconomic shocks – such as the oil crises of the 1970s, the 2008 global financial crisis, the COVID-19 pandemic, and the war in Ukraine – on operational costs. These scenarios incorporated fluctuations in input prices and labour markets, enabling a more nuanced understanding of their regional economic consequences.

Validation of cost models and assumptions was conducted through triangulation with existing academic models and EU-funded project data. Assumptions and methodological limitations were explicitly tested through sensitivity analysis, including error margins and uncertainty intervals.

Results and discussion

Cost and input analysis

The evolution of rural sewerage infrastructure in Europe and Poland reflects the technological, economic and social changes that have taken place over the years. The period from 1950 to 1990 was characterised by limited availability of modern materials and technologies, resulting in higher investment costs and low density of sewer networks. The subsequent period from 1990 to 2024 was a time of intensive modernisation, EU support and technology development, which enabled significant improvements in rural sanitation (Sikorski et al., 1994; Mędryk, 1986; Steele et al., 1980).

Between 1950 and 1990, rural sewerage networks in Europe were rare. Network density was only 0.3-0.5 km/m², which meant that most households had no access to sanitation (WHO, 1974). This was due to the prioritisation of investments in cities, where population density was higher, making such projects more cost-effective. In Poland, the situation was even more difficult; network density was only 0.25-0.4 km/m², and many villages used septic tanks or other primitive solutions. Investment cost in Western Europe and in Poland in 1950-1990 are presented in Figures 1a and 1b.

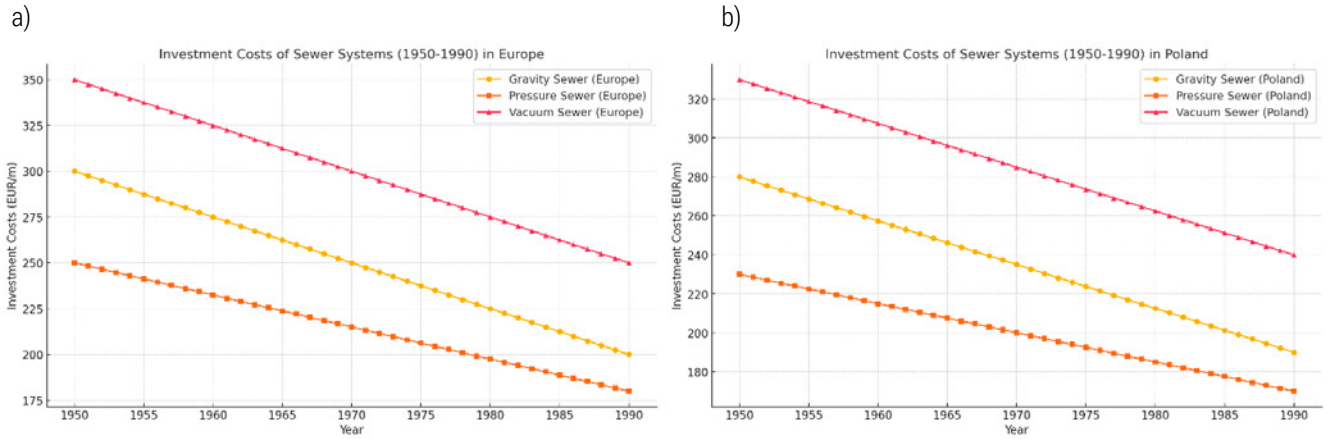


Figure 1. a) Investment cost in Western Europe in 1950-1990, b) Investment cost in Poland in 1950-1990

Between 1950 and 1990, the capital costs of building sewerage systems in Europe were significantly higher than today, which can be attributed to several factors. The first was the limited availability of modern materials such as PVC and PEHD, which today are the standard for sewer pipe construction (Massoud et al., 2009; WHO, 1974). At that time, heavy materials such as concrete or steel were predominant and expensive to manufacture, transport and install (Tchobanoglous et al., 2004). The cost of constructing gravity sewers in Europe averaged between €300 and €200 per running metre, due to the need for deep digging of trenches and the lack of efficient mechanical tools (Steele, 1980). Similarly, pressure sewerage was a relatively new development, whose use was limited by the high price of pumps and the lack of advanced power systems.

