Czech University of Life Sciences Prague

Faculty of Environmental Sciences

Department of Landscape and Urban Planning

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Diploma Thesis

Enhancing the wastewater treatment in Tehovec by using a Constructed Wetland

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DIPLOMA THESIS ASSIGNMENT

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Landscape Engineering
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Thesis title

Enhancing the wastewater treatment in Tehovec by using a Constructed Wetland

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Objectives of thesis

The aim of this thesis is to design a built wetland for Tehovec near Prague in order to improve wastewater treatment efficiency. To do so, a short review of the constructed treatment wetlands and an assessment of the current treatment method will be included.

Methodology

In the first stage, a comprehensive review of the constructed wetland topic in the science and research field will be conducted. In the second stage, a good description of the treatment process in the constructed wetland will be included as well. Then a full on-site description of the current state of the village Tehovec, the amount and quality of wastewater, and the current wastewater treatment method. The third stage will be devoted to selecting the place to build the new constructed wetland. The next stage will consist of the design of the specific new constructed wetland and the last part will be devoted to finishing the thesis.

The proposed extent of the thesis

50 pages including attachments

Keywords

constructed wetland, wastewater, sewage, organics, nutrients

Recommended information sources

Dotro, G., et al., 2018. Treatment Wetlands. Biological Wastewater Treatment Series, Vol. 7. IWA Publishing, London.

Langergraber, G et al. (eds.), 2019. Wetland Technology. Practical information on the design and application of treatment wetlands.Scientific and Technical report No. 27. IWA Publishing, London

Vymazal, J., Kröpfelová, L., 2008. Wastewater Treatment in Constructed Wetlands with Horizontal Subsurface Flow. Springer, Dordrecht.

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Declaration

I hereby declare that I am the sole author of this diploma thesis, titled "Enhancing the wastewater treatment in Tehovec by using a constructed wetland" and completed under Prof. Ing. Jan Vymazal's supervision. All of the data sources, literature, and publications that I used in this study have been cited.

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Prague 2021 Muhammad Merei

Acknowledgments

Above all, I want to express my gratitude to God for providing me with the support I needed to complete this thesis.

First and foremost, I'd like to express my gratitude to prof. Ing. Jan Vymazal for his advice and supervision throughout the development of my diploma thesis; his unwavering enthusiasm for this subject was both inspiring and motivating.

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Abstract

Constructed wetlands have a lot of potential for wastewater treatment, and they're used for a variety of things like farm wastewater, stormwater runoff, and mine drainage. Their application is for small communities and developments that lack wastewater treatment or to improve any type of wastewater treatment that already exists. In accordance with the requirements of sustainable development and decentralized systems, constructed wetlands can be an appropriate alternative to traditional centralized treatment plants.

This thesis aims to raise the quality of wastewater treatment in Tehovec to the highest possible level at the lowest possible cost and with the least amount of environmental impact.

The literature review section summarizes the design and implementation of the constructed wetlands, as well as the cleansing processes and procedures that exist in the treatment medium and plants. A short history of the Czech Republic's use of the constructed wetlands concept is also included.

The practical section of the thesis examines the current state of wastewater treatment in Tehovec before proposing a design for the new constructed wetland. The design is based on the village's current circumstances. A field survey was conducted before the design was proposed to assess the quantity and quality of wastewater generated by the village population. The next step is to choose a location for the new constructed wetland, which includes a detailed description of all plot features that affect the constructed wetland's function and, as a result, the entire surrounding area.

The thesis concludes with a detailed proposal for a new constructed wetland as well as preliminary drawings to implement the new design.

Keywords: constructed wetland, wastewater, sewage, organics, nutrients

Abstrakt

Umělé mokřady mají velký potenciál pro čištění odpadních vod a používají se na čištění různých typů odpadních vod, jako jsou splaškové vody, odpadní vody z farmy, dešťové vody a drenážní důlní vody. Jejich aplikace je určena pro malé obce, kterým chybí čištění odpadních vod, nebo ke zlepšení jakéhokoli typu čištění odpadních vod, který již existuje. V souladu s požadavky udržitelného rozvoje a decentralizovaných systémů mohou být umělé mokřady vhodnou alternativou k tradičním centralizovaným čistírnám.

Tato práce si klade za cíl zvýšit kvalitu čištění odpadních vod v Tehovci na nejvyšší možnou úroveň při nejnižších možných nákladech a při co nejmenším dopadu na životní prostředí.

Přehled literatury shrnuje návrh a realizaci umělých mokřadů, jakož i čisticí procesy a postupy, které existují ve filtračním médiu a rostlinách. Zahrnuta je také krátká historie využití koncepce umělých mokřadů v České republice. Praktická část diplomové práce zkoumá současný stav čištění odpadních vod v Tehovci před návrhem nového umělého mokřadu. Návrh vychází ze současných podmínek obce. Před návrhem projektu byl proveden terénní průzkum, jehož cílem bylo posoudit množství a kvalitu odpadních vod produkovaných obyvateli Tehovce. Dalším krokem je výběr místa pro novou vybudovanou mokřadní čistírnu, která obsahuje podrobný popis všech prvků pozemku, kterých se stavba kořenové čistírny dotkne včetně blízkéhoí okolí.

Práce je zakončena podrobným návrhem nově vybudované kořenové čistírny a předběžnými výkresy potřebnými k realizaci nového projektu.

Klíčová slova: kořenová čistírna, umělý mokřad, odpadní voda, splašky, organické látky, živiny

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1. Introduction

Natural processes have always cleansed water as it flowed through rivers, lakes, streams, and wetlands. In the last several decades, systems have been constructed to use some of these processes for water quality improvement. Constructed wetlands (CWs) are now used to improve the quality of point and non-point sources of water pollution, including stormwater runoff, domestic wastewater, agricultural wastewater, and coal mine drainage. Constructed wetlands are also being used to treat petroleum refinery wastes, compost and landfill leachates, fishpond discharges, and pretreated industrial wastewaters, such as those from pulp and paper mills, textile mills, and seafood processing (Davis, 1995).

Constructed wetlands are increasingly gaining ground for the treatment of domestic and agricultural wastewaters, coal mine drainage, and stormwater runoff, mainly because of a set of beneficial features, including environmental quality preservation, landscape conservation, and economic convenience. These would not be possible without activities such as monitoring and harvesting that can significantly contribute to both pollutant removal efficiency and sustainability of CWs (Ingrao, et al., 2020).

For some wastewaters, constructed wetlands are the sole treatment; for others, they are one component in a sequence of treatment processes. The treatment of wastewater by constructed wetlands can be a low-cost, low-energy process requiring minimal operational attention. As a result of both extensive research and practical application, insight is being gained into the design, performance, operation, and maintenance of constructed wetlands for water quality improvement. However, to be effective, they must be carefully designed, constructed, operated, and maintained. Constructed wetlands for water treatment are complex, integrated systems of water, plants, animals, microorganisms, and the environment. While wetlands are generally reliable, self-adjusting systems, an understanding of how natural wetlands are structured and how they function greatly increases the likelihood of successfully constructing a treatment wetland (Davis, 1995).

According to the findings of a recent study by Ingrao C. et al. published in 2020, states that it can be asserted that, though having a few limitations, constructed wetlands cause less greenhouse gases emissions and less environmental impacts than conventional wastewater treatment plants and contribute to sustainable enhancement of the ecological carrying capacity of the global ecosystem through wastewater treatment as part of global waste disposal. Moreover, thanks to their advantages in terms of pollutant removal efficiency, environmental sustainability, and economic convenience, constructed wetlands have stimulated the attention of researchers and scientists worldwide to extend their application also in other contexts as those of touristic and recreational facilities for water reusage in a circular economy perspective. In this direction, there has been increased interest to join landscape planning and design with CW systems, as a holistic system–based approach to improve the quality of the environment and the health of humans at the local and regional scale. Other environmental advantages are linked to harvested biomass that could offer several ecosystem benefits being used for soil amendment or fertilization or as livestock feed but also for energetic purposes (Ingrao, et al., 2020).

Tehovec is a small village on the western outskirts of Říčany, with a permanent population of 631 residents. Being on the lands where Rokytka begins, the quality of wastewater discharged into the stream from Tehovec has an effect on the overall water quality in Rokytka and, as a result, the Vltava river. While studying the quality of Rokytka water, I came across an evaluation of the Tehovec wastewater treatment facility, which calls for improving the current treatment solution, and this became the inspiration for this diploma thesis.

2. Objectives

The aim of this thesis is to design a constructed wetland for Tehovec, a village near Prague, in order to increase wastewater treatment efficiency. A brief review of the constructed treatment wetlands topic in the science and research literature, as well as an evaluation of the existing treatment method, will be included in this effort. Then present the realistic design outcomes that will improve wastewater treatment outcomes.

3. Methodology

A thorough review of the constructed wetland subject in the science and research literature will be conducted in the first stage. The second stage would include a thorough description of the treatment processes in the constructed wetland. Then a detailed description of the current state of the village of Tehovec, including the quantity and quality of wastewater produced, as well as the current wastewater treatment method. The third stage will be dedicated to determining where the new constructed wetland will be built. The next step will be to design the unique new constructed wetland, and the final stage will be to complete the thesis.

4. Wetlands

Wetlands have played a crucial role in human history. Major stages of the evolution of the life itself probably took place in a nutrient-rich environment. The early Sumerians knew the names of plants and animals that occupied the marshes of Tigris and Euphrates rivers, as evidence of clay tablets on which those names were inscribed. The Babylonians, who followed the Sumerians in Mesopotamia, not only had names of the wetland plants species, but also established municipal reed beds and reeds harvested from these reed beds were used to make rugs, coarse mats to strengthen walls of clay brick, and very fine mats to serve as a foundation for dikes made from material dredged from the river (Vymazal & Kröpfelová, 2008).

Wetlands have been recognized as providing many benefits including water supply and control (recharge of underground aquifers, drinking water, irrigation, flood control, water quality and wastewater treatment), mining (peat, sand and gravel), use of plants (staple plants, grazing land, timber, paper production, agriculture, horticulture, fertilizer and fodder), wildlife, fish and invertebrates, integrated systems and aquaculture (e.g. fish cultivation combined with rice production), erosion control, gene pools and diversity, energy, education and training, recreation and reclamation (Vymazal & Kröpfelová, 2008).

Wetlands are transitional environments. In a spatial pattern, they lie between the dry lands and the open water - at the coast, along the rivers, around lakes or as mires scattered in the landscape. In an ecological context, they are intermediate between terrestrial and aquatic ecosystems. In a temporal context, most wetlands are destined either to evolve into dry land as a result of lowered water tables, sedimentation or plant succession, or to be submerged by rising water tables associated with sea level rise or climate change (Vymazal & Kröpfelová, 2008).

Natural wetlands are characterized by extreme variability in functional components, making it virtually impossible to predict responses to wastewater application and to translate results from one geographical area to another. Although significant improvement in the quality of the wastewater is generally observed as a result of flow through natural wetlands, the extent of their treatment capability is largely unknown. While most natural wetland systems were not designed for wastewater treatment, studies have led to both a greater understanding of the potential of natural wetland ecosystems for pollutant assimilation and the design of new natural water treatment systems (Pries, 1994). It has only been during the past few decades that the planned use of wetlands for meeting wastewater treatment and water quality objectives has been seriously studied and implemented (Vymazal & Kröpfelová, 2008). The functional role of wetlands in improving water quality has been a compelling argument for the preservation of natural wetlands and the construction of wetland systems for wastewater treatment (Bastian, 1993).

CWs can be built with a much greater degree of control, thus allowing the establishment of experimental treatment facilities with a well-defined composition of substrate, type of vegetation, and flow pattern. In addition, constructed wetlands offer several additional advantages compared to natural wetlands, including site selection, flexibility in sizing, and the most importantly, control over the hydraulic pathways and retention time (Vymazal & Kröpfelová, 2008). The pollutants in such systems are removed through a combination of physical, chemical, and biological processes including sedimentation, precipitation, adsorption to soil particles, assimilation by the plant tissue, and microbial transformation (Brix, 1993).

4.1 Constructed wetlands

Constructed Wetlands (CWs) are engineered systems made to mimic the natural treatment processes that efficiently treat many different types of polluted water. CWs are man-made systems designed to do the same processes found in natural wetland environments and, therefore, are considered environmentally friendly and sustainable options for wastewater treatment.

CWs are engineered systems that have been designed and constructed to utilize the natural processes involving wetland vegetation, soils, and the associated microbial assemblages to assist in treating wastewaters. They are designed to take advantage of many of the same processes that occur in natural wetlands, but do so within a more controlled environment (Vymazal, 2010).

Compared to other wastewater treatment technologies, constructed wetlands have low operation and maintenance (O&M) requirements and the performance is less suspected to input variations. Constructed wetlands can effectively treat raw, primary, secondary or tertiary treated sewage and many types of agriculture and industrial wastewater (Dotro, et al., 2017). Constructed wetlands for wastewater treatment may in some locations have several advantages compared to conventional secondary and advanced wastewater treatment systems (Brix, 1993).

Some of these advantages are:

(1) low cost of construction and, especially, maintenance;

(2) low energy requirements;

(3) being a "low-technology" system, they can be established and run by relatively untrained personnel; and

(4) the systems are usually more flexible and less susceptible to variations in loading rate than conventional treatment systems (Brix & Schierup, 1989).

The major disadvantages of constructed wetland treatment systems are the increased land area required, compared to conventional systems, and the possible decreased performance during winter in temperate regions. Therefore, the disposal of wastewater into constructed wetlands is an especially attractive alternative to conventional wastewater treatment technologies for small to medium- sized communities, in sparsely areas, and in developing countries (Brix, 1993).

TABLE 1: Main advantages and disadvantages of constructed wetlands, Source: (von Sperling, 2007)

Advantages	Disadvantages
• High removal efficiency of BOD and coliforms • Practically no energy requirements • Simple construction, operation and maintenance • Reduced construction and operational costs • Good resistance to load variations • No sludge to be treated • Possibility of using the produced plant biomass	• High land requirements • Wastewater requires previous treatment (primary or simplified secondary) • Need for a substrate, such as gravel or sand • Susceptible to clogging • Need of macrophytes handling • Possibility of mosquitoes in surface flow systems

CWs have one main objective, i.e., treating water to make it suitable for a certain purpose. Other objectives, besides treating water can be (Langergraber, et al., 2019):

- Retaining water to store it to later evapotranspire it or attenuate flood waves;
- Evapotranspirating water, which is key for sludge treatment wetlands, but also for cooling and reducing urban heat island effects;
- Producing biomass;
- Harvesting nutrients;
- Creating a nice landscape, including for recreational purposes;
- Enhancing ecosystem services (mainly for FWS wetlands);
- Fostering biodiversity, directly or by creating habitats.

