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FanpLESStic-sea project report

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Summary

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The FanpLESStic-sea – “Initiatives to remove microplastics before they enter the sea” project funded by the EU Interreg Baltic Sea Region programme aimed at decreasing microplastic (MP) sources and removing MPs before they enter the Baltic Sea. As part of the project, novel and innovative removal technologies and methods for MPs in urban waters were developed and tested in four pilot systems by three project partners: a common reed filter for treatment of urban snow meltwaters and stormwaters by Natural Resources Institute Finland (Luke), an urban snow melting and filtering unit by Clewat Ltd. and Luke, a constructed wetland system for wastewater effluent by Gdansk Water Utilities, Poland, and a constructed wetland system for stormwater treatment by Gdansk Water.

The results obtained from the four MP removal pilots were very promising. The filter consisting of harvested and bundled common reed is cost-effective and locally adaptable. However, due the insufficient time available for maturation of the reed filter, its performance in MP removal remained uncertain. Novel snow melting and filtering technology developed by Clewat Ltd. solves the problem of dumping urban snow untreated into the sea in a sustainable way. In this project, the efficiency of the snow treatment unit in MP removal was optimized concerning the mesh size for the finer filter used. The constructed wetland systems piloted showed MP removal efficiencies up to 90% from urban stormwaters and wastewater treatment plant effluent.

In addition to retention of MPs present in various urban waters, high removal rates were demonstrated for total suspended solids, nutrients and various pollutants. However, additional longer-time pilot experiments are needed to optimize the performance of the systems, especially for those based on vegetation and biofilm formation. Environmental impact and techno-economic feasibility assessments were also performed for the piloted technologies.

Keywords: microplastic, removal technology, pilot, common reed, constructed wetland, snow, stormwater, wastewater

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List of abbreviations

AAU	Aalborg University
ATR-FTIR	attenuated total reflection-Fourier transform infrared spectroscopy
BOD_5	biochemical oxygen demand
cfu	colony forming unit
COD	chemical oxygen demand
CW	constructed wetland
DEHP	di-2-ethylhexyl phthalate
DIPD	diisobutyl phthalate
EoL	End-of-Life
FPA-μFTIR	focal plane array-based micro-Fourier transform infrared spectroscopy
FU	functional unit
GIWK	Gdansk Water Utilities Ltd.
GW	Gdansk Water Ltd.
HF-CW	horizontal flow constructed wetland
LCA	life cycle assessment
LIAE	Latvian Institute of Aquatic Ecology
LUKE	Natural Resources Institute Finland
MP	microplastic
MRR	mass removal rate
$N\text{-}NH_4$	ammonium-nitrogen
$N\text{-}NO_2$	nitrites
$N\text{-}NO_3$	nitrates
NORCE	Norwegian Research Centre
PE	polyethylene
PES	polyester
PP	polypropylene
PVC	polyvinyl chloride
TN	total nitrogen
TP	total phosphorus
TSS	total suspended solids
VF-CW	vertical flow constructed wetland
WWTP	wastewater treatment plant

1. FanpLESStic-sea project

This report is an output of the FanpLESStic-sea – "Initiatives to remove microplastics before they enter the sea" project (2019–2021) funded by the EU Interreg Baltic Sea Region programme. The project aimed at decreasing microplastics (MPs) sources and removing MPs before they enter the Baltic Sea (https://www.swedenwaterresearch.se/en/projekt/fanplesstic-2/9).

The report is a joint effort of the Activities 3.4 Pilot testing to develop and validate microplastic removal technologies led by Gdansk Water Utilities Ltd. (GIWK) and 3.3 Prepare investments for microplastic solutions led by the Natural Resources Institute Finland (Luke). The main aims of these activities were to 1) test the MP removal efficiency of the selected technologies in pilot-scale (A3.4), 2) estimate the environmental and economic sustainability of these technologies in full scale (A3.3), and 3) describe the business potential and further interest towards these technologies (A3.3). A literature review of existing and emerging technologies for MP removal was presented in a previous report of this project (Vahvaselkä & Winquist 2021).