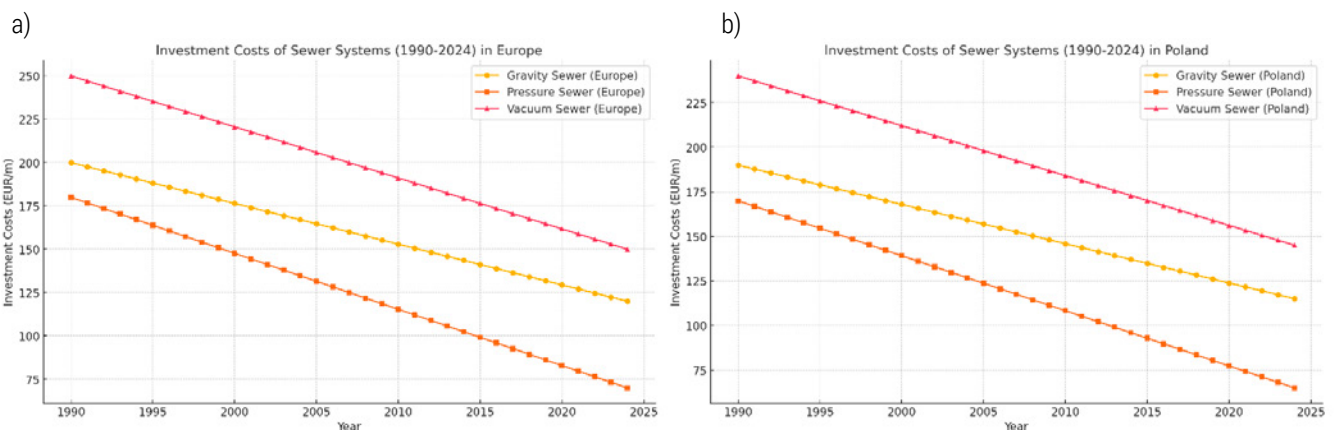


Figure 2. a) Investment cost in Western Europe in 1990-2024, b) Investment cost in Poland in 1990-2024

In the years preceding accession to the European Union, Poland was characterised by a significant deficit in sewerage infrastructure, particularly in rural areas. Only 54% of the population was connected to a sewerage network, while in Western Europe the rate was over 90% (EEA, 2019). Sewerage networks were underdeveloped, with a length of only 0.25 km/m² in rural areas, indicating huge technological backwardness (Mędryk, 1986). Local solutions such as septic tanks and systems discharging untreated wastewater directly into rivers were prevalent, contributing to the degradation of the aquatic environment. This state of affairs was due to limited financial resources and the

lack of appropriate regulations and technologies to meet environmental requirements. In Poland, sewerage construction costs were lower than the European average, mainly due to cheaper labour and simplified construction methods characteristic of a centrally planned economy (Sikorski et al., 1994). However, the quality of infrastructure was poorer, and sewerage networks were less durable, leading to frequent breakdowns and the need for repairs (Krawczyk, 2014; Jekel et al., 2014).

Gravity sewers, which were relatively simpler to build and operate, dominated, although their costs ranged from €280 to €190 per running metre. Pressure and vacuum systems were used to a limited extent, mainly in larger agglomerations or as pilot projects Figure 2a and 2b.

Analysing the period after 1990, the density of rural sewerage networks in Europe has increased to 0.6-1.0 km/m² (Mędryk, 1986). In Poland, after accession to the European Union, it reached 0.5-0.9 km/m², reflecting intensive investment in rural infrastructure supported by European funds (Eurostat, 2018; GUS, 2025). Changes are shown in Figure 3.

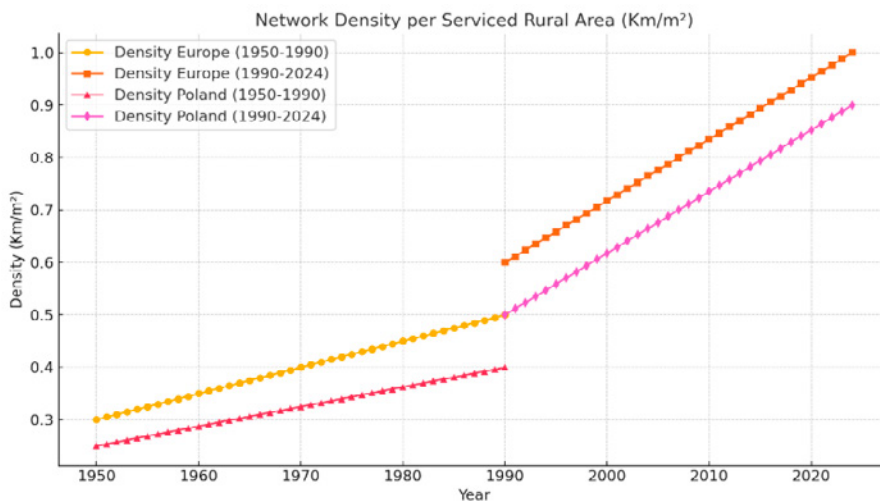


Figure 3. Network density per service rural area (km/m²)