The purpose for which treated water should be utilized defines the treatment objective. For example, if treated water is to be used for irrigation purposes, it makes less sense to remove nutrients that are beneficial for crop fertigation (Langergraber, et al., 2019).

Depending on the comprehensive work done by Marcos von Sperling in his book, Wastewater Characteristics, Treatment and Disposal (von Sperling, 2007), which was the first book in the Biological Wastewater Treatment series, we can summarize the main advantages and disadvantages of constructed wetland technology as shown in table (1).

4.2 History of Constructed Wetlands

The first experiments aimed at the possibility of wastewater treatment by wetland plants were undertaken by Käthe Seidel in Germany in the early 1950s at the Max Planck Institute in Plön (Vymazal, 2010). Seidel then carried out numerous experiments aimed at the use of wetland plants for treatment of various types of wastewater, including phenolic wastewaters, dairy wastewaters or livestock wastewater. Most of her experiments were carried out in constructed wetlands with either horizontal (HF CWs) or vertical (VF CWs) subsurface flow, but the first fully constructed wetland was built with free water surface (FWS) in the Netherlands in 1967. However, FWS CWs did not spread substantially in Europe where subsurface flow constructed wetlands prevailed in the 1980s and 1990s (Vymazal & Kröpfelová, 2008).

In North America, FWS CWs started with the ecological engineering of natural wetlands for wastewater treatment at the end of the 1960s and beginning of the 1970s (Kadlec, et al., 1979). This treatment technology was adopted in North America not only for municipal wastewaters but all kinds of wastewaters (Kadlec & Wallace, 2009). Subsurface flow technology spread more slowly in North America but, at present, thousands of CWs of this type are in operation (Kadlec & Wallace, 2009).

4.2.1 Constructed Wetlands in the Czech Republic

Wetlands have been intensively studied in the Czech Republic for more than five decades (Vymazal, 2002). However, most studies were aimed primarily at wetland ecology, ecophysiology of wetland plants (primary productivity, biomass, mineral nutrition, evapotranspiration, nutrient cycling), and the role of algae in shallow water bodies (Dykyjová & Květ, 1978). Many experiments were carried out in wetland sites affected by sewage outfalls as well as in experimental hydroponic systems using a defined nutrient medium. The results of these experiments were used to estimate the potential of emergent wetland macrophytes for wastewater treatment (Dykyjová, 1982).

The first full-scale CW for wastewater treatment was built at Petrov near Prague in May 1989 and was originally designed for the treatment of runoff from an adjacent dung-hill (Vymazal, 2002). The system was built on a volunteer basis without a good knowledge of constructed wetland design. Despite that and other operational problems some promising results were obtained (Vymazal, 1998). Prior to the Petrov project only small-scale experiments with municipal and agricultural wastewaters had been carried out in 1988. In 1991, three more full-scale CWs were built and since then the number of systems has increased considerably (Vymazal, 1998). At present, it is difficult to estimate the exact number of constructed wetlands in the Czech Republic. Until 1995, the exact number of CWs could be obtained, but recently CWs have been used more frequently for on-site treatment for single households and it is difficult to track all such systems. It is estimated that about 100 full-scale CWs are in operation in the Czech Republic in the year 2000 (Vymazal, 2002).

Majority of CWs in the Czech Republic were designed as horizontal subsurface flow (HSF) systems. Three of them were designed as hybrid systems, i.e. a combination of horizontal flow and vertical flow (VF) beds (Vymazal, 2002).

Most CWs in the Czech Republic were designed for the secondary treatment of municipal or domestic sewage. The majority of systems treat wastewater from combined sewerage, i.e. together with stormwater runoff. Several systems were designed for tertiary treatment. Other CWs treat wastewaters from dairy, abattoir, and bakery facilities, landfill leachate, and stormwater runoff (Vymazal, 2002).

Also, efficient mechanical pretreatment is necessary for high final treatment effect of HSF CWs because high concentrations of suspended solids may cause the filtration bed clogging and subsequent surface flow. Pretreatment in small systems designed for single households usually consists of a septic or settling tank. Pretreatment for larger sources of municipal or domestic wastewater usually consists of an Imhoff tank. These systems often also include a preliminary step, i.e. bar racks and screens. In the case of combined sewer systems, a grit chamber is also used to eliminate sand and soil particles from stormwater runoff. It is important to maintain the preliminary and pretreatment units regularly in order to maintain a high level of wastewater treatment. However, it has been found that in many cases the operators did not pay enough attention to maintenance resulting in deterioration of final effluent quality (Vymazal, 2002).

5. Types of constructed wetlands

Constructed wetlands for wastewater treatment may be classified according to the life form of the dominating macrophyte, into systems with free-floating, floating leaved, rooted emergent and submerged macrophytes (Brix & Schierup, 1989). Further division could be made according to the wetland hydrology (free water surface and subsurface systems) and subsurface flow CWs could be classified according to the flow direction (horizontal and vertical) (Figure 1) (Vymazal & Kröpfelová, 2008).

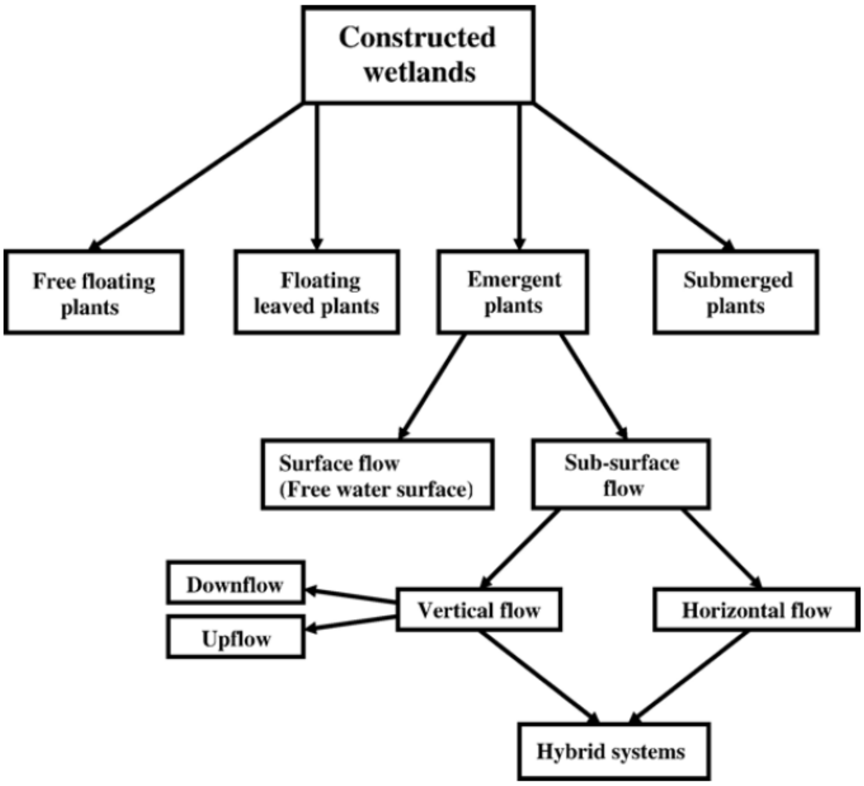


FIGURE 1: classification of constructed wetlands for wastewater treatment.
source: (Vymazal, 2001)

5.1 Constructed wetlands with free floating plants

Regular depth (50-70) cm

Plants: *Eichhornia crassipes L (water hyacinth)
*sp. Lemnaceae (duckweed)
*Pistia stratiotes (water lettuce)
*Ipomoea aquatica (water spinach)

The main advantage is the high efficiency in pollutant removal.

Among the disadvantages are: the high O&M cost, work seasonally, and need regular harvesting.

5.2 Constructed wetlands with floating leaved plants

Although it is very rare

Plants: *Nymphaeaceae (water lily)
*Nelumbo nucifera

There is no guidance on how to design them. Low treatment effect associated with high hydraulic load

5.3 Constructed wetlands with submerged plants

Regular depth (30-60) cm

Plants: *Myriophyllum spicatum (Eurasian watermilfoil)
*Elodea canadensis (common waterweed)
*Ceratophyllum demersum (coontail)

Submerged plants may grow only in well oxygenated water, so it is not applicable where the wastewater has high concentration of easily degradable organic matter. The high turbidity of wastewater is also a problem.

Lower filtration capacity.

Utilization mostly for final treatment.

Plants can survive winter; it could be used in cold climates.

5.4 Constructed wetlands with emerged plants

The most common type of CWs

Plants: *Phragmites australis
*Scirpus lacustris (Figure 2)
*Typha sp.
*Sagittaria latifolia

In accordance with water flow, the constructed wetlands are subdivided into: surface flow and subsurface flow.

Surface flow CWs have free standing water at the surface, they are usually called free water surface (FWS) constructed wetlands.

Subsurface flow CWs don’t have a visible standing water surface, they are designed so that the wastewater flows through a gravel substrate beneath the surface vegetation.

Subsurface flow constructed wetlands are also subdivided into Horizontal Flow (HF) and Vertical Flow (VF) wetlands depending on the direction of the water flow. In order to prevent the clogging of the porous filter material, HF and VF wetlands are generally used for secondary treatment of wastewater.

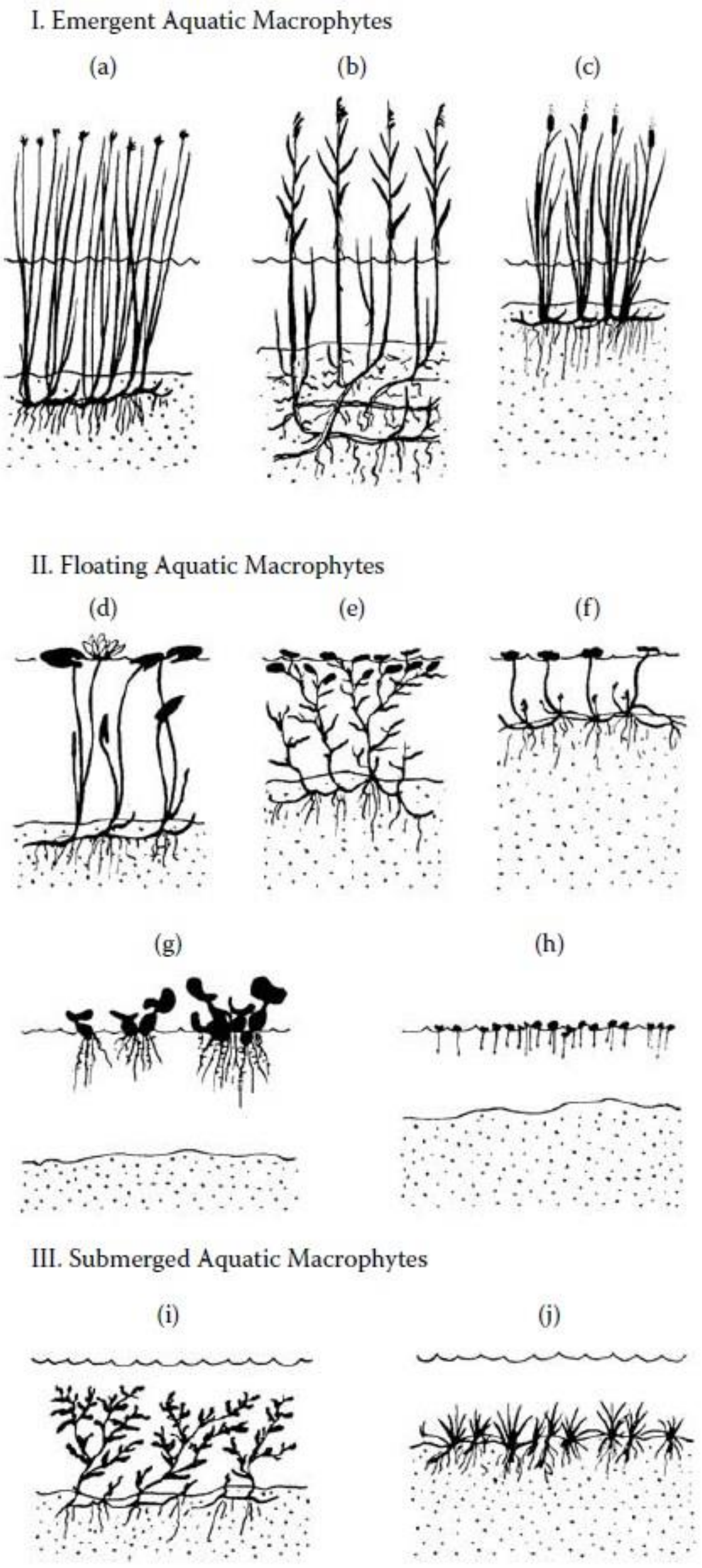


FIGURE 2: Sketch showing the dominant life forms of aquatic macrophytes.
Source: (Brix & Schierup, 1989)

The species illustrated are (a) Scirpus (Schoenoplectus) lacustris, (b) Phragmites australis, (c) Typha latifolia, (d) Nymphaea alba, (e) Potamogeton gramineus, (f) Hydrocotyle vulgaris, (g) Eichhornia crassipes, (h) Lemna minor, (i) Potamogetoncrispus, (j) Littorella uniflora.

5.4.1 Free Water Surface Constructed Wetlands (FWS CWs)

A typical FWS CW with emergent macrophytes is a shallow sealed basin or sequence of basins, containing (20–30) cm of rooting soil, with a water depth of (20–40) cm (Figure 3). Dense emergent vegetation covers a significant fraction of the surface, usually more than 50% (Vymazal, 2010). Besides planted macrophytes, naturally occurring species may be present (Kadlec, 1994).

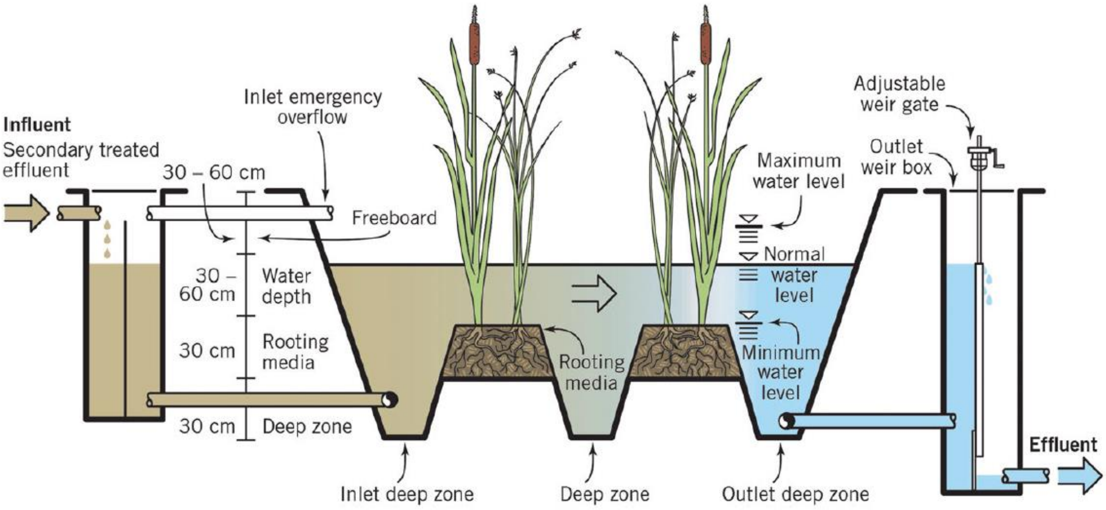


FIGURE 3: FWS CW overview, source (Dotro, et al., 2017)

Plants are usually not harvested, and the litter provides organic carbon necessary for denitrification which may proceed in anaerobic pockets within the litter layer (Vymazal, 2010). They are commonly used to treat non-point sources such as urban stormwater, agricultural runoff and metal-laden flows in addition to municipal wastewater (Vymazal, 2013).

