Introduction

Natural environments, including rivers, possess an inherent self-cleaning capacity that allows them to break down pollutants and recover from disturbances. This resilience enables ecosystems to regenerate after natural disasters or minor contamination events, provided they are given sufficient time and space. However, anthropogenic pollution differs significantly: it is constant, cumulative, and enters watercourses at numerous points along the stream. This continuous pressure overwhelms the river's natural ability to purify itself. Without appropriate treatment, municipal wastewater causes a critical build-up of contaminants, tipping the balance and leading to ecosystem collapse.

1. Characteristics of rural settlements and wastewater

Rural areas are characterized by low population density and scattered settlements, often situated within diverse and challenging topographies (e.g., hilly terrain, protected natural environments, or agricultural land). In these settings, connecting individual households to a centralized sewer network is often technically challenging and economically unfeasible due to the high cost of constructing and maintaining extensive pipeline infrastructure.

Furthermore, wastewater in rural catchments exhibits specific hydraulic and qualitative patterns, most notably:

- High hydraulic variability: significant fluctuations in daily flow rates.
- Variable loading: high concentrations of pollutants subject to sharp peaks (shock loads).

Beyond physical challenges, rural municipalities often face a shortage of specialized staff to operate complex infrastructure. Consequently, small-scale wastewater treatment plants (WWTPs) must be designed to meet specific criteria:

- Simplicity: Technology should be simple to operate and maintain with minimal intervention.
- Robustness: Systems require high process stability and sufficient reactor volume to buffer fluctuations in flow and concentration.
- Efficiency: Low sludge production to minimize disposal costs.

Ultimately, regardless of the technology selected, appropriate operation, monitoring, and maintenance are essential to ensure consistent treatment performance and environmental protection.

2. Treatment wetlands

Treatment Wetlands (TWs), also known as Constructed Wetlands (CWs), are engineered systems designed to utilize natural processes for wastewater treatment. The technology was pioneered in Germany in the 1950s by Dr. Käthe Seidel, with the first full-scale applications appearing in the late 1960s and 1970s. Since then, the technology has matured significantly, gaining widespread global adoption in the 1980s and 1990s.

Today, TWs are available in various configurations, ranging from extensive Free Water Surface (FWS) systems to compact Subsurface Flow (SSF) beds.

These systems align perfectly with the requirements for rural wastewater management: they are robust, reliable, and highly efficient at removing organic matter, nutrients, and pathogens. Furthermore, TWs are simple to construct, operate, and maintain. Beyond water purification, they offer valuable ecosystem services, including biodiversity support, microclimate regulation, biomass production, and the creation of aesthetic green spaces.

While TWs generally require a larger footprint than intensive technologies like activated sludge, they integrate seamlessly into the natural landscape. For complex treatment needs, they can be effectively combined with other technologies, such as Upflow Anaerobic Sludge Blanket (UASB) reactors, activated sludge systems, or high-rate algal ponds.

3. Treatment processes

In a TW, wastewater is remediated through a complex interplay of physical, chemical, and biological processes.

Primary Treatment (Sedimentation): In the majority of TW systems, the first stage involves a sedimentation tank (often a multi-chamber septic tank). Here, settleable solids accumulate at the bottom as sludge, which requires removal every few years. This stage also facilitates the initial anaerobic degradation of organic matter, typically removing 30–50% of the organic load before the water enters the wetland bed.

The Wetland Bed: Within the wetland bed, diverse mechanisms occur simultaneously, including filtration, sedimentation, adsorption, and microbial degradation.

The Role of Plants (Macrophytes): Although plants are the most visible component of a TW, their direct uptake of pollutants is often secondary to their indirect roles. Their primary function is to engineer the rhizosphere—the biologically active zone surrounding the roots. Plants release root exudates (carbon sources) and transfer small amounts of atmospheric oxygen into the soil (radial oxygen loss), stimulating a diverse community of microorganisms. Furthermore, root growth creates macropores in the substrate, stabilizing hydraulic conductivity and preventing clogging.

The Role of Microorganisms: The bulk of pollutant removal is performed by microorganisms. Aerobic and anaerobic bacteria degrade organic matter and drive the nitrogen cycle. Ammonia is oxidized to nitrate (nitrification) in aerobic zones, while nitrate is converted to nitrogen gas (denitrification) in anoxic/anaerobic zones.