The MP removal pilots developed and tested, and the results obtained in the FanpLESStic-sea project are described and discussed in Section 2. In Sections 3 and 4, the environmental impacts and the techno-economic feasibility of the technologies piloted are assessed, respectively. Finally, conclusions and recommendations drawn from the results are presented in Section 5.

Due to the COVID-19 pandemic starting in early 2020 and the extensive restrictions introduced in partner countries, original schedules for sampling were delayed and the numbers of MP samples taken at individual pilots were less than originally planned. Therefore, the results from the pilot experiments remain somewhat incomplete. However, valuable information on all the MP removal technologies piloted in the FanpLESStic-sea project was obtained and evaluated, as presented in this report.

2. Pilots on microplastics removal technologies

2.1. Introduction

Novel, innovative, cost-effective and locally adaptable technologies and methods for MP removal from urban waters were piloted in the FanpLESStic-sea project. There were four pilots from three project partners: a common reed filter for urban snow meltwater and stormwater treatment (Luke), a snow melting and filtering unit (Clewat Ltd./Luke), a constructed wetland system for polishing of wastewater effluent (Gdansk Water Utilities, GIWK) and a constructed wetland system for stormwater treatment (Gdansk Water, GW) (Table 1).

Table 1. The four pilots with various technologies for microplastics removal from wastewater effluent, urban stormwaters and snow meltwaters.

Pilot	Wastewater effluent	Stormwater	Urban snow meltwater
1. Common reed filter (Luke)		✓	✓
2. Snow melting and filtering unit (Clewat/Luke)			✓
3. Constructed wetland system (GIWK)	✓		
4. Constructed wetland system (GW)		✓	

One of the FanpLESStic-sea project goals was to harmonize the sampling, sample pretreatment and analysis methods for MPs to get more comparable results. Therefore, identical sampling, sample pretreatment and MP analysis protocols developed at Aalborg University (AAU) were used for all pilots (Rist et al. 2020).

2.2. Common reed

The plant common reed *(Phragmites australis)* played an essential role in three of the tested pilots, either as growing vegetation in constructed wetland systems in pilots 3 and 4, or as harvested and bundled filter material in pilot 1.

Common reed is a perennial reed grass found in freshwater and brackish wetlands throughout temperate and tropical regions of the world. The success of common reed as a robust cosmopolitan species is related to its high productivity, its rapid stand-scale expansion, its capacity to acclimate to adverse environmental conditions, and therefore its ability to rapidly invade new areas (Eller et al. 2017). Common reed stems usually grow to 2-4 meters tall and in favorable growing conditions even taller (Figure 1).

Figure 1. Common reed vegetation at Urajärvi, Southern Finland. Photo: M. Vahvaselkä.

Common reed efficiently takes up nutrients, especially nitrogen, and thereby can have a positive impact on water quality. Reeds also offer important habitats for various species, e.g., birds, fish and insects. However, extensive reed stands have become more common due to eutrophication and decrease in grazing (Lehtoranta et al. 2021). Therefore, reed beds are harvested especially for improved recreational use of coastline areas. Water quality is then improved by removal of nutrient-rich plant biomass and increase in water flow (Yin et al. 2021). The biodiversity of ecosystems in coastal areas is also enhanced. Further, methane gas produced by unharvested and decaying reed mass is avoided. Harvested reed can be utilized in various ways, e.g. for traditional thatched roofs. Due to its high efficiency in nutrient removal, common reed is the main plant species used in constructed wetlands (Eller et al. 2017, Zhou et al. 2022).

Microplastic particles can be attached on the surface of plants, e.g. on their leaves (Liu et al. 2020). For aquatic plants, potential mechanisms for MP accumulation include attachment via biofilms on their surfaces (Goss et al. 2018). Nanoscale plastics and small MPs are also taken up by plant roots and transported to other parts of the plant. They can also enter plant tissues through pores and cracks on the plant surfaces (Li et al. 2020). Recently, Yin et al. (2021) demonstrated that reed vegetation in six Chinese freshwater reed farms accumulated MPs, evidently on the surface of the plants. The number of MPs found in reed samples varied from 0 to 14 particles/individual (mean 5 particles/individual). The level of sediment MPs in the reed vegetation belt was also significantly higher than that at other locations of the lakes.