The increase in network density was made possible by the use of more flexible pressurised and vacuum systems, which allowed infrastructure to be adapted to dispersed rural development (Jekel et al., 2013). Following accession, Poland benefited from access to EU funds, including the Cohesion Fund and the European Regional Development Fund (ERDF), which were key to modernising water and wastewater infrastructure (Skoczko, 2012). Between 2004 and 2020, Poland allocated more than €10 billion to the development of its sewerage networks, which has had a significant impact on their length and quality (Eurostat, 2018). These investments allowed the length of the sewerage network to be increased by more than 100%, and the density of the network in rural areas grew to 0.9 km/m², bringing Poland closer to EU standards (EC, 2020). The development of sewerage networks was particularly visible in rural areas that had previously been neglected in terms of infrastructure. Thousands of sewerage network construction and modernisation projects have been carried out as part of EU investment, enabling hundreds of thousands of households to be connected to modern sewage disposal systems. As Terryn et al. (2014) note, this development was made possible by the use of modern technologies, such as pressurised and vacuum systems, which enabled the efficient construction of networks in hard-to-reach and dispersed settlements (Mędryk, 1986).

The years 1990-2024 brought a revolution in the construction and operation of sewerage systems (Jekel et al., 2013; WHO, 2012; WHO, 2015). In Western Europe, the cost of constructing gravity systems dropped to €200-120 per running metre, mainly due to the use of lighter and more durable materials such as PVC and the introduction of modern construction technologies such as prefabrication of components and mechanisation of excavation processes (EEA, 2018; UNESCO, 2006). Pressure and vacuum systems, previously costly and rarely used, have become more accessible, with costs decreasing to €70/m and €150/m respectively (Terryn et al., 2014). The increased availability of energy-efficient pumps and the automation of control systems have been key factors in reducing the operating costs of these technologies (EPA, 2018).

Since the early 2000s, there has been a steady decline in investment costs in the wastewater sector, which has been particularly evident in Western Europe (Figure 4). Thanks to technological advances, the introduction of lighter and more durable materials such as PVC and PEHD, and streamlined construction processes, the construction costs of sewerage systems in Europe have decreased by around 30% over this period (EC, 2020; Tchobanoglous et al., 2004). Gravity systems, which were the dominant solution at the beginning of the period under review, have become more accessible due to the mechanisation of excavation work and the prefabrication of sewer components. The cost of these systems fell from around €150/m in 2000 to €120/m in 2024. At the same time, the development of pressure and vacuum systems has enabled their wider use in difficult terrain, especially in rural and densely built-up areas. Their costs have fallen from €100/m and €200/m respectively to €70/m and €150/m in 2024 (WHO, 2015; UNESCO 2020, UNESCO 2022, EEA, 2018, GUS 2025).

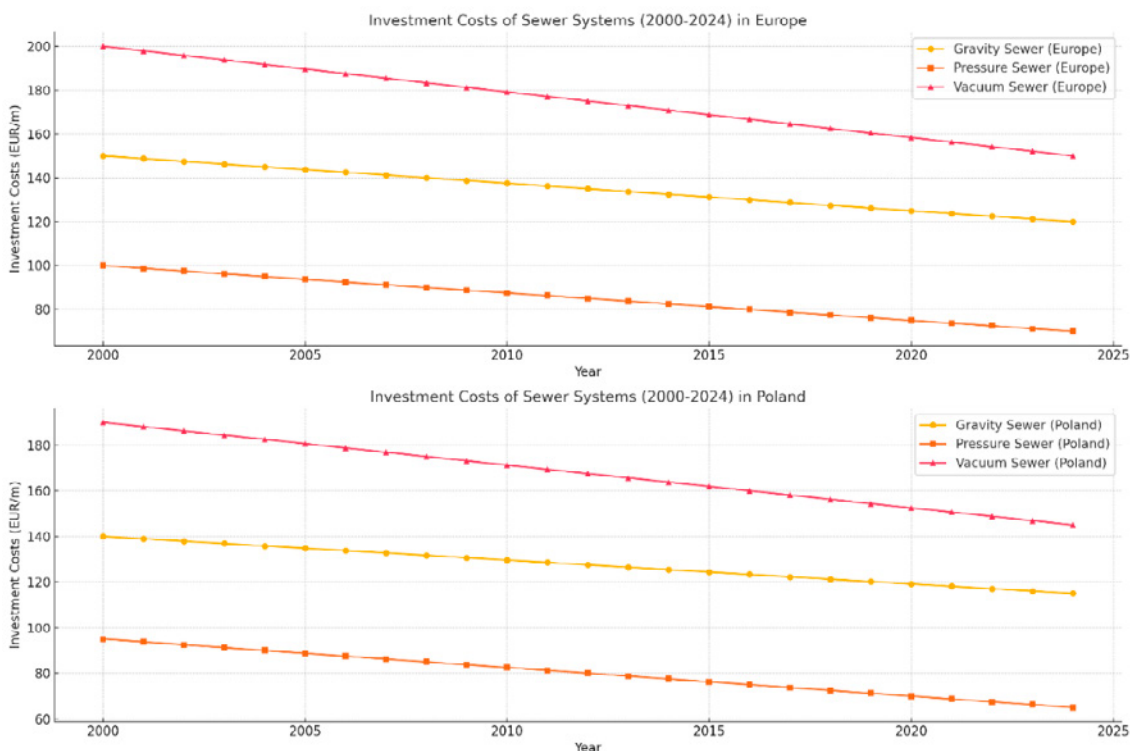


Figure 4. Investment costs in the wastewater sector in Europe and in Poland from 2000-2024