Nutrient & Micropollutant Removal: While plants uptake a fraction of nutrients, high-efficiency removal often requires additional engineering:

- Phosphorus: Often requires specialized sorption media (e.g., reactive filter materials) or chemical dosing (flocculants), as standard gravel saturates quickly.
- Nitrogen: Total nitrogen removal often requires recirculation of nitrified effluent back to the anoxic sedimentation tank to facilitate denitrification or combining vertical and horizontal flow TW.

Finally, TWs demonstrate capacity for removing heavy metals (via adsorption and phytostabilization) and emerging micropollutants, such as pharmaceutical residues.

4. Types of TW

For rural wastewater treatment, subsurface flow TW are the standard technology. In these systems, wastewater flows beneath the surface of a porous media (gravel or sand), preventing direct contact with the water. This design eliminates potential odors and prevents the breeding of mosquitoes or other vectors.

Maintenance of (individual) constructed wetland wastewater treatment systems, regardless of their type, mainly depends on the system's capacity and the installed technological components.

Special attention must be given to:

- Mechanical pre-treatment units (coarse and fine screens or grates) for the removal of larger solid particles, since these coarse solids could otherwise hinder the biological treatment process and cause clogging and operational disturbances in the entire system;
- The primary or Imhoff settling tank or septic tank, located after mechanical pre-treatment and before inflow to the constructed wetland bed. In this section, suspended solids and organic matter (primary sludge, fats) are removed, followed by anaerobic sludge digestion.

Primary stabilized sludge can be removed in two ways: either it is pumped to reed beds (3–6 times per year), where the stabilization and mineralization processes continue, or it is extracted using a vacuum tanker and transported to a larger wastewater treatment plant equipped with appropriate sludge treatment technology.

<u>Regular maintenance therefore includes:</u>

- Manual removal of particles and other waste (waste that does not belong in the sewer system!) accumulating on mechanical pre-treatment devices (smaller constructed wetland systems usually do not have mechanical pre-treatment units),
- Inspection of sludge volume and pumping sludge to reed beds located next to the constructed wetland system or transporting sludge to a larger wastewater treatment plant; and, if necessary,

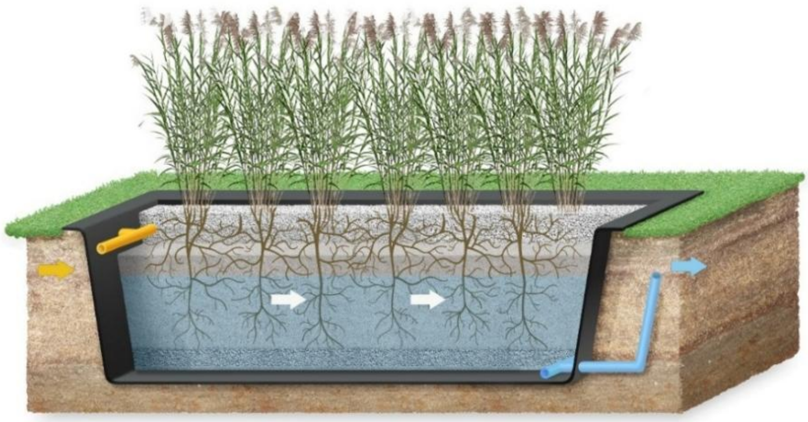
sludge removal from the system (primary settling tank, septic tank, Imhoff tank, etc.) — smaller (household) individual systems once per year, larger systems once per month,
- Cleaning of inlet and drainage pipes,
- Inspection of shut-off valves,
- Checking the operation of floats that regulate water dosing to the beds (sludge treatment),
- Annual mowing of vegetation, which can be used as insulation during winter (if needed) and removed to compost in spring,
- Replanting vegetation as needed,
- Monitoring the quality of effluent water.

According to the data obtained, the annual operating and maintenance costs for a constructed wetland wastewater treatment system with a capacity of 400 PE (population equivalent) are estimated to be between EUR 2,500.00 and EUR 4,000.00, including professional staff responsible for weekly operational inspections.

a. Horizontal flow TW (HFTW)

The HFTW was for long time the most established configuration. As the name implies, wastewater flows horizontally through a saturated filter bed. Because the media remains permanently submerged, oxygen availability is limited, and anaerobic processes dominate.

- *Pros:* HF systems are simple to construct and, if the terrain permits adequate slope, can operate via gravity without electricity. They are highly effective at removing organic matter (BOD, COD) and suspended solids.
- *Cons:* Due to oxygen limitations, nitrification (ammonia removal) is often incomplete.



Picture 1: Horizontal flow scheme.