The physical structure of an FWS wetland is as diverse as its potential application. They may be lined or unlined, constant or variable in depth, completely or partially vegetated, the vegetation can be emergent, submerged or floating and they can vary in size from a few square meters to multiple square kilometers. Yet there are several essential defining features. Water level is maintained above a rooting matrix of soil, sand or gravel that supports the growth of wetland plants that can survive continuously flooded conditions. Flow is horizontal but may take a circuitous path from inlet to outlet at a very low velocity (Dotro, et al., 2017).

FWS CWs are efficient in removal of organics through microbial degradation and settling of colloidal particles. Suspended solids are effectively removed via settling and filtration through the dense vegetation. Nitrogen is removed primarily through nitrification (in water column) and subsequent denitrification (in the litter layer), and ammonia volatilization under higher pH values caused by algal photosynthesis. Phosphorus retention is usually low because of limited contact of water with soil particles which adsorb and/or precipitate phosphorus. Plant uptake represents only temporal storage because the nutrients are released to water after the plant decay (Vymazal & Kröpfelová, 2008).

FIGURE 4: FWS CW for stormwater runoff in Woodcroft Estate near Sydney, NWS, Australia. photo credit: Jan Vymazal. source: (Vymazal, 2010)

FWS CWs need very little maintenance under normal operating conditions. Periodic inspection of inlet and outlet works, and plant health is advisable. Plants that are subjected to oxygen stress tend to concentrate roots closer to the surface, making them less tolerant of periodic deep-water conditions and more susceptible to lodging, thus complete submergence and death. The typical large scale of FWS CWs makes them susceptible to wave action, which can exacerbate plant lodging and increase the potential of wind-induced bank erosion (Dotro, et al., 2017). Figure 4 shows an example of FWS CW from Australia.

5.4.2 Constructed Wetlands with Horizontal sub-surface Flow (HF CWs)

HF CWs consist of gravel or rock beds sealed by an impermeable layer and planted with wetland vegetation (Figure 5). The wastewater is fed at the inlet and flows through the porous medium under the surface of the bed in a more or less horizontal path until it reaches the outlet zone, where it is collected and discharged (Vymazal, 2010). In the filtration beds, pollution is removed by microbial degradation and chemical and physical processes in a network of aerobic, anoxic, anaerobic zones with aerobic zones being restricted to the areas adjacent to roots where oxygen leaks to the substrate (Vymazal & Kröpfelová, 2008).

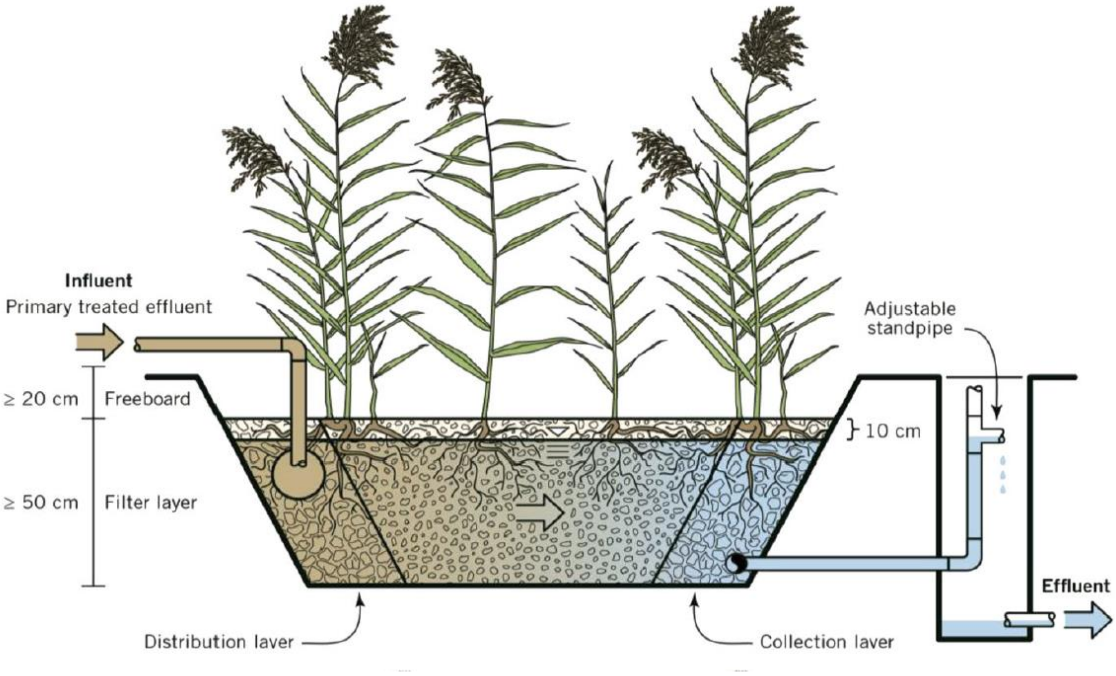


FIGURE 5: HF CW overview. source: (Dotro, et al., 2017)

HF CWs are used for secondary and tertiary treatment of domestic wastewater, as well as for a variety of industrial effluents (Vymazal & Kröpfelová, 2008). For HF wetlands treating domestic wastewater, primary treatment is generally achieved via a septic tank or an Imhoff tank. These systems are widely used in the Czech Republic, Spain, Portugal, Nicaragua, and North America among other countries for secondary treatment of domestic wastewater (Vymazal & Kröpfelová, 2008).

In a typical HF CW, the gravel bed is saturated and planted with emergent wetland plants. Water enters the treatment system at one end, flows through the gravel media, and is collected on the opposite end of the bed prior to being discharged. A standpipe located outside of the wetland bed controls the water level within the gravel media. The whole bed is isolated from the surrounding land by a combination of a plastic liner and a geotextile membrane (Dotro, et al., 2017). For secondary treatment of domestic wastewater, the gravel depth is generally 50 to 70 cm and the water level is kept 5 – 10 cm below the surface. In tertiary treatment applications in the UK, the depth of the basin itself is 1.0 to 1.5 m, of which approximately 60 cm is filled with gravel. HF systems in the UK are generally constructed with a longitudinal sloped base (1%) to facilitate draining of the bed if needed. The remaining bed volume is used for water storage during high flows or storm events (Dotro, et al., 2017).

The role of plants in HF CWs is mainly related to physical processes such as providing increased surface area for attached microbial growth, and for providing better filtration of TSS. In temperate and cold climates, the litter layer can provide extra thermal insulation during the winter (Dotro, et al., 2017). However, in hot, arid climates, it may be necessary to cut the vegetation on a regular (annual) basis. This is because the climatic conditions favour net accumulation of litter, needlessly insulating the bed whilst reducing the wetland storage capacity (Dotro, et al., 2017). For HF CWs providing secondary treatment of domestic wastewater, the contribution of plant uptake to nutrient removal is minimal. Plant-mediated oxygen transfer occurs, but is minimal in comparison to the oxygen demand exerted by the incoming wastewater (Brix, 1990). Figure 6 shows an example of HF CW from the UK.

FIGURE 6: HF CW at Staverton, United Kingdom, Photo credit: Jan Vymazal. Source: (Vymazal, 2010)

No treatment wetland system is maintenance free. The most critical operational issue for HF wetlands is clogging. This occurs when the pore spaces in the media are filled with solids (organic or inorganic), instead of wastewater, thus limiting the contact area and time between the biofilm and the water (Dotro, et al., 2017). Clogging is often due to improper maintenance of the septic tank (secondary treatment HF wetland) or final settling tanks (tertiary HF wetlands), or poor dimensioning of the wetland itself. Clogging can thus be minimized and the bed life extended by selecting appropriate media (e.g., gravel vs. sand) and loading rates (checking both hydraulic and mass pollutant loads) as explained in Chapter 2, and ensuring the upstream processes are correctly maintained to enable the bed to operate within the range of its intended design (Dotro, et al., 2017).

5.4.3 Constructed Wetlands with Vertical sub-surface Flow (VF CWs)

Vertical sub-surface flow constructed wetlands (VF CWs) (Figure 7,8) were originally introduced by Seidel to oxygenate anaerobic septic tank effluents (Seidel, 1965). However, the VF CWs did not spread as quickly as HF CWs, probably, because of the higher operation and maintenance requirements due to the necessity to pump the wastewater intermittently on the wetland surface (Vymazal, 2010).

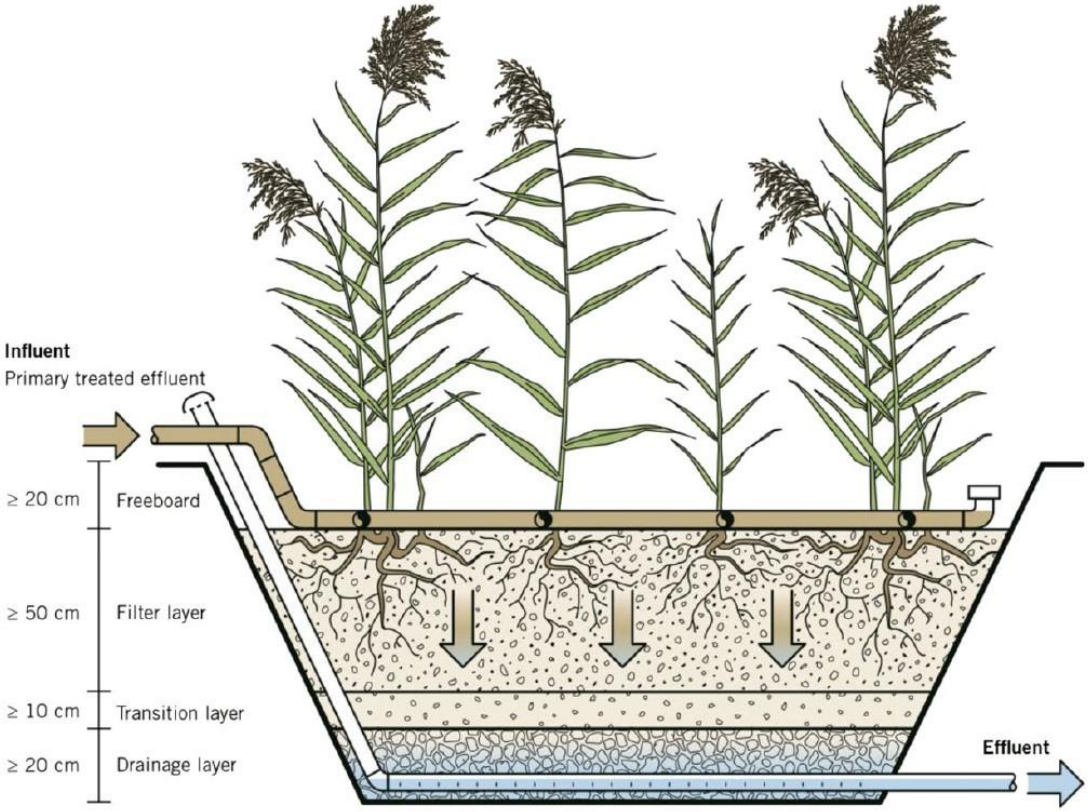


FIGURE 7: VF CW overview, source: (Dotro, et al., 2017)

VF CWs are also very effective in removing organics and suspended solids. Removal of phosphorus is low unless media with high sorption capacity are used (Vymazal & Kröpfelová, 2008). The water is fed in large batches and then the water percolates down through the sand medium. The new batch is fed only after all the water percolates and the bed is free of water. This enables diffusion of oxygen from the air into the bed. As a result, VF CWs are far more aerobic than HF CWs and provide suitable conditions for nitrification. On the other hand, VF CWs do not provide any denitrification.

The sand and/or gravel bed is planted with emergent macrophytes. Primary treated wastewater is loaded intermittently to the filter surface, and the large amount of water from a single loading causes good distribution of inflow water on the surface. The water percolates through the substrate then gradually drains and is collected by a drainage network at the base of the filter. Between loadings, oxygen re-enters the pore space of the media, transporting oxygen into the filter bed in order to sustain aerobic microbial processes. The whole bed is isolated from the surrounding land by a combination of a plastic liner and a geotextile membrane (Dotro, et al., 2017).

FIGURE 8: VF CW for treatment of raw sewage in Roussilon, France. Photo credit: Jan Vymazal, source: (Vymazal, 2011)

In general, contaminants that are degraded aerobically are easily removed using VF wetlands with intermittent loading. For domestic and municipal wastewater, organic matter (BOD5 or COD) and ammonia nitrogen are removed mainly through aerobic microbial processes. Solids (such as TSS) and pathogenic organisms are removed by physical filtration. The treatment efficiency of a VF wetland is directly related to the filter material used. If fine material is used, the retention time of the wastewater in the filter is longer, often enabling higher removal efficiencies; however, the HLRs are limited, as it takes longer for water to infiltrate and the potential for clogging increases. Coarser filter material enables higher HLRs and less clogging potential, but results in lower removal efficiencies. This can be partially overcome in some cases by increasing the depth of the main layer (Dotro, et al., 2017).

Emergent macrophytes, most often *Phragmites australis* (common reed), are used for planting VF wetlands. The roles of the macrophytes in relation to pollutant removal in VF wetlands are mainly related to physical processes. The roots provide surface area for attached microbial growth, and root growth is known to help maintain the hydraulic properties of the filter. The vegetation cover protects the surface from erosion. In temperate climates, litter provides an insulation layer on the wetland surface for operation during winter. Uptake of nutrients plays a minor role for common wastewater parameters compared to the degradation processes caused by microorganisms. If wetland plants are not harvested, some nutrients absorbed by the plant will be released to the system during decomposition, resulting in a possible secondary pollutant release to the wetland. Some plants also release organic compounds, which can be used to aid in denitrification (Dotro, et al., 2017).

