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DECENTRALIZED WASTEWATER TREATMENT - A SUSTAINABLE SOLUTION FOR PROTECTING WATER RESOURCES FROM POLLUTION

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Abstract

In locations with low population density or constraints in technology, resources, and personnel, the use of centralized wastewater treatment systems is not be justified. In such areas, decentralized wastewater treatment systems offer several advantages over centralized systems. In these systems, the treatment and disposal of effluent is close to the source of waste water production, which reduces investments in a long sewage network and enables the application of other methods of wastewater transport, such as pressure sewerage and vacuum sewerage. A significant advantage of decentralized systems is their ability to be installed quickly, while also enabling local water reuse and implementation of the principles of circular economy, thereby enhancing productivity. In Serbia, according to the 2011 census, there are 449 settlements with more than 2,000 equivalent inhabitants whose wastewater should undergo at least secondary biological treatment. Given that approximately 80% of these settlements have populations ranging from 2,000 to 10,000, the implementation of decentralized wastewater treatment systems becomes imperative for sustainable water protection in Serbia.This paper provides a brief overview of decentralized wastewater treatment systems and, using the example of the municipality of Pirot, highlights the advantages and significance of implementing decentralized treatment to ensure a safe, reliable, economically justified, and ecologically sound solution for protecting water resources from pollution.

Key words: *Decentralized Wastewater Treatment, Sustainability, Protection of Water Resources from Pollution*

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1. INTRODUCTION

The main goal of wastewater treatment is to enable the removal of organic matter and other pollutants from water without endangering human health or polluting the natural environment [1]. The two main approaches to planning wastewater treatment and disposal systems are: centralized treatment, characterized by large facilities serving expansive municipal or regional areas, and decentralized treatment, which utilizes smaller facilities located near the point of water consumption and wastewater generation, with more localized areas of service.

In the field of wastewater treatment, the division between centralized and decentralized systems is currently a focal point of discussion and subject to intensive research. This global discussion has highlighted various economic, technological, environmental, and social barriers in the choice between centralization and decentralization, making it difficult to determine priorities and select one strategy over the other. Therefore, it is necessary to consider the specific conditions of each location and to analyze and address each case individually.

Centralized wastewater treatment systems have been the most widely applied approach to addressing wastewater issues in well-developed urban areas. These systems have been in use since the mid-1800s and have served society well. However, in recent years, it has become increasingly clear that reliance solely on such systems may not be optimal in terms of sustainable wastewater management [2]. Due to the population growth, rapid urbanization, the simultaneous increase in water usage, water scarcity, climate change, and the need for disaster mitigation, there is a growing need to develop more sustainable approaches to wastewater and water resource management [3].

Decentralized wastewater management is increasingly being considered as an alternative or supplement to large centralized collection and treatment systems. Decentralized solutions are being explored to meet the needs of new development zones within or on the outskirts of large cities (even if they already have centralized facilities). Therefore, decentralized systems are becoming a more universal approach to addressing wastewater issues for suburban living.

Small villages and rural communities in both developing and developed countries are also facing the same question: whether to prefer centralized or decentralized systems for effective wastewater management. In locations where population density is low or where there are limitations in technology, resources, and personnel, the implementation of centralized systems is not justified. In such locations, decentralized wastewater treatment systems have several advantages over centralized ones [4].

This paper provides a brief overview of decentralized wastewater treatment systems, using the example of the municipality of Pirot to demonstrate the advantages and importance of implementing decentralized treatment for ensuring a safe and reliable, economically and environmentally sustainable solution for protecting water resources from pollution.

2. WASTEWATER TREATMENT SUSTAINABILITY

Although the concept of sustainability is not explicitly mentioned in EU legislation, it is crucial for the implementation of sustainable wastewater collection, drainage, and treatment systems. The main goal of sanitary systems and wastewater treatment systems is to protect and improve human health by providing a clean environment and interrupting the cycle of diseases. For a system to be sustainable, it must be not only economically viable, socially acceptable, and technically and institutionally appropriate but also protect the environment and natural resources. When improving existing and/or designing new sanitary systems, sustainability criteria related to the following aspects should be considered [5]:

1. Health and hygiene: This includes the risk of exposure to pathogens and hazardous substances that could affect public health at all points of the sanitation system, from toilets, through collection and treatment systems, to the point of reuse or disposal and downstream populations.
2. Environment and natural resources: This includes the necessary energy, water, and other natural resources for construction, operation, and maintenance of the system, as well as the potential environmental emissions resulting from exploitation of the system. It also includes the degree of recycling and potential reuse and its effects (e.g., reuse of wastewater; returning nutrients and organic matter for agriculture) and the protection of other non-renewable resources (e.g., through the production of renewable energy sources, e.g., biogas).
3. Technology and operation: This encompasses the functionality and ease with which the entire system, including collection, transport, treatment, and reuse and/or final disposal of water, can be built, operated, and monitored by the local community and/or technical teams of local municipal enterprises. The system's robustness, its vulnerability to power outages, water shortages, floods, etc., and the flexibility and adaptability of its technical elements to existing infrastructure, demographic, and socio-economic development are important aspects to assess.
4. Financial and economic aspects: These relate to the households' and communities' capacities to pay for sanitation, including construction, operation, maintenance, and necessary reinvestments in the system.
5. Socio-cultural and institutional aspects: Assess the socio-cultural acceptance and appropriateness of the system, suitability, systemic perceptions, gender issues, and impacts on human dignity, compliance with the legal framework, and stable and efficient institutional arrangements.

3. CENTRALISED WASTEWATER TREATMENT

A centralized system is characterized by the collection and treatment of wastewater through a combination of centralized sewage and a centralized wastewater treatment plant, followed by disposal in controlled conditions [6]. Centralized system appear as more feasible solutions for densely populated regions that are already connected to a sewage system. By definition, these systems serve large and densely populated areas with a high number of apartments and households. One of the main advantages of centralized wastewater systems is the uniformity in meeting water demand while adhering to quality standards for a large urban area.

The introduction of centralized wastewater collection and treatment systems as a standard in urban areas has been a key factor in improving sanitation and wastewater systems. However, over the last 20 years, it has become evident that existing centralized wastewater treatment systems have several drawbacks and often fail to meet sustainability criteria:

1. Despite the existing wastewater treatment systems and undeniable improvements in public health and the environment, the quality of many

surface and groundwater bodies is still negatively impacted by nutrients, microorganisms, and hazardous substances from discharged wastewater.

2. There is a need to recover nutrients from wastewater, especially phosphate, as it is an endangered fossil resource. Today, many countries have recognized the calls for new concepts that enable the safe use of nutrients from wastewater.
3. Centralized management of sewage and wastewater treatment is not the right response to climate change adaptation as it requires a lot of energy and does not close local water cycles.
4. High investment and operational costs, consequential expenses, and their inflexibility make centralized systems inaccessible and difficult to manage.

Given these shortcomings, recommendations from the scientific, expert, and political communities suggest that sanitation systems must change to enable decentralization, potentially down to the level of a single household or group of households. Water cycles should be closed locally, and nutrients in households should be available for safe reuse in agriculture. The fundamental principles of innovative sanitation and wastewater treatment concepts are treatment at the source, recycling/reuse of water and nutrients, and the aspect of decentralization.

4. DECENTRALIZED WASTEWATER MANAGEMENT CONCEPT

Small/decentralized wastewater treatment systems can be used for individual houses, small communities, or groups of small communities where centralized sewerage is not justified. They are highly suitable for small communities, sparsely populated areas, and specific industries. In such locations, decentralized wastewater treatment systems have many advantages over centralized ones.

The significance of smaller/decentralized plants in water pollution protection plans has been underestimated in current practice, and their specificities have not been considered in the planning and design of such systems. It is unprofessional and unacceptable to argue that there is no room for the construction of smaller plants, insisting instead on building regional drainage systems with centralized wastewater treatment at all costs. Based on the on-site conditions and collected data, a detailed analysis should be conducted before choosing between a large central plant or several smaller/decentralized wastewater treatment plants (Figure 1).