2.3. Pilot 1: Common reed filter (Luke)

2.3.1. Description

Traffic-related MPs are a major source of MPs in urban areas (Winquist et al. 2021). In the FanpLESStic-sea project, novel and innovative solutions for removal of MPs found in urban snow were developed and piloted. These MPs are often the result of traffic and road usage.

In the Kouvola area, Southern Finland, stormwater filters of harvested common reed have previously been built by a local co-operative "Sustainably from Nature" and the city of Kouvola. These filters with novel filtering materials: common reed bundles or bales, were tested for removal of solid particles and nutrients from stormwaters running in open ditches. The results were promising, and the reed filters have proven to be easily replicable and cost-effective. As a follow-up, the efficiency of common reed filters for removal of MPs from stormwaters and especially from meltwaters of urban snow was selected for piloting in the FanpLESStic-sea project.

During wintertime, snow from the city center of Kouvola is stored at a nearby snow collecting site (Figure 2). From this snow collecting site, the snow meltwater runs to a pond and further along a ditch to River Kymijoki leading to the Gulf of Finland, part of the Baltic Sea. The common reed filter pilot was built at the outlet ditch in November 2020 and the aim was to test the removal of MPs and other solid particles released from the collected urban snow piles.

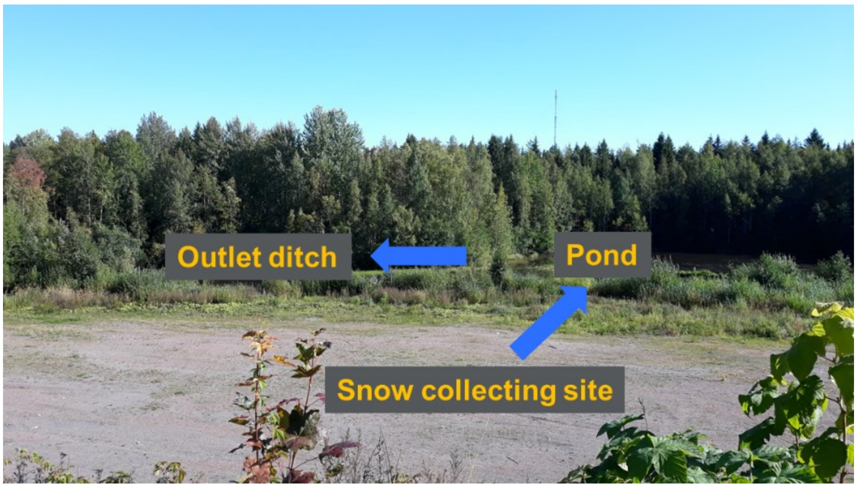

Figure 2. Tanttari snow collecting site in Kouvola in September 2020. Photo: M. Vahvaselkä.

The common reed was harvested in winter 2019/2020 at a local lake Urajärvi by the co-operative. About 350 bundles of this reed were used in the filter. The length of the bundles varied from 120 to 200 cm, the diameter of the bundles was ca. 20 cm and the weight of individual bundles 3-4 kg. The reed bundles were placed in the ditch parallel to the water flow by an excavator (Figure 3). Three logs were also put on top of the reed bundles to press the filter and to keep the bundles in place. The dimensions of the reed filter were: length 3.5 m, width 1.5 m and depth 0.7 m (Figure 3). An information board was also placed close to the reed pilot to deliver information on the aims of the pilot and the FanpLESStic-sea project to the local inhabitants.

Figure 3. Construction of the common reed filter (left) and measurement of the dimensions of the new filter (right) in November 2020. The filter consisted of common reed bundles with logs on top of them. Photos: M. Vahvaselkä.