5.4.4 Hybrid Constructed Wetlands

Constructed wetlands could be combined in order to achieve a higher treatment effect by using advantages of individual systems. Most hybrid constructed wetlands combine VF and HF stages (Vymazal, 2005). The VF-HF system was originally designed by Seidel as early as in the late 1950s and the early 1960s (Revitt, et al., 2004) but the use of hybrid systems was then very limited. In the 1980s VF-HF hybrid constructed wetlands were built in France and United Kingdom (Vymazal, 2010). At present, hybrid constructed wetlands are in operation in many countries around the world and they are used especially when removal of ammonia-N and total-N is required (Vymazal & Kröpfelová, 2008).

6. Treatment efficiency in constructed wetlands

The pollutants in CWs are removed by a complex variety of physical, chemical, and biological processes (Hammer, 1989). CWs show high efficiency when removing organics and suspended solids, but low nitrogen and phosphorus removal (30-50%) and (10-20%) respectively as detailed in table (2) (Dotro, et al., 2017).

The growth, death, and decay of plant biomass is an important biogeochemical cycle in treatment wetlands and imposes a seasonal cycle on many internal processes. During the growing season, nutrients such as nitrogen and phosphorus are taken up by the plants, and temporarily stored in the plant canopy. This uptake is significant for juvenile ecosystems where the plant canopy being established, and for periods of peak plant growth. At the end of the growing season, nutrients are returned to the system after the emergent portion of the plants die back (Kadlec & Wallace, 2009). The decay of plant biomass imposes nonzero background concentrations for many constituents in treatment wetlands and is important in some treatment processes, such as denitrification. Some portion of the phytomass is resistant to degradation, leading to a net accretion of refractory organic matter in treatment wetlands (Kadlec & Wallace, 2009).

TABLE 2: Typical treatment efficiencies of main constructed wetland types
Source: (Dotro, et al., 2017)

Parameters	HF	VF*	French VF	FWS
Treatment step	Secondary	Secondary	Combined	Tertiary
Total suspended solids	>80%	>90%	>90%	>80%
Organic matter	>80%	>90%	>90%	>80%
Ammonia nitrogen	20-30%	>90%	>90%	>80%
Total nitrogen	30-50%	<20%	<20%	30-50%
Total phosphorus	10-20%	10-20%	10-20%	10-20%
Coliforms	2 $\log_{10}$	2-4 $\log_{10}$	1-3 $\log_{10}$	1 $\log_{10}$
* Single stage VF bed, main layer of sand (grain size 0.06 - 4 mm)				

6.1 General performance of Constructed Wetlands

Performance of CWs for wastewater treatment is measured by removal efficiency and effectiveness of treatment. The treatment process in CW is affected by internal and external factors. Some of the external factors are the climate factors: temperature, water, humidity, wind speed and solar radiation. Internal factors include hydraulic and hydrological factors: hydraulic loading, flow rate, residence time of the water in the filter bed.

The Czech government in its order No. 61/2003 Code (hereinafter as the OG No. 61), has set the requirements of standard accepted emissions of wastewater treatment systems to the recipient water bodies as follows in table (3).

TABLE 3: Emission standards of indicators of acceptable wastewater pollution pursuant to the Order of the Government of the Czech Republic No. 61/2003 Code

Source size (P.E.)	**BOD$_5$**		**COD$_{cr}$**		**SS**		**N-NH4$^+$**		**N $_{total}$**		**P $_{total}$**	
	mg.l^{-1}		mg.l^{-1}		mg.l^{-1}		mg.l^{-1}		mg.l^{-1}		mg.l^{-1}	
	a	m	a	m	a	m	a	m	a	m	a	m
< 500	150	220	40	80	50	80	-	-	-	-	-	-
501 - 2000	125	180	30	60	40	70	20	40	-	-	-	-
2001 - 10 000	120	170	30	60	40	70	15	30	-	-	3	8
10001 - 100 000	90	130	20	40	25	50	-	-	15	30	2	6
Over 100 000	75	125	15	30	20	40	-	-	10	20	1	3

Where: P.E. means population equivalent load of one inhabitant; a: values are acceptable concentrations and may be exceeded within a tolerable extent; m: values are maximum concentrations, which may not be exceeded; BOD$_5$ is 60 per person per day; the N$_{total}$ and P$_{total}$ values are average annual. All these values are established in the Annex No. 5 to the OG No. 61.

6.2 Treatment Processes in the Constructed Wetlands

CWs are complex wastewater treatment systems possessing a diverse set of pollutant and pathogen removal pathways. Wetland plants play several important roles in CWs. Primarily, their roots and rhizomes provide attachment sites for microbial biofilms increasing the biological activity per unit area compared to open water systems such as ponds (Dotro, et al., 2017). Major treatment mechanisms are listed in table (4).

TABLE 4: Main pollutant and pathogen removal mechanisms in CWs. Source: (Dotro, et al., 2017)

Parameter	**Main removal mechanisms**
Suspended solids	Sedimentation, filtration
Organic matter	Sedimentation and filtration for the removal of particulate organic matter, biological degradation (aerobic and/or anaerobic) for the removal of dissolved organic matter

Table 4 Cont.

Nitrogen, ammonia	Ammonification and subsequent nitrification and denitrification, plant uptake and export through biomass harvesting
Phosphorus	Adsorption-precipitation reactions driven by filter media properties, plant uptake and export through biomass harvesting
Pathogens	Sedimentation, filtration, natural die-off, predation (carried out by protozoa and metazoa)

6.2.1 Removal of Nitrogen

Nitrogen exists in many forms and various interrelated processes convert it from one to another in a complex system called the nitrogen cycle. Nitrogen enters most primary and secondary treatment wetlands as organic N and ammonium (NH_4-N), with tertiary systems receiving a mixture of nitrogen species including nitrate (Dotro, et al., 2017). Nitrogen has a complex biogeochemical cycle with multiple biotic/abiotic transformations involving seven valence states. The compounds include a variety of inorganic and organic nitrogen forms that are essential for all biological life. The most important inorganic forms of nitrogen in wetlands are ammonium (NH_4^+), nitrite (NO_2^-) and nitrate (NO_3^-). Gaseous nitrogen may exist as dinitrogen (N_2), nitrous oxide (N_2O), nitric oxide (NO_2 and N_2O_4) and ammonia (NH_3) (Vymazal, 2007).

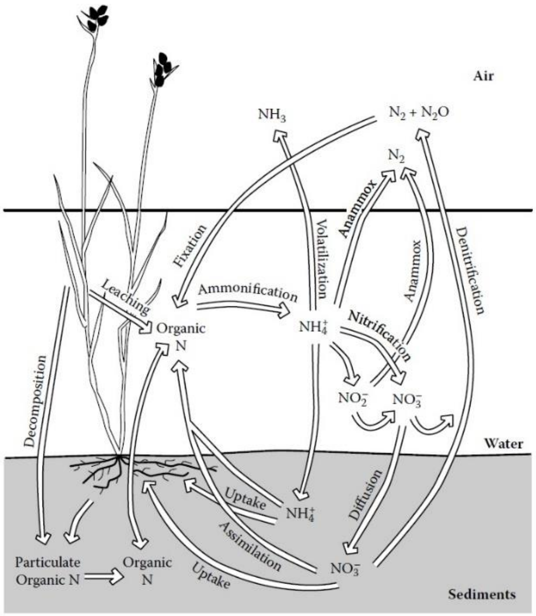


FIGURE 9: Simplified nitrogen cycle for a FWS CW, Source: (Kadlec & Wallace, 2009)

Virtually all pathways of the nitrogen cycle are active in treatment wetlands, including mineralization (ammonification), ammonia volatilization, nitrification, denitrification, plant and microbial uptake, nitrogen fixation, nitrate reduction, anaerobic ammonia oxidation, adsorption, desorption, burial, and leaching (Vymazal, 2007). (Kadlec & Wallace, 2009) have presented a simplified nitrogen cycle for a FWS CW as shown in Figure (9).

6.2.1.1 Ammonia volatilization

In surface-flow CW, ammonia volatilization is a physicochemical process where ammonium-N is known to be in equilibrium between gaseous and hydroxyl forms (Vymazal, 2007). The loss of NH3 through volatilization from flooded soils and sediments are insignificant if the pH value is below 7.5 and very often losses are not serious if the pH is below 8.0. At pH of 9.3 the ratio between ammonia and ammonium ions is 1:1 and the losses via volatilization are significant (Patrick & Reddy, 1984). Algal photosynthesis in wetlands as well as photosynthesis by submerged macrophytes often creates high pH values during the day. The pH of shallow flood water is greatly affected by the total respiration activity of all the heterotrophic organisms and the gross photosynthesis of the species present (Vymazal, 2007).

6.2.1.2 Ammonification

Ammonification consists of the conversion of organic N to ammonium through extracellular activity from enzymes excreted by microorganisms (Vymazal, 2007). Ammonification is considered a necessary first step to nitrogen conversion to nitrate and/or removal but is seldom a limiting step for subsequent total nitrogen (TN) removal (Dotro, et al., 2017).

6.2.1.3 Nitrification

Nitrification is usually defined as the biological oxidation of ammonium to nitrate with nitrite as an intermediate in the reaction sequence. This definition has some limitations where heterotrophic microorganisms are involved but is adequate for the autotrophic and dominant species (Hauck, 1984). For the process to take place, the microorganisms, oxygen, alkalinity and micronutrients must be present in the wastewater (Dotro, et al., 2017).

6.2.1.4 Denitrification

Denitrification is most commonly defined as the process in which nitrate is converted into dinitrogen via intermediates nitrite, nitric oxide and nitrous oxide (Hauck, 1984). Denitrification is often difficult to achieve in secondary treatment wetlands (and most wastewater treatment systems in general) because the nitrification process is typically a prerequisite to convert the influent ammonia into nitrate, which cannot take place until the sufficient organic carbon is consumed (Dotro, et al., 2017).

6.2.1.5 Fixation

Nitrogen fixation is the conversion of gaseous nitrogen (N2) to ammonia. Nitrogen fixation requires nitrogenase, an oxygen-sensitive iron-, sulfur- and molybdenum- containing enzyme complex which also brings about the reduction of other substrates containing triple covalent bonds (e.g., nitrous oxide, cyanides or acetylene) (Stewart, 1973). In wetland soils, biological N2 fixation may occur in the floodwater, on the soil surface, in aerobic and anaerobic flooded soils, in the root zone of plants, and on the leaf and stem surfaces of plants (Buresh, et al., 1980).

6.2.1.6 Plant uptake (and assimilation)

Nitrogen assimilation refers to a variety of biological processes that convert inorganic nitrogen forms into organic compounds that serve as building blocks for cells and tissues (Vymazal, 2007). A common misconception is that plants remove most of the nitrogen in treatment wetlands (Dotro, et al., 2017). Emergent macrophytes do store nitrogen in their tissue and plant uptake results in nitrogen removal ranging from 0.2 to 0.8 g N/m2·d, depending on the macrophyte species considered (Vymazal, 2007).

Some of this stored nitrogen can be removed by regular harvesting of above ground biomass, however more than half of the nitrogen uptake may be stored in below ground tissue and timing is important as plants translocate nitrogen between above and below ground tissue depending on the season. Harvesting is also an operational cost and its cost effectiveness is questionable unless the system is lightly loaded. If plants are not harvested, no net nitrogen removal occurs because any nitrogen in plant tissue is eventually released during decomposition of the plant matter (Dotro, et al., 2017).

6.2.1.7 Ammonia adsorption

Ionized ammonia may be adsorbed from solution through a cation exchange reaction with detritus, inorganic sediments or soils. The adsorbed ammonia is bound loosely to the substrate and can be released easily when water chemistry conditions change (Vymazal, 2007). Sorption may be near 100% of the influent for a short time after start-up of a wetland system. However, the sorption capacity of all media is finite and once all sites are saturated very little additional sorption can take place (Vymazal, 2007).

Though adsorption is a minor removal mechanism, it can aid the nitrification-denitrification removal process in CWs that are loaded intermittently by temporarily storing ammonium, allowing time for heterotrophs to consume most of the organic matter, then exposing the sorbed ammonium to oxygen during the waiting period. Nitrification can then take place. Upon the next dose, the nitrate can react with the new dose of organic matter, allowing denitrification to take place and restoring the sorption site for a new molecule of ammonium. Extremely high sorptive capacities or very low loading rates are required for this mechanism to dominate operation of intermittent systems such as VF wetlands (Dotro, et al., 2017).

6.2.1.8 Organic nitrogen burial

Some fractions of the organic nitrogen incorporated in detritus in a wetland may eventually become unavailable for additional nutrient cycling through the process of peat formation and burial. The values of organic nitrogen burial have been reported for various natural wetlands, however, in constructed wetlands there are practically no data available (Vymazal, 2007).

6.2.1.9 ANAMMOX

Anaerobic ammonium oxidation (ANAMMOX) is the anaerobic conversion of $NO2$ − and $NH4$ + to $N2$ (Muldera, et al., 1995). It was demonstrated that in ANAMMOX process, nitrate was used as an electron acceptor. During further examination of this process indications were obtained that nitrite could also serve as a suitable electron acceptor for ANAMMOX process (van de Graaf, et al., 1995). More recently, it has become clear that nitrite is the key electron acceptor (Strous, et al., 1997).

6.2.2 Removal of Phosphorus

Phosphorus enters most CWs primarily as organic phosphorus and orthophosphate, but most organic phosphorus is converted to orthophosphate as part of organic matter degradation (Dotro, et al., 2017). Phosphorus in wetlands occurs as phosphate in organic and inorganic compounds. Free orthophosphate is the only form of phosphorus believed to be utilized directly by algae and macrophytes and thus represents a major link between organic and inorganic phosphorus cycling in wetlands (Vymazal, 2007).

Mechanisms that play a part in phosphorus removal in CWs include chemical precipitation, sedimentation, sorption and plant and microbial uptake. Unfortunately, most of these processes are slow or not active unless special media are used to enhance abiotic processes. As with nitrogen, plants incorporate phosphorus into their biomass, but this can be a removal mechanism only if plants are harvested and is thus subject to the same limitations as nitrogen plant uptake as a removal mechanism (Dotro, et al., 2017).

6.2.3 Removal of Organic matter

Soluble organic compounds are, for the most part, degraded aerobically by bacteria attached to plant and sediment surfaces. However, anaerobic degradation may in some cases be significant (Brix, 1990). The oxygen needed to support the aerobic processes is supplied directly from the atmosphere via diffusion through the sediment or water atmosphere interface, by photosynthetic oxygen production within the water column, and by oxygen leakage from macrophyte roots. Anaerobic degradation will occur during periods with oxygen depletion in the water column and in anaerobic sediments (Brix, 1993).