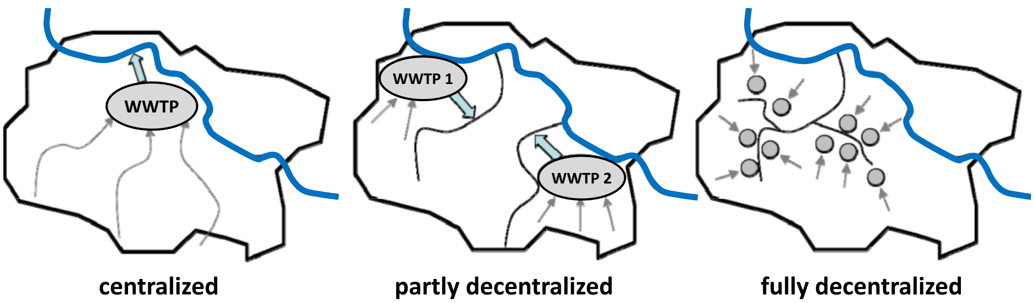

Figure 1. Centralized and decentralized wastewater treatment [7]

In decentralized systems, the treatment and disposal of effluent occur close to the source of wastewater production, resulting in a short wastewater transport network. This reduces the need for extensive investments in sewer networks and pumping stations. The small size of the network allows for the use of various wastewater transport methods in addition to gravity, such as pressurized sewer systems and vacuum sewers.

The implementation of small/decentralized plants typically does not result in savings in the construction of the facilities themselves. However, it is often a much cheaper option compared to a centralized system when considering the cost of the sewer system for collection and conveyance of wastewater. Small/decentralized wastewater treatment plants are easier to finance, simpler to plan, and quicker to implement because each project is much smaller than a conventional centralized system. A large percentage of the costs can be covered by private investments from direct users. A significant advantage of decentralized systems is that they can be installed quickly when needed.

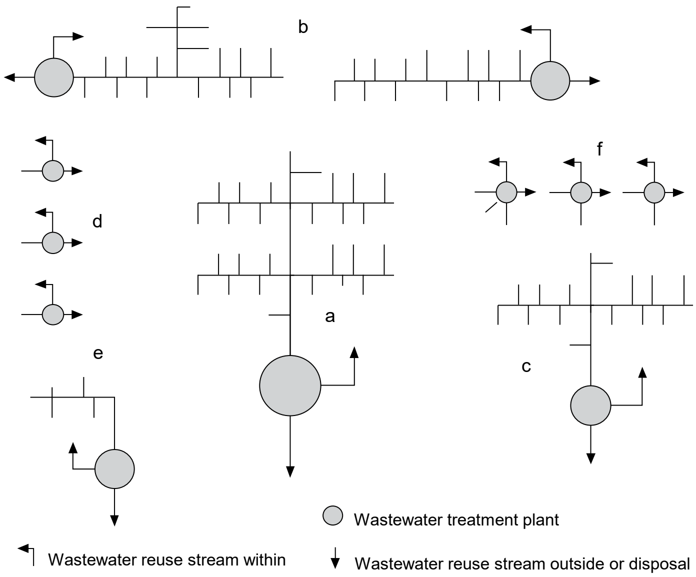

Figure 2. Schematic diagram of decentralized wastewater management concept for a small community [8]

a) Subsystem for residential and commercial centre, b) Subsystems for residential neighborhoods, c) Subsystems for industrial development, d) Subsystem for individual residences, e) Subsystem for new development, f) Subsystems for establishments or clusters of homes

Decentralized wastewater treatment systems enable local water reuse and the implementation of circular economy principles, thereby increasing productivity. Decentralized wastewater management involves managing wastewater as close to the potential reuse point as possible.

A decentralized wastewater management system for a small settlement or group of settlements can consist of several smaller subsystems for collection, treatment, and reuse. The size of each subsystem is determined by administrative and drainage boundaries, as well as other prevailing social and economic conditions. The smallest system can serve a single household [8]. Figure 2 provides a schematic representation of the decentralized wastewater management concept.

Decentralized management is flexible and can utilize a combination of cost-effective solutions and technologies [9] adapted to the prevailing conditions in different parts of the community. For example, conventional wastewater treatment systems can be applied to highly developed and densely populated commercial and residential centers within the community, while natural wastewater treatment systems or onsite systems can be applied to sparsely populated residential neighborhoods.

Decentralized wastewater treatment systems that are properly managed can be a cost-effective and sustainable option for achieving public health and water quality goals, especially for small suburban communities and rural areas.