Poland experienced intensive development of its sewerage infrastructure after its accession to the European Union in 2004 (Skoczko et al., 2015). Thanks to EU funding, the cost of sewerage systems in Poland has approached European levels. Technical standards have also risen. Between 2000 and 2024, the cost of gravity systems in Poland dropped from around €140/m to €115/m, bringing it closer to the European average, while pressure and vacuum systems also saw significant reductions. They have become widely used in rural areas with dispersed buildings, with costs ranging from €65 to €70/m. Poland has become one of the leaders in the use of EU funds for sewerage projects, which have been crucial for improving water and wastewater infrastructure (Krawczyk et al., 2014).

Looking at Figure 5, presenting the last decade, 2014-2024, more dynamic changes in investment costs could be observed. The sewerage sector was particularly affected by the energy crisis in Europe, the COVID-19 pandemic and the war in Ukraine. In Europe, the pandemic led to increases in the costs of raw materials and construction materials, resulting in a temporary rise in sanitation construction costs. However, in Western European countries, thanks to advanced technologies and greater market stability, the increase was relatively marginal at around 5-10% (EC, 2021). The cost of gravity systems remained relatively stable, oscillating between €120-125/m, due to the continuous high level of technology and strong competition in the construction market (Terry, 2014). Pressure and vacuum systems, on the other hand, have already registered cost increases between 2020 and 2021, linked to

disruptions in supply chains and rising prices of raw materials such as plastics and metals (Berber, 2020; WHO 2015).



Figure 5. Investment costs in the wastewater sector in Europe and in Poland from 2014-2024

In Poland, the COVID-19 pandemic had a greater impact on the increase in investment costs than in Western Europe. Increases in the cost of materials and problems with access to workers have delayed investments and resulted in higher costs of sewerage systems construction.

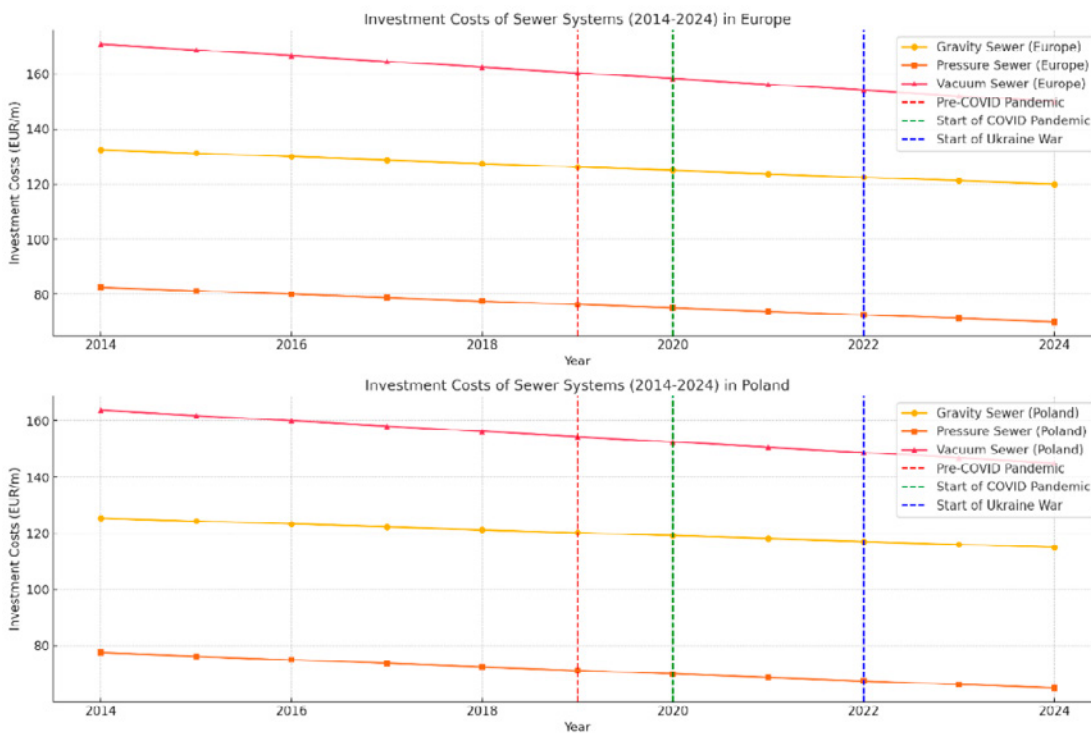


Figure 6. Impact of the pandemic and the war in Ukraine on the investment cost for sewage systems