6.2.4 Removal of total suspended solids

In constructed wetlands total suspended solids (TSS) are removed very efficiently. Settleable and suspended solids are removed primarily in the mechanical pretreatment unit, which is usually installed in front of the actual wetland. The suspended solids that remain in the wastewater after mechanical pretreatment are removed in the wetland by sedimentation and filtration. These purely physical processes also remove a significant proportion of other wastewater constituents (BOD, nutrients, and pathogens) (Brix, 1993).

6.2.5 Removal of pathogens

CWs technology offers a suitable combination of physical, chemical and biological mechanisms required to remove pathogenic organisms. The physical factors include filtration and sedimentation, and the chemical factors include oxidation and adsorption to organic matter. The biological removal mechanisms include oxygen release and bacterial activity in the root zone (rhizosphere), as well as aggregation and retention in biofilms, natural die-off, predation, and competition for limiting nutrients or trace elements (Dotro, et al., 2017).

7. Units of the CW treatment system

The wastewater treatment methods are composed by unit operations and processes, and their integration makes up the treatment system. The concept of unit operation and unit process are frequently used interchangeably, because they can occur simultaneously in the same treatment unit (von Sperling, 2007). In general, there are three main types of unit operations: physical, chemical and biological. Physical unit operations: treatment methods in which physical forces are predominant (e.g. screening, mixing, sedimentation, filtration). Chemical unit processes: in which the removal or the conversion of the contaminants occurs by the addition of chemical products or due to chemical reactions (e.g. precipitation, adsorption, disinfection). Biological unit processes: the removal of the contaminants occurs by means of biological activity (e.g. nitrification, denitrification) (Metclaf & Eddy, 1991). A typical flowsheet of a CW system is shown in Figure (10).

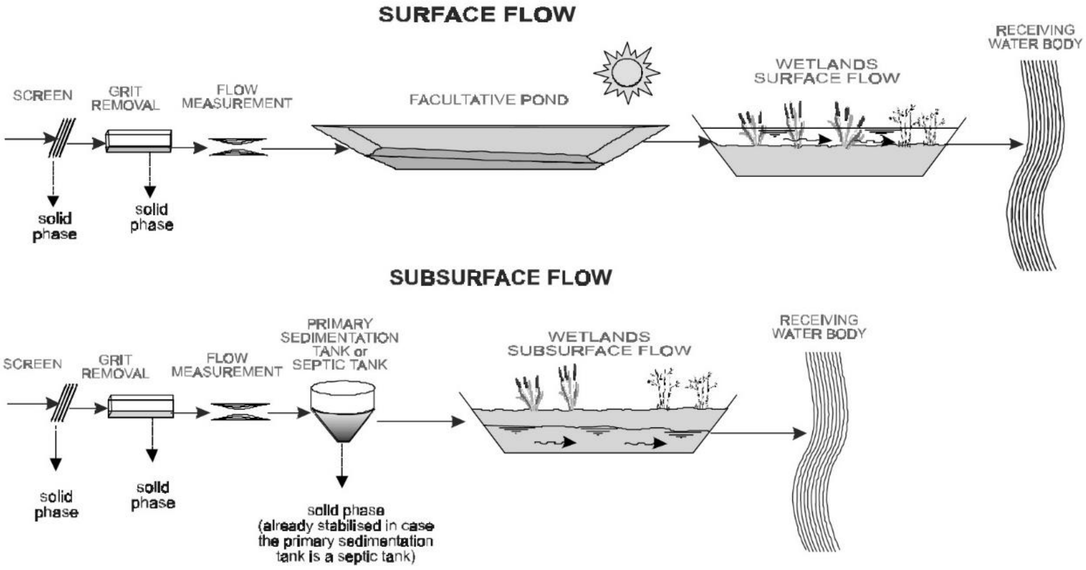


FIGURE 10: Flowsheet of CW system.
Source (von Sperling, 2007)

7.1 Preliminary Treatment

Preliminary treatment is mainly intended for the removal of grit and coarse solids. The basic removal mechanisms are of a physical order (von Sperling, 2007).

7.1.1 screens

The removal of coarse solids is frequently done by screens or racks. In screening, material with dimensions larger than the spaces between the bars is removed (Figure 11). These screens have 50 mm spans. The removal of retained material can be manual or mechanized (von Sperling, 2007). The main objective of the removal of coarse solids are:

* protection of the wastewater transport devices (pumps and piping)

* protection of the subsequent treatment units

* protection of the receiving bodies

7.1.2 Grit chamber

The removal of sand contained in the sewage is done through special units called grit chambers or sand traps. The sand removal mechanism is simply by sedimentation: the sand grains go to the bottom of the tank due to their larger dimensions and density, while the organic matter, which settles much slower, stays in suspension and goes on to the downstream units. There are many processes, from manual to completely mechanized units, for the removal and transportation of the settled grit (von Sperling, 2007).

FIGURE 11: Screens and sand trap in Kámen u Havlíčkova Brodu. Photo credit: Jan Vymazal. Source: (Vymazal, 2004)

7.2 Primary treatment

Primary treatment aims at the removal of settleable suspended solids and floating solids. After passing the preliminary treatment units, sewage still contains non-coarse suspended solids, which can be partially removed in sedimentation units. A significant part of these suspended solids is comprised of organic matter in suspension (von Sperling, 2007).

7.2.1 Septic Tanks

The sedimentation tanks can be circular or rectangular. Sewage flows slowly through the sedimentation tanks, allowing the suspended solids with greater density than the surrounding liquid to slowly settle to the bottom. The mass of solids accumulated in the bottom is called raw primary sludge. This sludge is removed through a single pipe in small tanks or through mechanical scrapers and pump in large tanks (US-EPA, 2020).

Floating material, such as grease and oil, tends to have a lower density than the surrounding liquid and rise to the surface of the sedimentation tanks, where they are collected and removed from the tank for subsequent treatment. The septic tanks (Figure 12) and their variants, such as Imhoff tanks, are basically sedimentation tanks, where the settleable solids are removed to the bottom. These solids remain at the bottom of the tank for a long period of time (various months) which is enough for their digestion. This stabilization occurs under anaerobic conditions (von Sperling, 2007).

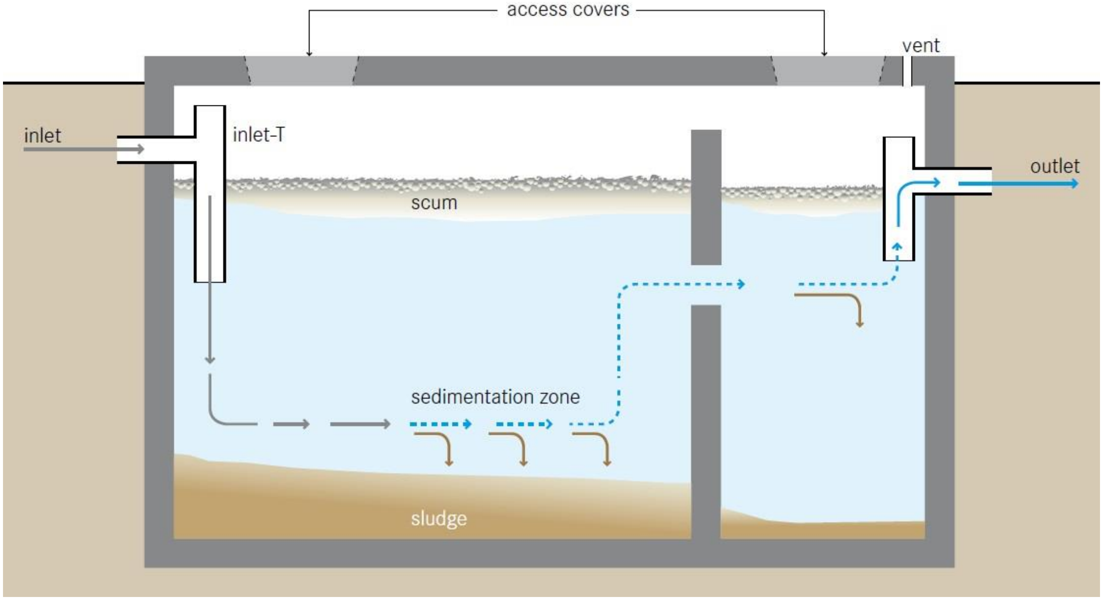


FIGURE 12: Schematic of a Septic Tank
Source: (Tilley, et al., 2014)

7.2.2 Imhoff Tanks:

The Imhoff tank obtained its name from its inventor, Dr. Karl Imhoff of Germany. The technology was developed in the Emscher District of Germany and patented in 1906 by Dr. Imhoff. The first plant was put into operation two years later. The Imhoff tank is a primary treatment technology for raw wastewater, designed for solid-liquid separation and digestion of the settled sludge (Figure 13). It consists of a V-shaped settling compartment above a tapering sludge digestion chamber with gas vents (Tilley, et al., 2014). Imhoff tanks are basically sedimentation tanks, where the settleable solids are removed to the bottom. These solids (sludge) remain at the bottom of the tanks for a long period of time

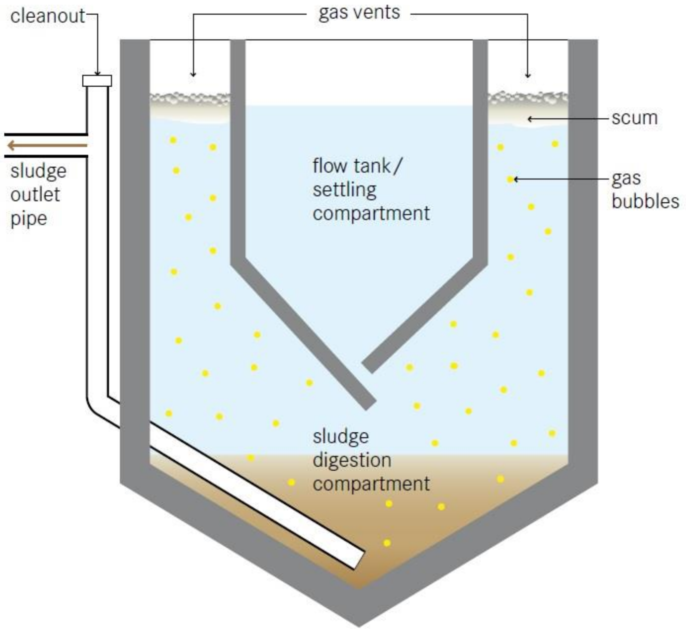


FIGURE 13: Schematic of an Imhoff Tank,
Source: (Tilley, et al., 2014)

(various months) which is sufficient for their digestion. This stabilization occurs under anaerobic conditions (von Sperling, 2007).

7.3 Secondary treatment

The main objective of secondary treatment is the removal of organic matter. The essence of secondary treatment is the inclusion of a biological stage. While preliminary and primary treatments have predominantly physical mechanisms, the removal of the organic matter in the secondary stage is carried out through biochemical reactions, undertaken by microorganisms (von Sperling, 2007). The secondary treatment process in a CW system happens in the filtration bed as explained in the previous chapter 5.

8. Characteristics of the study area (Tehovec)

8.1 Location of Tehovec

Tehovec is a village in Říčany municipality, which is part of Prague-East district (CZ0209) in the Central Bohemian region (Figure 14). The cadastral code for Tehovec is (599719).

Tehovec is about 5 km away from Prague to the eastern outskirts of Říčany town. According to the Czech Statistical office, currently 631 persons live here (294 males, 337 females) with an average age of 37.9 years (CZSO, 2021). Tehovec consists of two parts Vojkov and Tehovec.

FIGURE 14: Map of the Czech Republic with Tehovec. Source: Wikipedia 2021

The total area of the village in the cadastral system is 278 Ha. The total number of buildings is 248 (counted by the author).

The altitude in Tehovec varies from the highest point 458 meters above sea level to the lowest point 415 m. a.s.l. The first written mention of Tehovec goes back to 14th century (Úřad, 2018). Figure 15 shows an orthophoto map of Tehovec and the main surrounding villages.

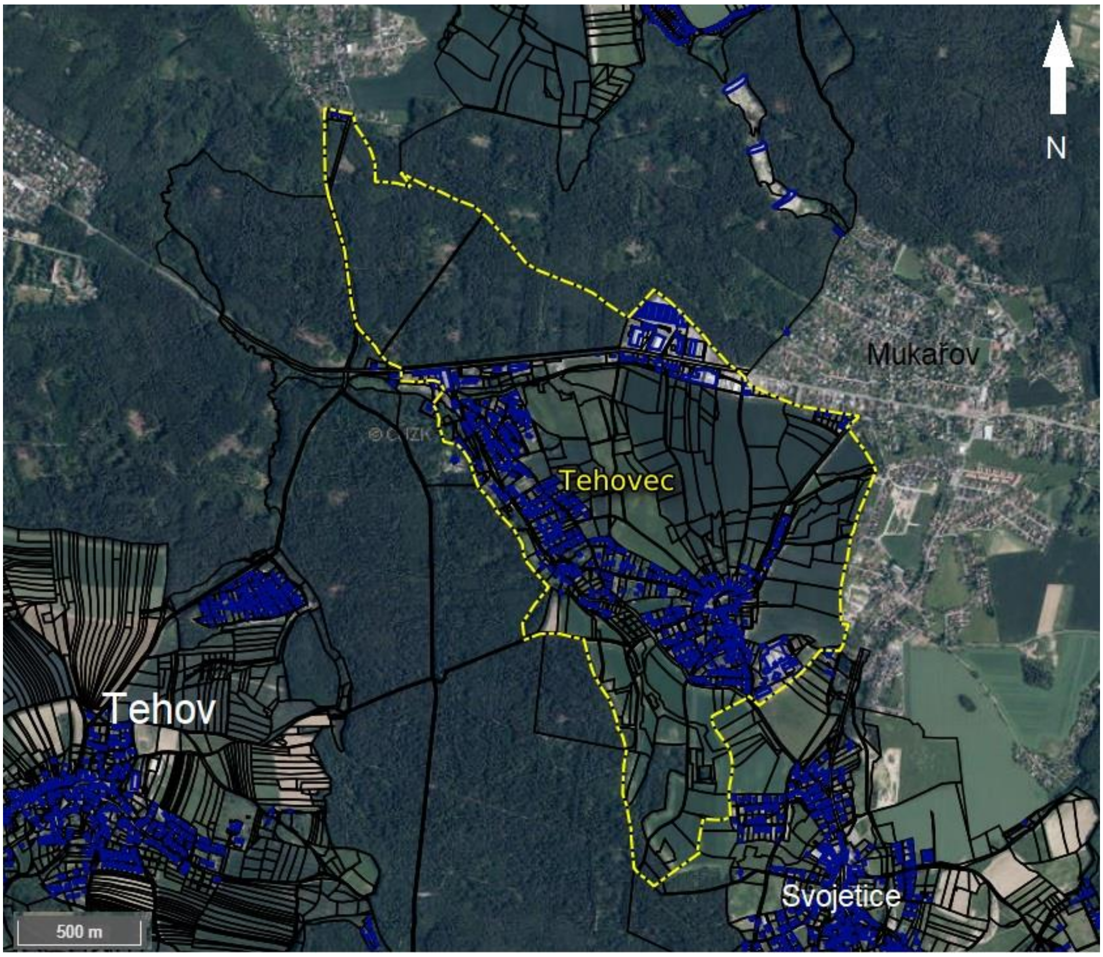


FIGURE 15: Orthophoto map of Tehovec
Source: (Geoportal, 2021)