4.1. Technologies for wastewater collection

Technologies for wastewater collection applicable in small communities or for transport of wastewater to decentralized treatment plants can be divided into two groups: greywater separation as an alternative management scheme for individual households and alternatives to conventional gravity sewerage [10].

4.1.1. Onsite Systems

The primary component of onsite wastewater collection is typically a septic tank; all wastewater generated in the house is collected in the septic tank, which provides flow equalization as well as initial wastewater treatment [10].

When it comes to wastewater collection, alternative management is possible if greywater and fecal waste are managed separately. This approach is attractive when disposal of wastewater into the ground is prohibited or when there is interest in reuse of greywater on the location, potentially along with treated fecal matter. However, some local regulations either prohibit or have unclear provisions for certain types of greywater disposal and separate fecal waste management.

The definition of greywater varies depending on the country. It is typically defined as used water that does not contain fecal matter, such as water from sinks, showers, dishwashers, or washing machines, although definitions may differ depending on local regulations. Greywater is wastewater with low solids content, with much lower concentrations of biochemical oxygen demand (BOD), nutrients, and pathogens compared to combined wastewater, and it does not require much treatment before disposal or reuse. Subsurface disposal of greywater is often possible without any treatment. Separate collection and disposal of greywater are particularly attractive if it can be reused for landscape irrigation after treatment.

4.1.2. Alternative Sewerage

Several alternatives to conventional gravity sewerage have been developed for wastewater collection applicable to small communities or for transport of wastewater to decentralized treatment plants, offering significant advantages for small and decentralized communities. The most common types of alternative solutions are: small-diameter sewers, pressurized sewers, or vacuum sewers. All of these alternatives use cheaper materials, typically polyvinyl chloride, because they can accommodate smaller diameter pipes. Additionally, they can utilize smaller gradients, allowing pipes to be installed at shallower depths compared to conventional gravity sewerage, resulting in significant savings in cost of construction (materials, excavation, and manholes). However, whether alternative sewerage can be built at a lower cost than conventional gravity sewerage depends on many other factors [10].

Construction of alternative sewerage is more favorable than conventional gravity sewerage for low-density residential areas because excavation and material costs are lower. In some areas, such as those with rocky terrain or high water tables, excavation to larger depths for conventional sewerage construction is undesirable, making construction of alternative sewerage a more cost-effective solution. Finally, alternative sewerage construction is more economical if the wastewater treatment plant is located at a similar or higher elevation than the households. Any of the alternatives can provide complete sewerage for the community or can be used in combination with conventional gravity sewerage as needed.

4.2. Wastewater treatment technologies

For individual households and small communities, a wide range of wastewater treatment technologies are available. At one end of the spectrum are highly mechanized technologies that use pumps to distribute wastewater, mechanical equipment for mixing, aeration, filtration, and other processes. Significant advancements in technology have emerged in this spectrum in recent years. At the other end of the spectrum are technologies that rely on gravity flow, have few or no moving parts, and rely on natural processes to achieve the required treatment. These technologies tend to have lower costs, minimal or no energy requirements, and require less maintenance. However, for wastewater treatment, they rely more on climatic conditions and environmental conditions, resulting in variations in treatment efficiency. Wastewater treatment technologies are generally known and will not be discussed separately in this paper. Below are only basic notes related to these technologies [10].

4.2.1. Onsite Wastewater Treatment

The most common configuration for onsite wastewater treatment systems consists of two components: a septic tank (ST) and a soil absorption system (SAS). Conventional ST-SAS systems are typically passive and operate entirely by gravity flow without the need for energy. The purpose of the septic tank is to provide removal of larger particles through sedimentation. Usually, a two-compartment or three-compartment septic tank is utilized. The mass of solid particles accumulating in the tank decreases over time due to anaerobic degradation. However, periodic removal of this sludge is necessary. Effluent from the septic tank is discharged into the soil absorption system, which aims to distribute wastewater into the soil, where it percolates through the unsaturated soil layer to the groundwater. During percolation, wastewater undergoes further purification through natural processes, primarily adsorption onto soil particles and biodegradation. An alternative to direct discharge into the soil absorption system is to provide additional treatment through intermittent filters. Typical filters use sand or fine gravel media, but synthetic media, which offer better performance compared to granular media, are increasingly being used [10].