Between 2020 and 2021, construction costs for gravity systems moved from €110/m to €120/m (EurEau, 2021; UNESCO, 2022). The war in Ukraine in 2022 further intensified energy price issues, which particularly affected pressurised and vacuum systems, which are more energy intensive. Between 2022 and 2024, the costs of these systems increased by around 15% compared to 2017-2019, making it significantly more difficult to implement new projects in rural areas (Sikora et al., 2021). The increase in costs was temporary, and in 2023-2024 these costs started to decrease again due to economic stabilisation and a return to normal manufacturing conditions (UNESCO, 2022; GUS, 2025).

The analysis of sewerage systems' operating costs

The operating costs of sewerage systems have changed significantly over the past 70 years, reflecting technological, economic and environmental transformations. The years 1950-1990 covered a period of post-war infrastructure reconstruction, industrialisation, and economic stabilisation in Western and Eastern Europe. In contrast, the years 1990-2024 reflect the impact of globalisation, technological advances, Poland's integration into the European Union and growing climatic and economic challenges. Operating cost dynamics, like investment costs, were influenced by variables such as rising energy prices, materials, labour costs and global events, including the COVID-19 pandemic and the war in Ukraine.

During the period of infrastructure reconstruction and development in the 1950s and 1960s, the operating costs of sewerage systems were relatively low, mainly due to their simple design and the limited number of high-tech components. In Western Europe, these costs ranged from €2 to €4/m/year converted to present-day prices, and in Eastern Europe from €1.5 to €3/m/year (Steele et al., 1980). Gravity systems were dominant due to their low construction and maintenance costs. Energy was cheap, and labour costs were stable. In Poland and other Eastern Bloc countries, as part of a planned economy, there was a strong emphasis on the massive expansion of urban infrastructure, resulting in numerous but less efficient systems (Stasiak, 1992).

Rising energy costs, driven by the oil crises of the 1970s, significantly increased the operating costs of pressure and vacuum systems, which began to be introduced in the more industrialised regions of Western Europe. In the 1980s, energy costs increased by about 70% compared to the previous decade, pushing the operating costs of pressurised systems from €5 to €8/m/year in Western Europe (Sikora, 2021; Hendriks, 2008; Ojo et al., 2024). In Poland and other Eastern European countries, operating costs also increased, but to a lesser extent, from about €2 to €4/m/year, due to energy subsidies and low incomes. Technologically, the systems remained less advanced, which limited their potential savings (Kowalski et al., 2020).

The collapse of the Eastern Bloc in 1990 and Poland's transition to a market economy increased operating costs, particularly due to rising energy and material prices (Sikora-Fernandez, 2019; Skoczko, 2012; Skoczko et al., 2015; Krawczyk, 2014). Operating costs for pressurised systems rose from €4/m/year in 1990 to €6/m/year in 2000, and for vacuum systems from €6 to €8/m/year (Chant & Goodman, 1999). In Western Europe, advances in energy efficiency and the use of modern materials were evident, limiting cost increases to around 20 per cent in this decade. By contrast, in Poland and other central and eastern European countries, the political transformation has resulted in greater cost growth dynamics, especially in terms of repairs and maintenance (Kowacki, 2015).

Poland's accession to the European Union in 2004 contributed to the modernisation of water and wastewater infrastructure with the support of EU funds. The operating costs of gravity systems in Poland increased from €4/m/year in 2000 to €6/m/year in 2014 (+50%), driven by improvements in service quality and the introduction of more technologically advanced materials and equipment (Krawczyk et al., 2014). In Western Europe, costs increased moderately, from around €7/m/year in 2000 to €9/m/year in 2014 (+28%). Modernisation and the use of smart technologies allowed for partial compensation of rising energy prices (Sikora-Fernandez, 2019; Janson & Hamerla, 2025).