8.2 Climatical description:

Tehovec and the surrounding area belong to the MT2 (moderately warm) region according to Quitt classification (Figure 16). Quitt's climate classification is the most used classification in the Czech Republic and Slovakia. The classification system was created by the Czech climatologist Evžen Quitt and published in 1971 in the book

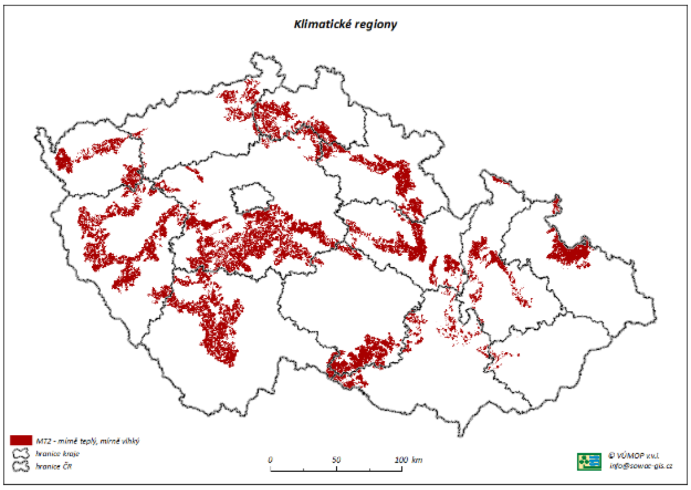


FIGURE 16: MT2 Climate region in CZ
Source: (VÚMOP, 2020)

Climate Area of Czechoslovakia (Hruban, 2018). The Quitt's climatic classification (Figure 17) is based on dividing a territory into climate regions (units) according to complex climatological characteristics. These units represent specified classes defined by the combination of values of 14 climatological characteristics. All units are included in three basic climatic regions: warm, moderately warm and cold (Figure 16). The classification is popular as it allows the definition on a single map of site boundaries where there are changes in climatic characteristics. There are 17 climatic units (from a 23 possible units) recognized for the given time period in the Czech Republic (Vondráková, et al., 2013).

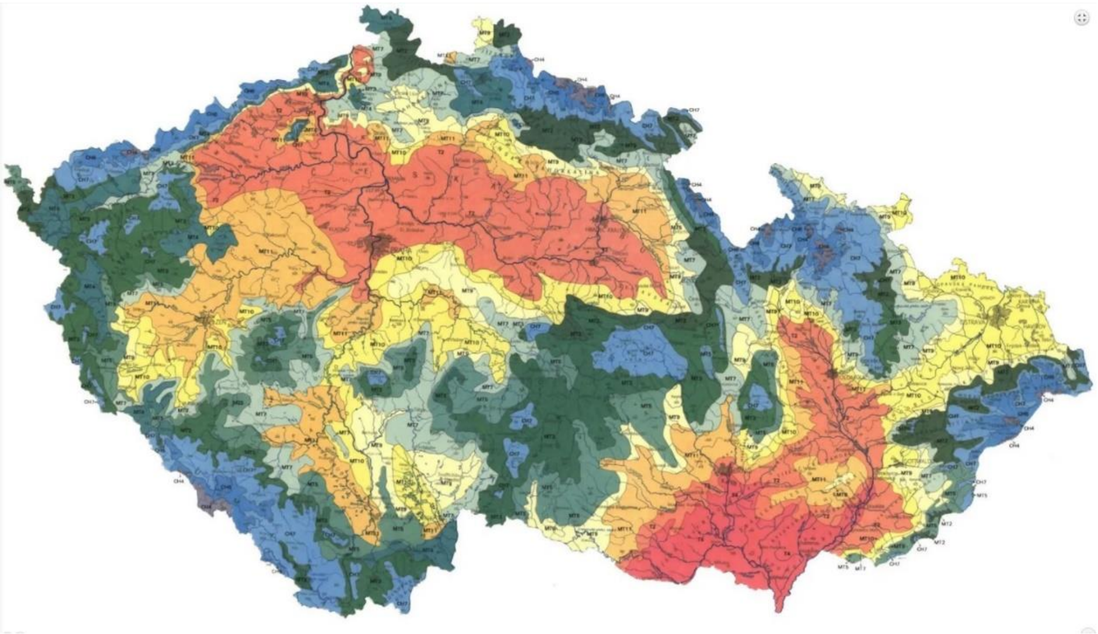


FIGURE 17: Climatic regions of the Czech Republic
Source: (Quitt, 1971)

MT stands for moderately warm (Mírně Teplé in Czech language). In the MT2 area: spring is short and mild, summer is short, mild to slightly cold, slightly humid, autumn is short and mild, winter is mild, normally long, dry with a normal snow cover. Table 5 shows the main characteristics of the moderately warm areas according to Quitt's book in 1971 (Quitt, 1971). Table 5 summarizes the basic characteristics of the Quitt climatic regions.

TABLE 5: Climatic characteristics of a moderately warm area
Source: (Quitt, 1971)

Climatic characteristics of a moderately warm area	MT11	MT10	MT9	MT7	MT3	MT2
Number of summer days	40-50	40-50	40-50	30–40	20-30	20-30
Number of days with avg. at a temperature of 10 ° C or more	140–160	140–160	140–160	140–160	120–140	140–160
Number of days with frost	110–130	110–130	110–130	110–130	130–160	110–130
Number of ice days	30–40	30–40	30–40	40-50	40-50	40-50
Avg. January temperature	-2 to -3	-2 to -3	-3 to -4	-2 to -3	-3 to -4	-2 to -3
Avg. July temperature	17–18	17–18	17–18	16–17	16–17	16–17
Avg. April temperature	07-08	07-08	06-07	06-07	06-07	06-07
Avg. October temperature	07-08	07-08	07-08	07-08	06-07	06-07
Avg. number of days with precipitation of 1 mm and more	90–100	100–120	100–120	100–120	110–120	120–130
Sum of precipitation in the growing season	350–400	400–450	400–450	400–450	350–450	450–500
Sum of precipitation in winter	200–250	200–250	250–300	250–300	250–300	250–300
Total amount of precipitation	550–650	600–700	650–750	650–750	600–750	700–800
Number of days with snow cover	50–60	50–60	60–80	60–80	60–100	80–100
Number of cloudy days	120–150	120–150	120–150	120–150	120–150	150–160
Number of clear days	40-50	40-50	40-50	40-50	40-50	40-50

8.3 Pedological description:

In the Czech Republic, comprehensive large-scale soil surveys were conducted in the 1960s on the entire state's territory, with the exception of urbanized areas. A soil map for the entire Czech Republic was created based on this survey

BPEJ 2199, the ecological classification of soil. This specific category was further subdivided into the following 13 soil types during the survey (VÚMOP, 2020):

Black soils (Černozemě PT 1),
Brown soils (Hnědozemě PT 2),
Luvi soils (Luvizemě PT 3),
Rendziny and pararendziny (Rendziny a pararendziny PT 4),
Rego soils (Regozemě PT 5),
Cambi soils (Kambizemě PT 6),
Pod soils (Kambizemě dystrické, podzoly, kryptopodzoly PT 7),
Lito soils (Kambizemě, rankery, litozemě PT 8),
Heavily sloping soils (Silně svažité půdy PT 9),
Pseudogley (Pseudogleje PT 10),
Fluvi soils (Fluvizemě PT 11),
Blackish (Černice PT 12),
Gley (Gleje PT 13).

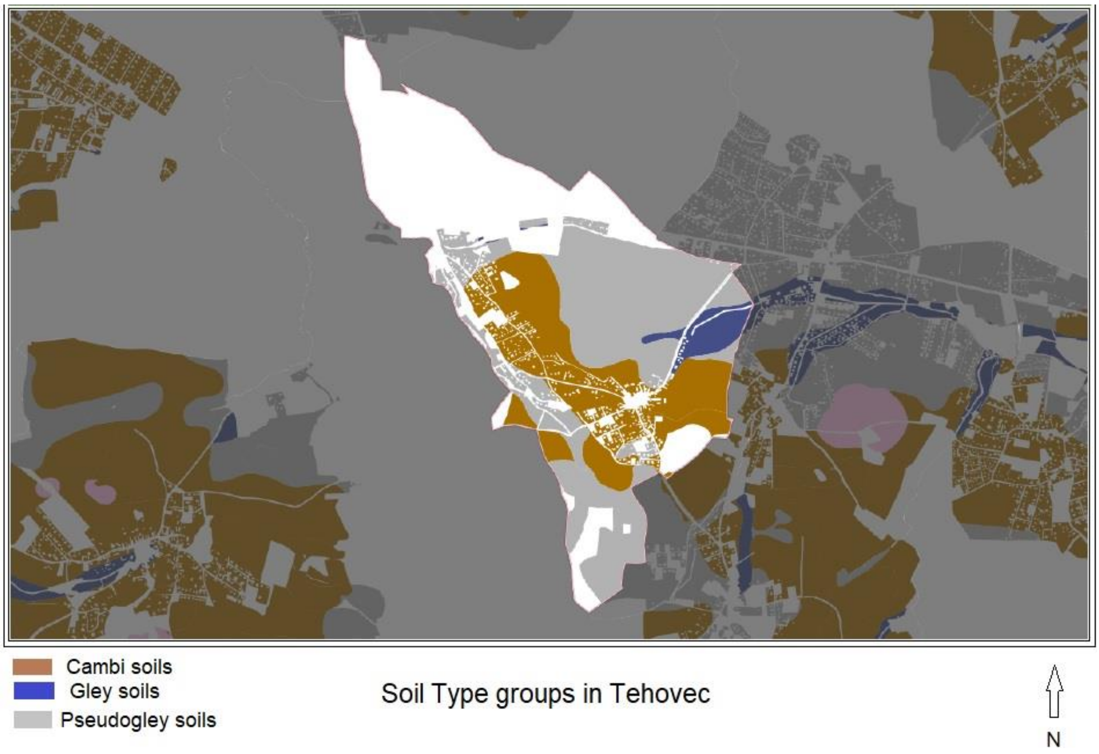


FIGURE 18: Soil Types in Tehovec
Source: (VÚMOP, 2020)

In Tehovec there are three soil types: pseudogley (PT 10) at 92 ha counts for 57% and cambi soils (PT 6) at 61 ha counts for 34%, and the other soil type found in the village is gley (PT 13) at 8.5 ha which presents only 9% of the village non-built area (Figure 18). All the buildup areas in Tehovec are not included in the classification (VÚMOP, 2020).

Pseudogley (Pseudogleje PT 10): the basic feature of this group of soils is the periodic wetting of the profile, especially in the spring. Unlike luvi soils, the soil profile must have significant features of periodic surface wetting. These soils are widespread in slightly warm to cold areas, where they occur in flat or slightly sloping or depressed terrain.

Cambi soils (Kambizemě PT 6): this group includes mainly soils on solid rocks. Strongly skeletal soils were separated from this group - shallow, strongly sloping and some light and heavy soils as separate groups. Cambodia are typical soils of hills and lower and middle highlands.

Gley (Gleje PT 13): the occurrence of these soils is in a very complex relief, therefore, in addition to genetic classification, sorting according to the nature of the relief was used. In addition to the relief, the second most important feature is the degree of hydro-morphism.

8.4 Hydrogeological description:

There are two water courses start from Tehovec its surroundings: Rokytka and Jevanský (Figure 19). Being at the source of both Rokytka and Jevanský, the quality of the urban surface water and the wastewater in Tehovec affects the whole Rokytka and Vltava river. Figure 19 shows the watershed edges in the lands of Tehovec. Rokytka starts at elevation of 448 m. a.s.l and joins the Vltava at elevation 182m.

Soils in Tehovec in general have a low infiltration rate, Soils with a medium rate of infiltration even at full saturation, including mainly soils of medium to deep, medium to well drained, sandy loam to loamy (VÚMOP, 2020).

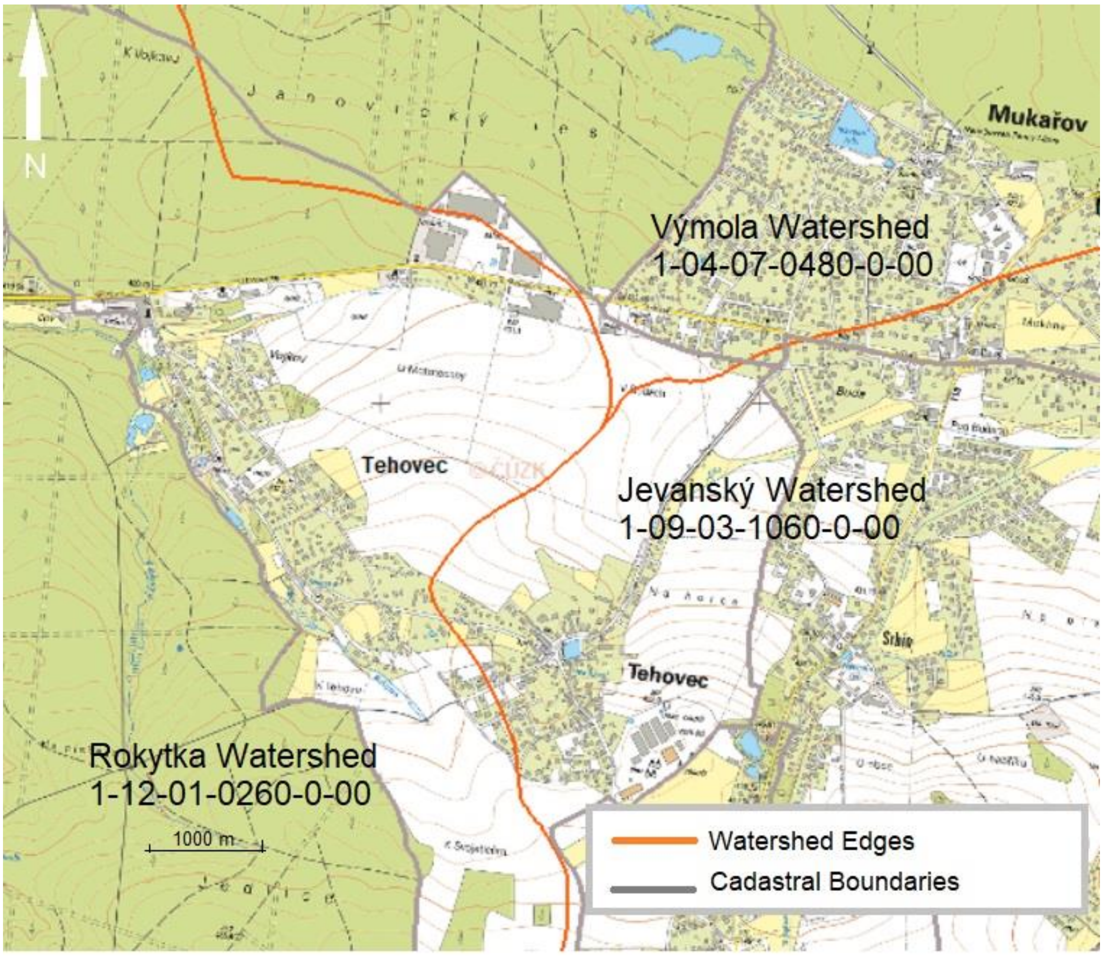


FIGURE 19: Watershed Boundaries in Tehovec
Source: Hydroecological Information System (Hydroecological, 2021)

9. Current state of treatment in Tehovec

Water supply for public use is owned by the municipality of Tehovec and it is connected to the South Region Water Supply group. From there, the water is brought to the Tehovec’s reservoir and then diverted into storage lines to customers. An additional source is the local drilling and water treatment plant, which will be removed in the future by the new municipality master plan (Figure 20). There is a gravity sewage system for public use owned by the municipality of Tehovec which includes three sewage pumping stations (Figure 21). The recipient of wastewater is the Rokytka stream. (Úřad, 2018). The current treatment system is based on the septic tank treatment technology.