Correctly designed ST-SAS systems should achieve sufficient wastewater treatment to prevent unacceptable contamination of groundwater, which ultimately receives the wastewater [10].

Alternative to ST-SAS systems are compact standalone wastewater treatment units. There are a large number of compact units available from different manufacturers. Most compact units use some form of biological treatment, which can be based on aerobic, anaerobic, or anoxic conditions and utilize attached or suspended organisms. Other processes such as membrane filtration and disinfection with chlorine, ultraviolet light, or ozone can also be incorporated into compact units. Some compact units are designed to provide water reuse and can produce extremely high-quality effluent [10].

4.2.2. Small and Decentralized Wastewater Treatment

Every intensive and extensive technology is applicable to decentralized wastewater treatment plants, as well as to large centralized plants, with the note that of course different technologies have their own advantages and disadvantages that need to be considered when choosing a technology [10].

As with centralized treatment plants, the conventional wastewater treatment process consists of a combination of physical, chemical and biological processes and operations for removal of solid pollutants, organic matter, and occasionally, nutrients from wastewater.

In wastewater treatment plants, intensive biological processes intensify the natural phenomena of degradation of organic matter and removal of nutrients. The most developed and advanced technologies are the activated sludge system with aeration, which requires a stable supply of electrical energy and skilled personnel for operation and maintenance, and trickling filters, which are well-known technologies and represent the standard in biological treatment.

Over the past few decades, there has been a growing focus on the need for more affordable, sustainable, and efficient wastewater treatment technologies, based on ecological principles and technologies based on natural wastewater treatment systems [9]. In natural systems, pollutants from wastewater are removed or transformed through natural processes. Natural treatment systems can be categorized into soil-based processes (including subsurface, slow-rate surface, rapid infiltration, overland flow) and aquatic-based processes (like wastewater stabilization ponds, wetlands, floating aquatic plants, and fish ponds...).

The main advantages of natural treatment systems are that they use little to no energy and chemicals, have lower construction and operational costs compared to mechanized systems, require less labor and maintenance, and have the ability to recover resources (water and nutrients) for reuse. The main drawbacks are the higher variability in effluent quality due to the dependence of treatment on climate factors and the need for large land areas. This often makes them impractical for large populations. Their application is recommended for communities with fewer than 5,000 inhabitants, but they can also be used for larger settlements with sufficient available land.

When selecting a wastewater treatment technology, several factors require careful study depending on the quality of the wastewater and the desired level of treatment, including reliability of operations and the ability of adaptation to changing loads, concentration of suspended and dissolved materials at the treatment plant outlet, noise and gas emissions, lifespan of facilities and equipment, energy consumption and use of other operational resources and chemicals, availability of equipment and spare parts in the domestic market [11].

Treatment processes cannot be directly copied and applied to every wastewater source or every location. It should be noted that small/decentralized plants should not simply be scaled-down versions of large treatment plants, nor should they rely on standard or off-the-shelf solutions, considering their specificities, such as: variations in the quantity and quality of influent are greater than in large urban plants, there are challenges in the treatment and disposal of sludge, which typically needs to be adapted for later use in agriculture, operational reliability should be prioritized over space and time savings, thus simpler yet more robust technologies and equipment are recommended [11].

It's important to note that regardless of the chosen wastewater treatment technology, the effluent discharged from the treatment plant must meet the established criteria and regulations for discharnging water into receiving water bodies, as defined by relevant legislation.

5. CASE STUDY – PIROT MUNICIPALITY

According to the 2011 census, there are 449 settlements with more than 2000 equivalent inhabitants (EI) in Serbia, whose wastewater should undergo at least secondary biological treatment, which accounts for 92.9% of the total number of settlements. Considering that around 80% of these settlements have a population between 2000 and 10,000 inhabitants, the implementation of decentralized wastewater treatment systems emerges as imperative for sustainable water protection in Serbia [11].

The municipality of Pirot is located in southeastern Serbia, in the Pirot Basin. The city of Pirot serves as the center of the Pirot municipality and Pirot district, functioning as an industrial, economic, cultural, and administrative center for the upper Ponišavlje region. Situated on the banks of the Nišava River, on the edge of the Pirot Basin, the city lies in an area characterized by fertile land suitable for agriculture. With a surface area of 1232 km², the Pirot municipality ranks third in Serbia in terms of area, while in terms of population, it ranks 26th, and it can be considered a representative municipality in terms of wastewater management [12].