Example of HFTW system: Sveti Tomaž ll (Slovenia), 500 PE

The Limnowet® constructed wetland was built in 2014 to treat wastewater from the settlement of Sveti Tomaž and nearby hamlets in the Municipality of Sveti Tomaž. The system consists of three treatment fields with a total surface area of 1,250 m². All wastewater is collected at the lowest point and pumped to a settling tank, after which it flows by gravity through the entire constructed wetland system.

Picture 2: Sveti Tomaž ll (Slovenia), 500 PE.

b. Vertical flow TW (VFTW)

Nowadays VFTW are most common type of TW for domestic wastewater treatment in rural areas. In VFTW, wastewater is applied intermittently across the surface of the bed and flows vertically down through the media to a drainage network. This intermittent loading is key: as water drains, it pulls fresh atmospheric air into the pore spaces, acting like a passive pump. This maintains high oxygen levels within the bed.

- *Pros:* The oxygen-rich environment promotes rapid aerobic degradation and complete nitrification. Consequently, VF wetlands require a smaller areal footprint than HF systems to treat the same organic load.
- *Cons:* If Total Nitrogen removal is required, the nitrified outflow (rich in nitrate) must be recirculated back to the anaerobic sedimentation tank for denitrification or combined with at HFTW.

Picture 3: Vertical flow CW scheme.

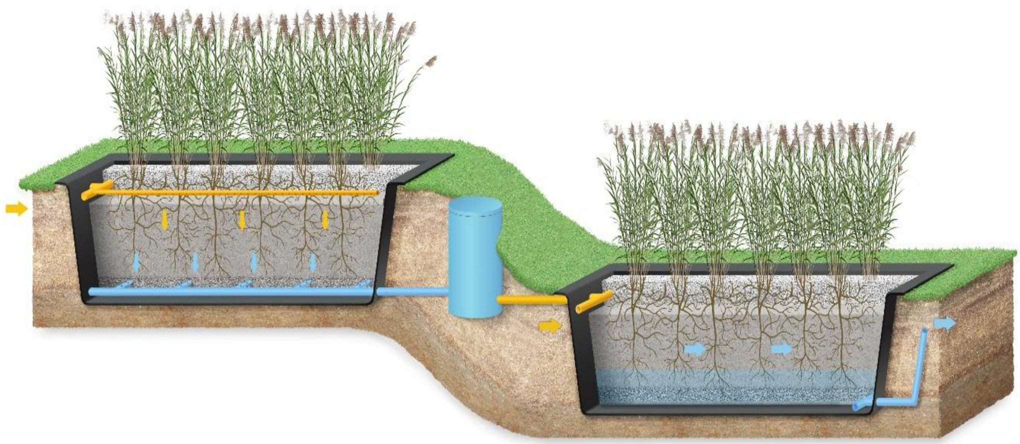
Example of VFTW system: Individual house (Slovenia), 8 PE

The Limnowet® constructed wetland was built in October 2016, and the planting of vegetation was carried out in spring 2017. It is designed for the treatment of wastewater from an organic farm. Since the farm is located in a flat area, a submersible pump with a float switch is installed to convey wastewater to the treatment system. Due to its intermittent operation throughout the year, the pump consumes very little electrical energy.

Picture 4: Individual house (Slovenia), 8 PE.

c. Hybrid TW

Hybrid systems combine the specific advantages of HF and VF wetlands to achieve superior effluent quality. The most common configuration is a VF stage (for nitrification) followed by an HF stage (for denitrification and polishing). While often deployed for larger settlements or more complex effluents, they provide robust, high-performance treatment adaptable to strict discharge limits.



Picture 5: Mixed flow (horizontal-vertical) CW scheme.

Example of Hybrid TW: Prud (Croatia), 540 PE

The Limnowet® constructed wetland was built in 2016 as part of the Project for the Protection of Waters from Pollution in the Coastal Area 2, serving the settlement of Prud in the municipality of Metković, in the

Dalmatian region of Croatia. The system consists of three treatment fields with a total surface area of 1,400 m^2. Its operation requires pumps that deliver wastewater to the first treatment field.