A research was carried out in 2018 to assess the existing condition of these programs. This assessment was carried out by Vodohospodásk rozvoj a vstavba a.s., a consulting firm based in Prague. The organization indicated in the assessment report that the current structure is unsuitable for the long term and recommended that the current system be extended.

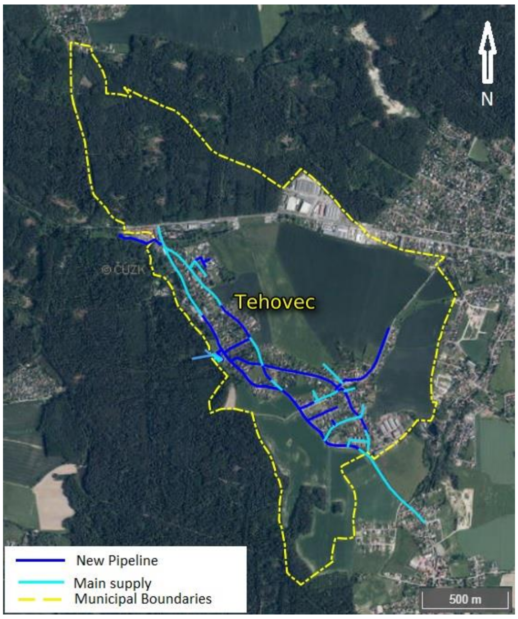


FIGURE 20: Water supply in Tehovec
Source: (Geoportal, 2021)

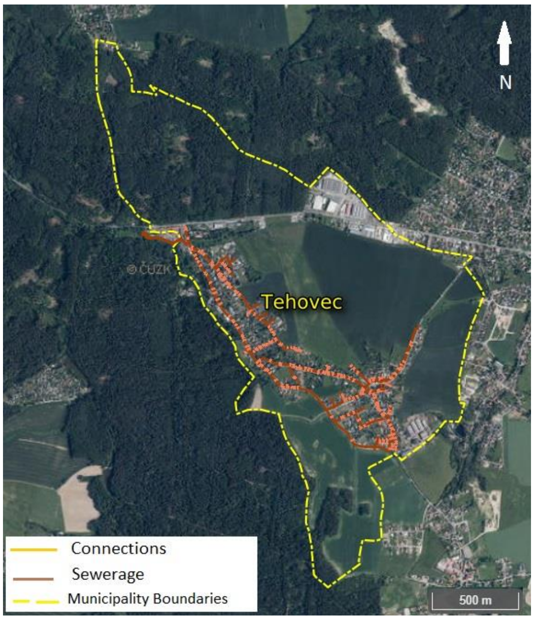


FIGURE 21: Wastewater line in Tehovec
Source: (Geoportal, 2021)

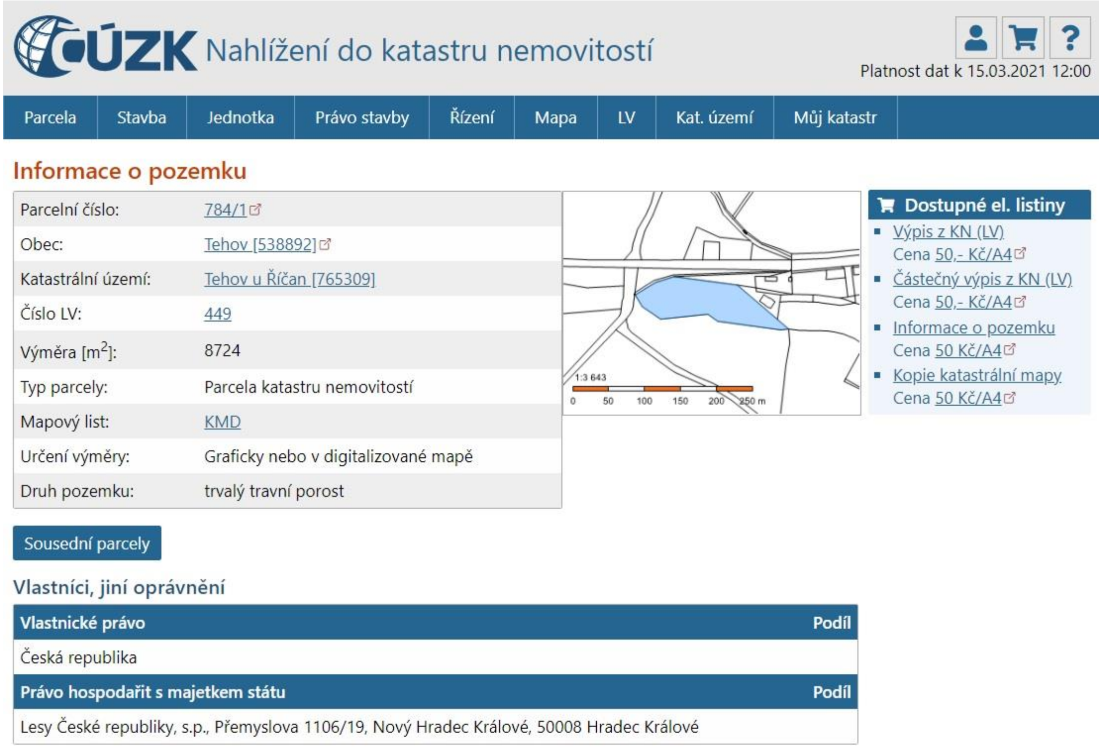
Also, this evaluation and the financial recovery plan based on an increase of 5% year on year in the prices of water supply and wastewater management, and a population increase of 50 persons annually, suggests that the expenses on the rent and maintenance of the current system will pay-off a new system by the year 2028 (Úřad, 2018).

There is a hospital for long term sicknesses in Tehovec (LDN na Vojkově). This hospital is for serious and long-term diseases, especially in the field of internal medicine. It focuses on the early rehabilitation of patients after recent accident (Úřad, 2018). The hospital has his own wastewater treatment facility located in the south-western side of the hospital and diffuses the treated water to Rokytka.

10. Design of a constructed wetland for Tehovec

10.1 Location of the new Constructed wetland

The current treatment facility is located at the edge of the village, and the plot is owned by the village, so it is convenient to expand and build the new constructions on this plot or any other available land close to it, in order to save any renting or buying costs. The area of this plot is small (only 821 m^2) and only enough for what it already has.



Informace o pozemku

Parcelní číslo:	784/1
Obec:	Tehov [538892]
Katastrální území:	Tehov u Říčan [765309]
Číslo LV:	449
Výměra [m^2]:	8724
Typ parcely:	Parcela katastru nemovitostí
Mapový list:	KMD
Určení výměry:	Graficky nebo v digitalizované mapě
Druh pozemku:	trvalý travní porost

Dostupné el. listiny

- Výpis z KN (LV)
  Cena 50,- Kč/A4
- Částečný výpis z KN (LV)
  Cena 50,- Kč/A4
- Informace o pozemku
  Cena 50 Kč/A4
- Kopie katastrální mapy
  Cena 50 Kč/A4

Vlastníci, jiní oprávnění

Vlastnické právo	Podíl
Česká republika	

Právo hospodařit s majetkem státu	Podíl
Lesy České republiky, s.p., Přemyslova 1106/19, Nový Hradec Králové, 50008 Hradec Králové	

FIGURE 22: Information about the location of the proposed CW
source: The Czech cadastral office (ČÚZK, 2021)

The plot 784/1 is next to current facility and owned by the Czech Republic with an area of (8724 m^2) which should be sufficient for the new facility (Figure 22).

This plot's best attribute is its location, as it is on the outskirts of the city and is surrounded on almost all sides by a forest, which provides a natural shelter and prevents any unwanted odors away from the inhabitants (Figure 23, 24). Another significant benefit of this plot is its proximity to the Rokytka stream, which flows adjacent to the plot's south side. After the wastewater has been treated, it can be discharged into Rokytka without the need to use any machinery.

FIGURE 23: Location of the proposed Constructed Wetland
Source: (ČÚZK, 2021) modified by the author

FIGURE 24: Current state of the proposed location, Photo taken by Author

10.2 Hydraulic calculations

For the future population growth, an increase of 10% on the permanent residents will be calculated, which will add 63 to the current 631 persons living in Tehovec. The total Population Equivalent is 694 PE.

Wastewater balance: the total amount of wastewater is the amount of water consumed per capita per day, and it is measured by residential facilities (such as toilets, bathrooms, and showers). Drinking water intake is approximately equivalent. For the Czech Republic the total amount of wastewater is recommended to be calculated between (110 – 120) l/person/day. The maximum recommended amount will be taken into account 120 liter per person per day.

$Q_{24}= Q_d*PE = 120 * 694 = 83280$ l/day = 83.3 m^3/day

$Q_{24} = 0.964$ l/s

Maximum daily wastewater flow:

$Q_{dmax}=Q_{24}*k_d= 83.3*1.5= 124.95$ m^3/day = 1.44 l/s

$Q_{dmax} = 1.44$ l/s

Maximum hourly wastewater flow:

$Q_{hmax}= Q_{24}*k_d *k_h/24=83.3*1.5*2.2/24 = 11.45$ m^3/h = 0.13 l/s

$Q_{hmax} = 0.13$ l/s

Coefficients kd and kh are taken from the Czech standards

TABLE 6: Coefficient kd according to the population

Population	To 1000	1000-5000	5000-20000	20000-100000	Above 100000
kd	1.5	1.4	1.35	1.25	1.15

TABLE 7: coefficient kh according to the population

Population	30	40	50	70	100	300	400	500
kh	7.2	6.9	6.7	6.3	5.9	4.4	3.5	2.6
Population	1000	2000	5000	10000	20000	30000	50000	100000
kh	2.2	2.1	2.0	2.0	1.9	1.8	1.7	1.5

a) Amount of wastewater: From the Czech standard no. 75 6402, the production of wastewater for population equivalent is:

BOD_5	694*60 g/person.day	=41.64 kg/day
COD_{cr}	694*120 g/person.day	=83.28 kg/day
SS	694*55 g/person.day	=38.17 kg/day

b) The concentration pollution

BOD_5	500 mg/l
COD_{cr}	459.6 mg/l
SS	458.2 mg/l

c) Designing the filtration units: by considering a 30% efficiency from the pretreatment stage (the septic tanks)

Then the concentration of pollutants at the source of the filtration beds is 350 mg/l

Then the area of the filtration beds (the required BOD_5 6-10)

A_1= 350 * 83.3 / 10 = 2915.5 m^2

A_2= 350 * 83.3 / 6 = 4859.5 m^2

Then A_{min} = 2915.5 m^2 and A_{max} = 4859.5 m^2

Vertical flow CWs are usually designed with area of 4 m^2/PE, then we can calculate an approximate area of the filtration bed to be:

A_{approx}= 4 * 694 = 2776 m^2

Based on the available land, the proposed filtration beds are two rectangle shaped beds with area 35*45= 1575 m^2 each, then the total area of the filtration is 3150 m^2. By proposing the depth of the units to 80 cm, then the volume of the filtration bed is

V=A*d = 3150 * 0.8 = 2520 m^3

The hydraulic retention time for the first unit is

t= V*n/Q_{24} = (1575*0.35) / 83.3 = 6.62 days = 158.8 hours

where n is the porosity of the filtration bed.

TABLE 8: The basic design parameters

The basic parameters used to design the constructed wetland		
Current population	631	PE
Designed population capacity	694	PE
Average inflow	83.3	m^3/day
Maximum daily inflow	124.95	m^3/day
Maximum hourly inflow	11.45	m^3/h
Designed BOD_5	41.64	kg/day
Area of the filtration beds	3150	m^2

10.3 Parts of the proposed constructed wetland:

10.3.1 Sewerage pipes: the existing sewerage connections will be used. All the houses and other buildings are connected to the treatment location as shown in figure 20.

10.3.2 the Constructed Wetland: the treatment unit consists of the screens, sedimentation tank, septic tank, distribution well, the filtration beds, collection well, regulation and measuring well, and the outflow.

* The screens are used to capture coarse objects carried with the wastewater; they are cleaned manually so they will be installed removable. They will be installed inclined to the trough bottom at 40° and the spacing between the bars will be 15 mm. The screens are installed before the inlet of the septic tank. A safety overflow will allow the wastewater to pass to the septic tank if the screens were completely clogged.

* The septic tank: after the screens, the wastewater flows to the septic tank which is a waterproof concrete tank with two separate spaces. The shape of the tank is rectangular, when the wastewater flows through the tank, the settleable particles fall to the bottom by gravity force. The septic tank should be cleaned regularly when needed, at least twice a year.

* The flow control unit: A pump, a control unit, and a measuring system are all included in the flow control unit. After the septic tank, the Parshall Gutter, which is typically used for flow measurement in open channels, will be mounted.

* The vertical flow constructed wetland (the filtration bed): the filtration beds are two rectangular shaped units (35*45 m). Both beds have an area of 1575 m^2. The plants to use are phragmites australis (common reed). Excavation of the soil and compacting the site of the CWs, as well as the application of the filtration medium, would be part of the earthwork. The layers above the ground would include:

a) a leveling layer,

b) a geo-textile layer to defend against roots and earth animals,

c) impermeable liner (HDPE 1.5 mm) to prevent unwanted flow of water in or out of the filter,

d) conventional drainage pipes to collect the treated water,

e) The biological treatment layer which is made up of a gravel layer (aggregate size 2-8 mm) with a depth of around 20 cm, a sand layer (aggregate size 0-2 mm) with a depth of more than 50 cm, and a coarse aggregate layer on top (aggregate size 8-16 mm) where the reeds is planted, and on the very top is

f) the distribution pipes which will distribute the wastewater evenly.