In recent years, dynamic changes in energy prices and disruptions in supply chains have significantly affected the operating costs of wastewater systems. Energy costs have increased by around 60% between 2020 and 2022, which has particularly affected pressure and vacuum systems (IEA, 2025). In Europe, operating costs for gravity systems rose from €5.00/m/year in 2000 to €12.50/m/year in 2024, meaning an increase of 150%. In Poland, the escalation was equally significant – from €4.00/m/year to €11.50/m/year (+187.5%) (EurEau, 2021; GUS, 2025). The reason for this growth

was the rising costs of labour and materials, which are the basis for maintaining simple gravity systems (Kowacki, 2015). The increase in energy prices between 2000 and 2024 particularly affected pressurised systems, which are more energy-intensive due to the use of pumps (IEA, 2025). In contrast, the cost of vacuum systems in Europe rose from €15.00/m/year in 2000 to €37.50/m/year in 2024 (+150%), and in Poland from €14.00/m/year to €34.50/m/year (+146%) (EurEau, 2021; GUS, 2025). These were the most expensive systems to operate, with costs driven not only by energy prices but also by the high frequency of repairs and maintenance.

Between 2017 and 2024, covering the COVID-19 pandemic and the war in Ukraine, operating costs rose fastest (UNESCO, 2020). In Europe, more had to be paid for the use of gravity systems (increasing from €7.00/m/year in 2017 to €12.50/m/year in 2024 (+78.6%)) and in Poland from €6.00/m/year to €11.50/m/year (+91.7%). The main drivers of the increase were higher energy prices and increased labour costs. With pressurised systems, costs climbed from €14.00/m/year in 2017 to €25.00/m/year in 2024 (+78.6%) in Europe, and from €12.00/m/year to €23.00/m/year (+91.7%) in Poland. There was a clear impact from component supply disruptions during the pandemic. The largest percentage expansion was for vacuum systems in Poland between 2017 and 2024, with record levels reached between 2022 and 2023 (from €21.00/m/year in 2017 to €37.50/m/year in 2024 (+78.6%), and from €18.00/m/year to €34.50/m/year in Poland (+91.7%) (EurEau, 2021; GUS 2025). This was due to rising electricity prices and maintenance and repair costs, which were particularly harsh for technologically demanding systems (Gajdzik et al., 2024).

Possibilities to reduce the operating costs of wastewater systems

The operating costs of sewerage systems are an important part of maintaining water and wastewater infrastructure, especially in the face of rising energy, material and labour prices. Optimising these costs is key to ensuring sustainable water and wastewater management. One of the main components of operating costs is electricity, especially in pressure and vacuum systems. The implementation of high-efficiency pumps and energy recovery systems can significantly reduce energy requirements. An example of this can be pumps equipped with variable speed drives that adjust energy consumption according to the current system load (Hendriks, 2008; Ojo, 2024). Additionally, the integration of renewable energy sources, such as photovoltaic panels, can reduce reliance on expensive electricity (UNESCO, 2022).

IoT (Internet of Things) technologies enable the introduction of remote monitoring and management of sewage systems (Riel et al., 2016; Salam, 2020). Smart sensors can monitor flow, detect leaks and predict failures, allowing for more efficient maintenance planning and reduced repair costs (Jansen, 2025; Salam, 2020). Implementing such solutions in pressure and vacuum systems can save 20-30% per year (IEA, 2025). Long-term cost modelling and the implementation of public-private partnerships (PPPs) can help to better manage financial and investment resources. Such models enable more efficient planning of investments in system upgrades and the implementation of new technologies, thereby reducing operating costs in the long term (Wang et al. 2024, Salam, 2020).

Regular preventive maintenance is a key element in the reduction of operating costs. The use of predictive analytics and advanced algorithms for maintenance scheduling can minimise the risk of failures and the associated repair costs (Krawczyk, 2014; Gajdzik et al., 2024). In sewerage systems, water losses and leaks generate additional costs due to the need for increased pumping and emergency repairs. The use of trenchless technologies for pipeline repairs, such as relining (internal rehabilitation), can quickly and efficiently reduce losses and minimise system disruption (Balkema et al., 2002). Especially in vacuum systems, where failures can be costly, optimising the maintenance schedule can reduce maintenance costs by 15-25%. The use of modern materials such as high-density polyethylene (PEHD) pipes, which have greater durability and corrosion resistance, can reduce the costs associated with infrastructure repair and replacement. Examples of the use of such materials in Europe show a reduction in operating costs of 10-15% per decade (EC, 2021).

Future trends in rural wastewater systems: technological, environmental and economic perspectives

Rural sewerage infrastructure will have to face the challenges of global demographic, climate and socio-economic changes in the coming decades. Processes such as urbanisation, the intensifying effects of climate change and increasing environmental and energy efficiency requirements are placing new demands on sewerage systems. Future solutions will not only have to be technologically advanced but also adapted to the specific features of rural areas, which are characterised by scattered housing and limited investment budgets.