On the territory of the Pirot municipality, according to the 2011 census, there were 72 settlements: 70 settlements with fewer than 2,000 inhabitants (constituting 97.2% of the total number of settlements) where 12,460 people lived (25.12% of the total population), and 2 settlements with more than 2,000 inhabitants, the city of Pirot and Gnjilan, with a total population of 37,141 inhabitants (74.88% of the total population), of which 34,942 residents live in Pirot and 2,199 in Gnjilan [12].

Based on the Directive on Urban Waste Water Treatment (91/271/EEC) [13], it is necessary to provide collection and secondary treatment of municipal wastewater for settlements larger than 2,000 Population Equivalents (PE), which, in the municipality of Pirot, are only the city of Pirot and the suburban settlement of Gnjilan. For other settlements in the Municipality of Pirot, according to the Directive, it is not necessary to provide collection and treatment of wastewater [12].

The city of Pirot and the suburban settlements of Novi Zavoj, Gradašnica, Berilovac, Gnjilan, Barje Čiflik, and Poljska Ržana have a sewer network built for collection of wastewater from the city and suburban areas. However, the sewage is discharged untreated into the Nišava River downstream of Pirot. To comply with the Directive, it is necessary to construct a centralized Wastewater Treatment Plant (WWTP) for the city of Pirot, where wastewater from the city and suburban settlements connected to the existing urban sewer network will be treated [12].

Due to the significance of the Nišava River for the city, one of the key issues receiving considerable attention in the municipality of Pirot is the protection of water from pollution.

The most favorable solution proposed by the General Sewerage Plan for wastewater from the villages of Poljska Ržana, Trnjana, Veliki Jovanovac, Mali Jovanovac, Veliko Selo, and Krupac in the Municipality of Pirot [14] is the construction of a regional sewerage system connected to the city's sewer network. This entails building sewerage networks within the villages and a main collector with three pumping stations to connect the villages to the regional system. Wastewater would then be directed towards the city's sewer network and central treatment plant.

In the study Analysis of the State of Wastewater Collection, Conveyance, and Disposal on the Territory of the Municipality of Pirot [15], an analysis of all settlements in the municipality of Pirot was conducted regarding the collection, conveyance, and disposal of wastewater, along with a proposed concept for water protection in the municipality's territory. For the city of Pirot and suburban settlements within the General plan area, it was proposed that wastewater treatment be carried out at the central municipal plant. For other settlements along the banks of the Nišava River upstream from Pirot, given their significant distance from the city, shared sewerage is not justified. Therefore, in accordance with modern principles and positive global experiences, the solution proposed is the collection and treatment of wastewater through small/decentralized plants for one or more settlements, depending on the conditions on the terrain. For all other settlements, it is suggested that the collection and disposal of wastewater be addressed individually through impermeable septic tanks and on-site technologies. The Municipality of Pirot has adopted the water protection concept proposed in the study (Figure 3).