* The storage unit is a wooden structure with a tilted roof, measuring (2.2*1.8 m) and standing at a height of 2.2 m. The storage will be installed into a concrete panel that has already been cast. It will be used to keep all of the required operational equipment.

* The slag filter: which removes phosphorous from the treated wastewater until it is released into the receiving water body. The rectangular cluster form of the slag filter allows for quick replacement if it becomes clogged.

* The outlet hole: it will be made with natural stones available onsite, then the treated wastewater flows to Rokytka stream we can use the existing structure shown in Figure 25 as an outlet discharge.

An arrangement of the proposed construction is shown in Figure (26).

FIGURE 25: Existing location for the outlet hole, Photo taken by Author

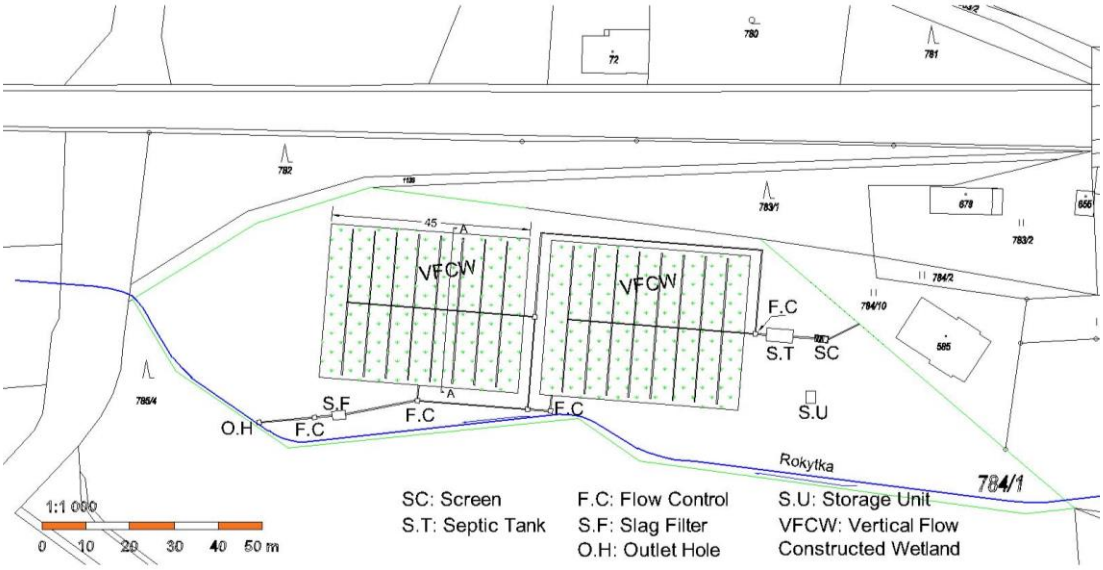


FIGURE 26: An overview of the new situation

11. Discussion

Constructed wetlands have been used to treat wastewater in the Czech Republic for more than 50 years (Vymazal & Kröpfelová, 2008), and for several more years in other countries; they have been proven to function properly and clean the wastewater to meet all of the minimum requirements in the wastewater treatment field; however, we still lack public acceptance of these systems, restricting their implementation, even among some public authorities, we continue to struggle with their negative view on the constructed wetland technology. In short, some of us still believe that if a system is not designed with a biological mechanical cleaning mechanism, it will not function properly.

Alternative wastewater treatment systems (like constructed wetlands) have both benefits and drawbacks. However, disadvantages can be minimized on a wide scale, resulting in a positive outcome. It was a solution that met all of the criteria for discharged water quality as far as the environment and the watercourse administrator were concerned, but it was difficult to demonstrate such results during the project authorization process, where assumptions and theoretical calculations were used.

Many long-term studies on the treatment efficiency over time and whether nutrient removal rates are affected over time have shown that when vegetation and inlet and outlet systems are cared for, the CWs output does not deteriorate, and removal rates remain constant over time (Ingrao, et al., 2020). After several years of service, Table 9 shows the care efficiency of the CWs in the Czech Republic.

TABLE 9: CWs treatment efficiency in CR, Source: (Vymazal, 2004)

Parameter	Inflow (mg/l)	Outflow (mg/l)	Efficiency (%)
BOD_5	150	14.4	85.8
COD_{cr}	333	53	76.1
TSS	165	11.9	84.8
TN	56	27.6	47
$NH4^+$-N	27.5	18	33.4
$NO3^-$-N	5.8	2.45	40.9
TP	6.8	3.3	41.4

In this thesis, I chose to view local conditions, even on the most cost-effective alternative, if possible, without requiring any energy resources. The planned constructed wetland is subject to the village authority's zoning plan as well as the need to expand the current facility.

As opposed to traditional wastewater treatment systems, constructed wetland operating costs are considerably lower due to lower energy demands. The proposed cleaning method would protect the environment while also allowing for the necessary partial decentralization of wastewater treatment. The cleaning process will be in line with the village of Tehovec's development.

12. Conclusion

The thesis' aim was to explain how constructed wetland technology works in terms of wastewater treatment. Then, in Tehovec, define the wastewater situation and plan a new constructed wetland for the village.

After studying the current population of Tehovec and considering potential population increase, I planned the constructed wetland for 694 PE and an average daily wastewater inflow of 83.3 m^3/day at a concentration of BOD_5 500 mg/l.

The proposed constructed wetland for Tehovec consists of two vertical flow filtration beds, each with an area of 1575 m^2. The beds' shape is determined by the land's boundaries. Screens, a septic tank, a flow control, a measuring device, filtration beds, a storage unit, the slag filter, and the stream outlet hole are all part of the planned constructed wetland.

Constructed wetland is a viable alternative to the Tehovec village sewage system, with numerous benefits. When deciding on a wastewater treatment system, it's critical to consider the potential environmental implications as well as existing technologies and new designs. If the existing sewage disposal situation in Tehovec is not resolved, groundwater and surface water quality in the region would deteriorate. It is also worth noting that the development of a municipal sewage system in municipalities contributes significantly to the improvement of living standards in the village of Tehovec.

References

Bastian, R. K., 1993. *Constructed Wetlands for Wastewater Treatment and Wildlife Habitat.* s.l.:EPA, USA.

Brix, H., 1990. Gas exchange through the soil-atmosphere interphase and through dead culms of phragmites australis in a constructed reed bed receiving domestic sewage. *Water Research,* 24(2), pp. 259-266.

Brix, H., 1993. Wastewater treatment in constructed wetlands: system design, removal processes, and tratment performance. In: *Constructed wetlands for water quality improvement.* s.l.:Lewis Publishers.

Brix, H. & Schierup, H.-H., 1989. The Use of Aquatic Macrophytes in Water-Pollution Control. *AMBIO A Journal of the Human Environment,* pp. 100-107.

Buresh, R. J., Casselman, M. E. & Patrick Jr, W. H., 1980. Nitrogen fixation in flooded soil systems: a review. *Advances in Agronomy,* Volume 33, pp. 149-192.

ČÚZK, 2021. *ČÚZK.* [Online]
Available at:
https://nahlizenidokn.cuzk.cz/ZobrazObjekt.aspx?encrypted=3r_3TeR7dgRF6nr-Do-vaa8YSd3F9rjY4SqvskOxmvy6_bVz2I3PgxbYKmuvfjqtJQNRj6Ua81x5ZpN_p6f9p4Xp0ao6t-vMuWz48HMpr7PwzRm7cTr71uAZLkcY7kxGJC2chUlt_EtCNeUy8XBMTA==

CZSO, C. S. o., 2020. *Obyvatelstvo.* [Online]
Available at: https://www.czso.cz/csu/xs/obyvatelstvo-xs-obce

Davis, L., 1995. *A HANDBOOK OF CONSTRUCTED WETLANDS.* Washington: US Environmental Protection Agency.

Dotro, G. et al., 2017. *Treatment wetlands.* s.l.:IWA Publishing.

Dykyjová, D., 1982. *The Significance of Macrophytes in Water Management, Water Hygiene and Fishery.* Ceske´ Budejovice, ČSVTS, pp. 82-93.

Dykyjová, D. & Květ, J., 1978. *Pond Littoral Ecosystems Structure and Functioning.* Berlin: Springer.

Geoportal, 2021. *Tehovec.* [Online]
Available at: https://portal.mapotip.cz/tehovec

Hammer, D. A., 1989. *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural.* s.l.:Lewis Publisher.

Hauck, R. D., 1984. Atmospheric nitrogen chemistry, nitrification, denitrification, and their relationships. In: *The Natural Environment and the Biogeochemical Cycles.* Berlin: Springer-Verlag, pp. 105-125.

Hruban, R., 2018. *Climate classification.* [Online]
Available at: http://moravske-karpaty.cz/prirodni-pomery/klima/klasifikace-klimatu/

Hydroecological, I., 2021. *Water Management map.* [Online]
Available at:
https://heis.vuv.cz/data/webmap/isapi.dll?map=mp_heis_voda&TMPL=HVMAP_MAIN&IFRAME=0&lon=14.7255045&lat=49.9824164&scale=15120

Ingrao, C., Failla, S. & Arcidiacono, C., 2020. A comprehensive review of environmental and operational issues of constructed wetland systems. *Current Opinion in Environmental Science & Health,* Volume 13, pp. 35-45.

Kadlec, R., 1994. *Surface Flow Constructed Wetlands.* Guangzhou, China, ICWS Secretariat, pp. 1-12.

Kadlec, R. H., Tilton, D. L. & Ewel, K. C., 1979. The use of freshwater wetlands as a tertiary wastewater treatment alternative. *C R C Critical Reviews in Environmental Control ,* pp. 185-212.

Kadlec, R. H. & Wallace, S. D., 2009. *Treatment wetlands.* Boca Raton: CRC Press.

Langergraber, G. et al., 2019. *Wetland Technology.* London: IWA Publishing.

Metclaf & Eddy, 1991. *Wastewater engineering : treatment, disposal, and reuse.* 3 ed. s.l.:Metcalf & Eddy Inc.

Muldera, A., Graaf, A. A. v. d., Robertson, L. A. & Kuenen, J. G., 1995. Anaerobic ammonium oxidation discovered in a denitrifying fluidized bed reactor. *FEMS Microbiology Ecology,* 16(3), pp. 177-183.

Patrick, W. H. & Reddy, K. R., 1984. Nitrogen transformations and loss in flooded soils and sediments. *C R C Critical Reviews in Environmental Control,* 13(4), pp. 273-309.

Pries, J. H., 1994. *Wastewater and Stormwater Applications of Wetlands in Canada.* s.l.:Sustaining wetlands, Issue paper No. 1994-1.

Quitt, E., 1971. *Climatic regions of Czechoslovakia.* Brno: Geografický ústav ČSAV.

Revitt, D. et al., 2004. The performances of vegetative treatment systems forhighway runoff during dry and wet conditions. *Science of the Total Environmen,* pp. 261-270.

Seidel, K., 1965. Neue Wege zur Grundwasseranreicherung. In: *Vol. II. Hydrobotanische.* Krefeld: GWF Wasser/Abwasser, pp. 831-833.

Stewart, W., 1973. Nitrogen fixation. In: *The biology of the blue-green algae.* Berkeley, California: University of California Press, pp. 260-278.

Strous, M., van Gerven, E., Kuenen, J. G. & Jetten, M., 1997. Effects of Aerobic and Microaerobic Conditions on Anaerobic Ammonium-Oxidizing (Anammox) Sludge. *APPLIED AND ENVIRONMENTAL MICROBIOLOGY,* 63(6), pp. 2446-2448.

Tilley, E. et al., 2014. *Compendium of Sanitation Systems and Technologies.* 2nd Revised Edition ed. Duebendorf, Switzerland: Swiss Federal Institute of Aquatic Science and Technology (Eawag).

Úřad, O., 2018. *Historie.* [Online]
Available at: https://www.tehovec.cz/obec/historie/

Úřad, O., 2018. *Vodovod a kanalizace.* [Online]
Available at: https://www.tehovec.cz/urad/vodovod-a-kanalizace/

US-EPA, 2020. *Types of Septic Systems.* [Online]
Available at: https://www.epa.gov/septic/types-septic-systems
[Accessed 2021].

van de Graaf, A. A. et al., 1995. Anaerobic oxidation of ammonium is a biologically mediated process. *Applied and Environmental Microbiology,* 61(4), pp. 1246-1251.

von Sperling, M., 2007. *Wastewater Characteristics, Treatment and Disposal.* London: IWA Publishing.

Vondráková, A., Vávra, A. & Voženílek, V., 2013. Climatic regions of the Czech Republic. *Journal of Maps,* pp. 425-430.

VÚMOP, 2020. *Tehovec soil in Numbers.* [Online]
Available at: https://statistiky.vumop.cz/?core=stat&typ=obec&kod=599719

Vymazal, J., 1998. Czech Republic. In: *Constructed wetlands for wastewater treatment in Europe.* Leiden, The Netherlands: Backhuys Publishers, pp. 95-121.

Vymazal, J., 2001. Types of constructed wetlands for wastewater treatment: their potential for nutrient removal. In: *Transformations of nutrients in natural and constructed wetlands.* Leiden, The Netherlands: Backhuys Publishers, pp. 1-93.

Vymazal, J., 2002. The use of sub-surface constructed wetlands for wastewater treatment in the Czech Republic: 10 years experience. *Ecological Engineering,* pp. 633-646.

Vymazal, J., 2004. *Kořenové čistírny odpadních vod,* Třeboň, CZ: ENKI o. p. s..

Vymazal, J., 2005. Constructed wetlands with horizontal sub-surface flow and hybrid systems for wastewater treatment. *Ecological Engineering ,* pp. 478-490.

Vymazal, J., 2007. Removal of nutrients in various types of constructed wetlands. *Science of the Total Environment 380,* pp. 48-65.

Vymazal, J., 2010. Constructed Wetlands for Wastewater Treatment. *Water,* Volume 2, pp. 530-549.

Vymazal, J., 2011. Constructed Wetlands for Wastewater Treatment: Five Decades of Experience. *Environmental Science & Technology,* pp. 61-69.

Vymazal, J., 2013. Emergent plants used in free water surface constructed wetlands:A review. *Ecological Engineering,* pp. 582-592.

Vymazal, J. & Kröpfelová, L., 2008. *Wastewater Treatment in Constructed Wetlands with Horizontal Sub-Surface Flow.* Dordrecht: Springer.

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