Technological innovations in wastewater systems

Technological developments will significantly influence the future of rural sewage systems (UNESCO 2020, 2022). One of the key directions is the development of decentralised wastewater treatment systems that allow wastewater to be managed on site. Domestic wastewater treatment plants, hybrid systems combining features of gravity and pressure sewers, and vacuum technologies are gaining interest, especially in areas with dispersed development (Kowacki, 2015). As Tchobanoglous et al. (2004) point out, decentralisation of water and wastewater systems reduces the costs associated with the construction of extensive sewerage networks and minimises water losses (Berber, 2020). Developments in digital technologies and automation, such as the Internet of Things (IoT) and artificial intelligence (AI), are changing the way sewerage systems are monitored and managed. As Riel with a team (2016) and Salam (2020) note, the introduction of intelligent control systems can change the way sewer networks are managed, especially in areas with difficult access to infrastructure. Integrated monitoring systems, equipped with sensors to detect leaks and analyse water quality, enable faster response to failures and reduce environmental losses. Wang's team (2024) highlight that automation also allows for the optimisation of treatment processes, reducing operational costs and environmental impact.

Environmental challenge and adaptation to climate change

Climate change, such as increasingly frequent droughts and heavy rainfall, has a direct impact on the functioning of sewerage systems. In rural areas, where water infrastructure is less developed, the effects of these phenomena can be particularly severe (WHO, 2024). Increased rainfall intensity leads to overloaded sewerage systems and risk of flooding, while droughts reduce water availability, complicating treatment processes. As the European Environment Agency (EEA, 2015) points out, future sewerage systems must be designed with changing climatic conditions in mind. In rural areas, rainwater retention systems that can store water during heavy rains and use it in times of scarcity are of particular importance. These solutions, supported by EU funds under the Green Deal policy, are becoming increasingly popular in regions with high rainfall variability. As noted by Krawczyk (2014), the use of local water retention systems in rural areas improves their resilience to droughts and reduces pressure on water resources. According to Jekel et al. (2015), these systems not only reduce the risk of flooding but also contribute to the sustainable management of water resources. Sewerage systems of the future will increasingly integrate the treatment of rainwater and wastewater, enabling better use of infrastructure and reducing environmental impact. Such solutions, supported by innovative materials and technologies, allow for better environmental performance while reducing investment and operating costs (Balkema et al., 2002).

Economic aspects of rural sewage systems development

The economics of rural sewerage systems play a key role in their implementation. Due to the dispersed settlement in rural areas, the construction costs of traditional sewerage systems are much higher than in urban areas. EU funds, such as the European Regional Development Fund, play an important role in financing investments in rural areas, but access to these funds involves meeting stringent design requirements (EC, 2020). As Sikora-Fernandez (2019) and Skoczko (2012, 2015) point out, decentralised solutions such as domestic wastewater treatment plants are often more cost-effective in the long term as they eliminate the need for extensive transmission networks.

In addition, rising energy prices pose new challenges for wastewater systems, especially those that require intensive use of pumps and other energy devices. In the future, low-energy technologies, such as natural treatment systems, may play a greater role in reducing operating costs (UNESCO, 2010). Multi-functional wastewater systems that combine the functions of wastewater treatment, rainwater management and energy production are becoming increasingly popular. Biogas plants using waste and wastewater for energy production are particularly attractive in rural areas, where they can contribute to improving the local energy economy. As noted by Bieker et al. (2010), the multifunctionality of the systems enables better use of resources and generates long-term savings.

An additional direction of innovation is the development of closed-loop systems, in which treated wastewater is reused, for example, in agriculture or industry. According to Chant and Goodman (1999), implementing such solutions can significantly reduce water consumption, which is crucial given increasing water scarcity in many rural areas.

Demographic change and urbanisation

Population migration from rural to urban areas is a global trend that affects the development of water and wastewater infrastructure. As noted by WHO (2012), the declining rural population is changing the financial outlook for sewerage projects, which are becoming less viable due to falling user numbers. At the same time, expanded urbanisation, especially of areas closely surrounding cities, is putting increasing loads on urban sewerage systems, which may lead to greater support for local, rural solutions.

Conclusions

The choice of an appropriate sewerage system in rural areas should consider local, environmental, economic and social conditions. Gravity systems remain the dominant technology in favourable site conditions, while pressure and vacuum systems are becoming increasingly popular due to their flexibility. Innovations in automation, monitoring, and materials will play a key role in the future, with the potential to reduce operating costs and improve infrastructure sustainability.

Each of the sewerage systems considered in this paper has a unique cost profile, which determines its use in different site conditions. Gravity sewers are most cost-effective in areas with favourable terrain, despite their high construction costs. Pressure sewerage provides savings in capital costs, but requires more expenditure to operate. Vacuum sewers are technologically advanced, but their initial costs limit their application to areas with specific needs. The choice of sewerage system should take into account both the current costs and the long-term environmental and economic benefits.