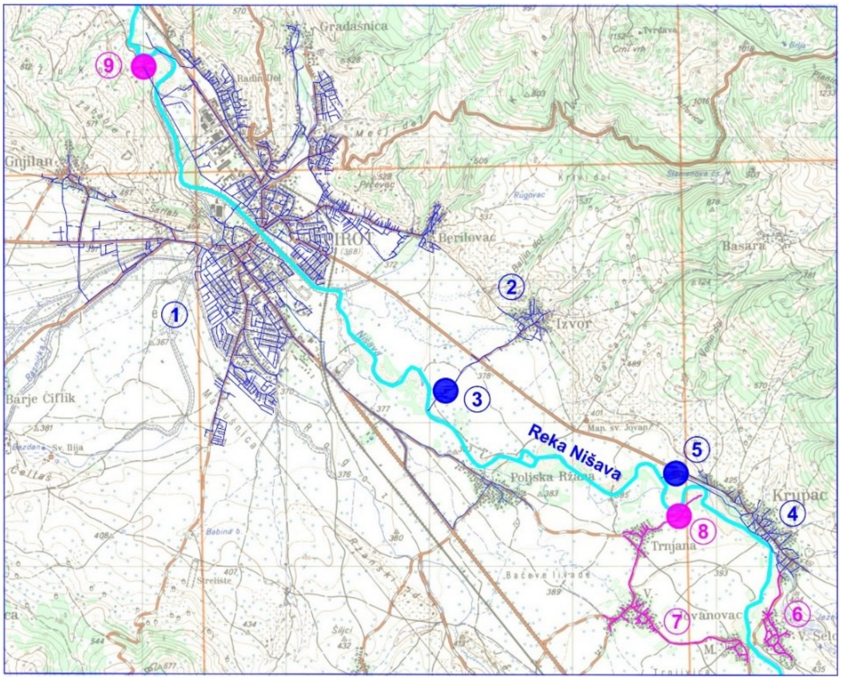

Figure 3. The concept of wastewater treatment in the municipality of Pirot

1- existing sewer system of the city of Pirot and suburban settlements, 2- existing sewer system of the village Izvor, 3- existing WWTP Izvor (1000 PE), 4- existing sewer system of the village of Krupac, 5-existing WWTP Krupac (2500 PE), 6- newly designed sewage network of Veliko Selo settlement, 7-newly designed joint sewage network for the settlements of Veliki and Mali Jovanovac and Trnjana, 8- newly designed joint decentralized WWTP Trnjana (900 PE) for the settlements Veliki and Mali Jovanovac and Trnjana, 9-central city WWTP Pirot (60000 PE)

In accordance with this concept, for the settlement of Krupac located on the right bank of the Nišava River with an established sewerage network, a compact decentralized WWTP (2500 PE) has been built. For the settlement of Izvor, also located on the right bank of the Nišava River, a sewerage network and a compact decentralized WWTP (1000 PE) have both been constructed. Furthermore, activities have been undertaken to develop technical documentation for the construction of a central urban WWTP (60000 PE), the construction of a sewerage network for the settlement of Veliko Selo to connect to the existing sewerage network and the existing compact decentralized WWTP (2500 PE) in the settlement of Krupac. Additionally, technical documentation is being prepared for the construction of a shared sewerage network and a compact decentralized WWTP (900 PE) for the settlements of Veliki Jovanovac, Mali Jovanovac, and Trnjana.

Considering that the construction of wastewater treatment plants represents an economic activity that requires significant resources to achieve an increase in services within a certain time frame, with the ultimate goal of meeting the needs of the population and environmental protection requirements, a Cost-benefit analysis of proposed variants of centralized and decentralized water protection systems in the municipality of Pirot was conducted. Based on the analysis, it was established that the adopted variant of the decentralized system is both financially and economically more viable than the variant of the centralized system.

The municipality of Pirot has undertaken a series of activities in accordance with modern principles and positive global experiences to ensure the most favorable solution for the collection and disposal of wastewater in the municipality. This creates conditions for sustainable and economically justified protection of water resources, primarily the Nišava River, in accordance with regulatory requirements.

6. CONCLUSION

Accelerated expansion of wastewater management services in small communities is of paramount importance for addressing concerns about water scarcity, pollution of water resources, and public health protection.

Planners and decision-makers often favor conventional centralized wastewater treatment systems, which are costly and water-intensive. However, introducing conventional centralized sewage systems in small communities is not sustainable and cannot be justified.

The development of wastewater management services requires improvement in the planning processes that tailor solutions to the social, cultural, ecological, and economic conditions in target areas. Solutions should be location-specific, sustainable, and cost-effective. Guidelines for selection and development of wastewater management systems in small communities greatly facilitate the decision-making process.

The basic principles that should be respected in the development of wastewater management services in small communities are that wastewater should be viewed as a resource that can and must be recovered and reused, and that wastewater should be managed as close as possible to its source and to the point where reuse is feasible. Applying these principles involves adoption of the concept of decentralized wastewater management, aiming to develop treatment systems that are more financially accessible, socially responsible, and environmentally sustainable than conventional centralized systems.

In Serbia, according to the 2011 census, there are 449 settlements with populations larger than 2000 Equivalent Inhabitants (EI) whose wastewater should undergo at least secondary biological treatment. Considering that around 80% of these settlements have populations ranging from 2000 to 10000 inhabitants, the implementation of decentralized wastewater treatment systems emerges as imperative for sustainable water protection in Serbia.

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