Picture 6: Prud (Croatia), 540 PE.

d. French type of TW

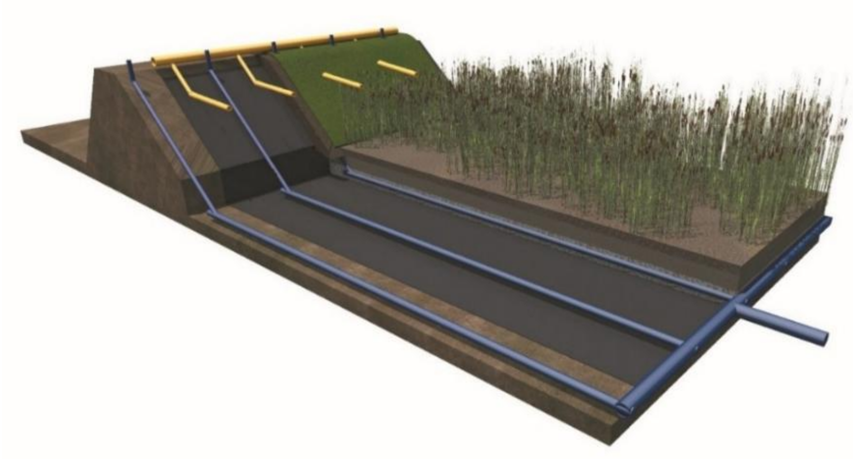
The "French System" is a specific configuration of vertical flow wetlands developed in France, where it has become a standard solution for rural communities.

No Sedimentation Tank Required: Unlike classical systems, the French system accepts raw wastewater directly onto the filter surface. The primary sedimentation tank is eliminated, which significantly reduces construction costs and avoids the regular handling of septic sludge.

The system typically consists of two vertical flow stages arranged in series:

- **First Stage:** Raw wastewater is applied here. Suspended solids are retained on the surface of the gravel bed, forming a sludge layer.
- **Resting Periods:** To prevent clogging, the first stage is divided into multiple parallel beds (usually three). These beds are fed alternately (e.g., 3-4 days of feeding followed by 7 days of rest). During the resting period, the accumulated sludge dries and mineralizes (composts) rapidly due to the oxygen-rich environment.
- **Second Stage:** The filtrate from the first stage flows to a classical vertical flow bed for further polishing and nitrification.

Sludge Management: The sludge accumulated on the surface mineralizes into a soil-like humus. Due to this significant volume reduction, sludge removal is required only once every 10 to 15 years. The removed material is stabilized and often suitable for agricultural reuse.



Picture 7: Scheme of sludge application to sludge drying reed bed.

Example of French type of TW: Ljubijankići (Bosnia and Herzegovina), 600 PE

In 2011, Una Consulting d.o.o., in cooperation with Limnos d.o.o., constructed a constructed wetland for wastewater treatment in the settlement of Ljubijankići, located within the Pivnica water protection zone. The project represents a strong example of decentralized wastewater management in Bosnia and Herzegovina. The facility is designed to treat sanitary wastewater from households and commercial activities. The system is based on a two-stage vertical filtration process using a gravel filter bed planted with reeds. Wastewater is first evenly distributed over the filter surface, then flows vertically through the filter media, where it undergoes mechanical and biological treatment.

Picture 8: Ljubjankići (Bosnia and Herzegovina), 600 PE.

5. References and Literature

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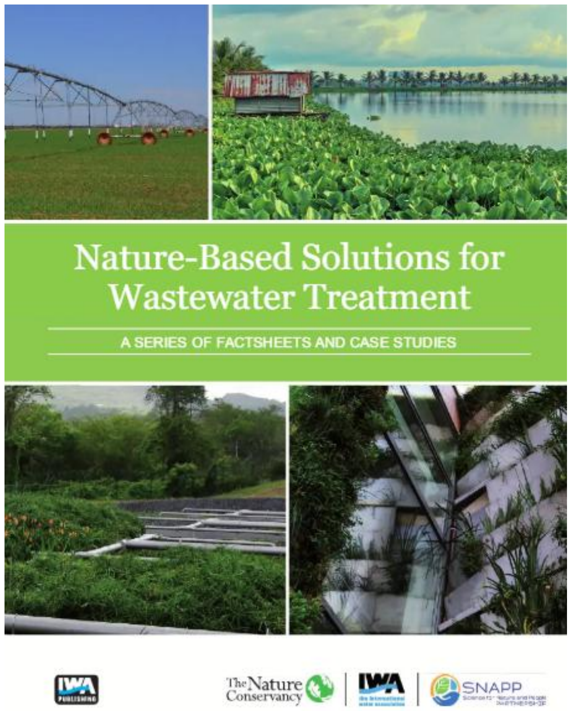
Limnos d.o.o., reference projects, available at Our Projects | LIMNOS.

Available literature on sustainable (treatment wetland) sanitation: Nature Bases Wasteewater-IWA | PDF | Sanitation | Sewage Treatment.



Picture 9: IWA handbook (2023).