A comparison of the two historical periods shows how technological advances, economic changes, and international support have significantly impacted the development of sewerage infrastructure. Between 1950 and 1990, infrastructure was limited, expensive and less efficient, resulting in low network density in rural areas. Modern technological developments, supported by sustainable development policies and EU funds, have significantly improved the availability and efficiency of sewerage infrastructure, especially in Poland. As a result, sanitation in the countryside advanced considerably, which is of key importance for public health and environmental protection.

The figures presented in this paper illustrate the complex, multidimensional changes in the investment costs of sewerage systems in Europe and Poland. In the long term, the period 2000-2024 saw significant cost reductions due to technological advances and EU investments. The period 2014-2024 was characterised by more dynamic changes due to economic crises and global events such as the COVID-19 pandemic and the war in Ukraine. A comparison of data for Poland and Western Europe shows that although Poland has made significant progress in the development of its sewerage infrastructure, it remains more vulnerable to cost fluctuations and market disturbances than more developed Western European countries.

The development of materials such as PVC and PEHD and the optimisation of construction processes have reduced sewer construction costs by around 20-30% since 2000. On the other hand, the technology of sewer component prefabrication has reduced the time required for investment and

labour costs. On the other hand, increases in electricity prices in many countries (especially in recent years) have raised the operating costs of pressure and vacuum systems.

An analysis of the operating cost dynamics of sewerage systems between 1950 and 2024 shows that the largest cost escalation occurred as a result of the energy crises, globalisation and the COVID-19 pandemic. Vacuum and pressure systems are particularly susceptible to fluctuations in energy prices, while gravity systems, although less susceptible to fluctuating energy costs, remain more expensive to maintain due to higher maintenance requirements over longer periods of time. Rising labour and material costs have further increased the financial burden, especially in Poland, where the rate of growth has been higher than in Western Europe.

Despite significant achievements, the development of sewerage networks in Poland still faces some challenges. In many rural regions, some farms remain unconnected to the network due to financial and technical limitations. In addition, rising energy and raw material costs pose new challenges to the water and wastewater sector, requiring further development of innovative technologies and more efficient infrastructure management.

Reducing the operating costs of sewerage systems requires implementing innovative technologies, optimising management processes, and long-term financial planning. The use of intelligent monitoring systems, the modernisation of infrastructure and the use of renewable energy sources can significantly reduce the financial burden associated with the operation of wastewater systems. The implementation of such solutions is key to ensuring the sustainability of water and wastewater management, especially in the face of increasing economic and environmental challenges.

The future of rural sewerage systems will be shaped by technological innovation, changing climatic conditions and demographic needs. Decentralised systems, digital management, and integration of rainwater retention systems will become key elements of this infrastructure. Systems based on natural processes, smart monitoring technologies and new materials have the potential to meet the demographic, environmental and economic challenges of the 21st century. Despite the economic and environmental risks, the availability of EU funding and developments in technology offer an opportunity for the sustainable development of rural sewage systems that can meet the demands of the 21st century.

Acknowledgments

This research was funded by the Polish Ministry of Higher Education and Science, Grant number W/WB-IIŚ/2/2021.

The contribution of the authors

Conceptualisation, I.S., K.W.; formal analysis, IS.; investigation, I.S., K.W.; methodology, K.W.; resources & supervision, I.S.; writing, I.S., K.W.

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KOSZTY INWESTYCYJNE I EKSPLOATACYJNE SYSTEMÓW KANALIZACYJNYCH W POLSCE I EUROPIE W LATACH 1950-2024

STRESZCZENIE: Na obszarach wiejskich odpowiedni system kanalizacyjny ma kluczowe znaczenie dla ochrony środowiska i zdrowia publicznego. Systemy kanalizacyjne na obszarach wiejskich ewoluowały znacząco, dostosowując się do rosnących wymagań środowiskowych, technicznych i ekonomicznych. Przedstawiona w niniejszym artykule analiza kosztów inwestycyjnych w sektorze kanalizacyjnym w Polsce i Europie w latach 1950-2024 odzwierciedla wpływ zmian technologicznych, gospodarczych i społecznych na rozwój infrastruktury wodno-ściekowej. Na przestrzeni lat kształtowały się różne trendy w zakresie kosztów kanalizacji grawitacyjnej, ciśnieniowej i podciśnieniowej. Kluczowe okresy, takie jak przystąpienie Polski do Unii Europejskiej, globalny kryzys finansowy, pandemia COVID-19 czy wojna na Ukrainie, wpłynęły na zmienność kosztów i dynamikę rozwoju tej infrastruktury. Analiza danych porównawczych dla Europy i Polski pozwala zrozumieć, jak specyficzne uwarunkowania gospodarcze i polityczne wpływają na sektor kanalizacyjny.

SŁOWA KLUCZOWE: koszty inwestycyjne, koszty operacyjne, kanalizacja, obszary wiejskie