2.3.2. Experimental plan and sampling

To evaluate the concentrations of MPs in Kouvola urban snow and the removal efficiency of the reed filter, MP samples were taken from the urban snow at the Tanttari snow collecting site and during snow melting from the ditch water before and after the filter. Additional water samples for other chemical analyses were also collected to further assess the functionality of the filter.

Snow samples were collected from the snow collecting site in March 2021 when new loads of snow were still being brought from the city to the site and the snow had not started to melt (Figures 4 and 5). Two snow piles were collected by an excavator from different parts of the snow masses at the snow collecting site. From both piles, snow samples were collected into three 80 L polypropylene (PP) buckets.

Figure 4. Tanttari snow collecting site in Kouvola and the common reed filter at the ditch in March 2021. The arrow indicates the reed filter under a snow blanket. Photo: M. Vahvaselkä.

Figure 5. Snow sampling for microplastics analysis at Tanttari in March 2021. Photo: M. Vahvaselkä.

The snow samples in covered PP buckets were left to melt at room temperature for four days. Then, the meltwater was filtered using the UFO filtration system developed at AAU to collect MP particles and other solid material in the size range of 10–5,000 µm. As a blank sample, one clean PP bucket was filled with tap water and the water was filtered in the same way as the snow meltwater samples.

The steel filters from UFO with sample material were collected into glass petri dishes and stored at 4°C before pretreatment at the Norwegian Research Centre (NORCE) and analysis for MPs at AAU. Sample pretreatment was performed according to the protocols of AAU (Rist et al. 2020), but without lipase treatment. Microplastic detection and quantification for the samples was carried out by the AAU project group as described by Rist et al. (2020). Focal Plane Array-based micro-Fourier Transform Infrared Imaging Spectroscopy (FPA-μFTIR-Imaging) was used for particles in the size range of 10-500 μm, and for particles larger than 500 μm, Attenuated Total Reflection (ATR)-FTIR was applied.

Microplastic samples from the ditch water before and after the reed filter were collected in May 2021 when snow at the snow collecting site was melting and the meltwaters were running to the pond nearby. With the AAU sampling device, 230 and 270 L water samples were filtered before and after the reed filter, respectively (Figure 6).

Figure 6. The UFO sampling device from Aalborg University was used for collecting microplastic samples from the ditch water before and after the common reed filter pilot. Photo: M. Vahvaselkä.

Additional ditch water samples were collected once a month from December 2020 until June 2021 and analyzed at Kymi Environmental Laboratory Ltd. The analyses performed from water samples before and after the reed filter were: temperature, pH value, turbidity, total suspended solids (GF/C 1.2 μm), conductivity, concentrations of zinc and total sulphur. Flow rate of the ditch water was measured after the filter.

2.3.3. Results and discussion

Winter 2020/2021 was very snowy and cold in Southern Finland. Snow samples were collected at the Tanttari snow collecting site in March. Black dirt was observed on the surface of the snow meltwater (Figure 7), possibly originating from traffic oil spills and atmospheric deposition from local industry. After filtration of the samples, high amounts of solid material depositing at the bottom of the buckets were observed. This solid material consisted mainly of coarse gravel and sand with inorganic and organic macro litter (Figure 7). The concentrations of the solid material in the two snow samples collected were 3.1 and 4.8 kg dry matter per m^3 of snow. This corresponds to 5.4 and 8.9 kg dry matter per m^3 of snow meltwater.

Figure 7. Melted snow samples with black dirt floating on the surface (left). Solid materials collected from the bottom of the snow buckets (center and right). Photos: M. Vahvaselkä.

In the Kouvola snow samples, MP concentrations of 3,200-6,000 MP particles per m^3 of snow (530-580 µg per m^3 of snow) were detected (Table 2). Previously, Pikkarainen (2017) has reported MP levels of 300-9,500 MP per m^3 of urban snow collected from three locations in Helsinki, Finland (mesh sizes 300-4,000 µm used in sampling).

The most abundant polymer types detected in the Kouvola snow samples were PP (52% of MP particles), followed by polyethylene (PE, 45%) and polyester (PES). Urban snow contained MP particles especially in the smallest size ranges studied, 10-100 µm (Figure 8).

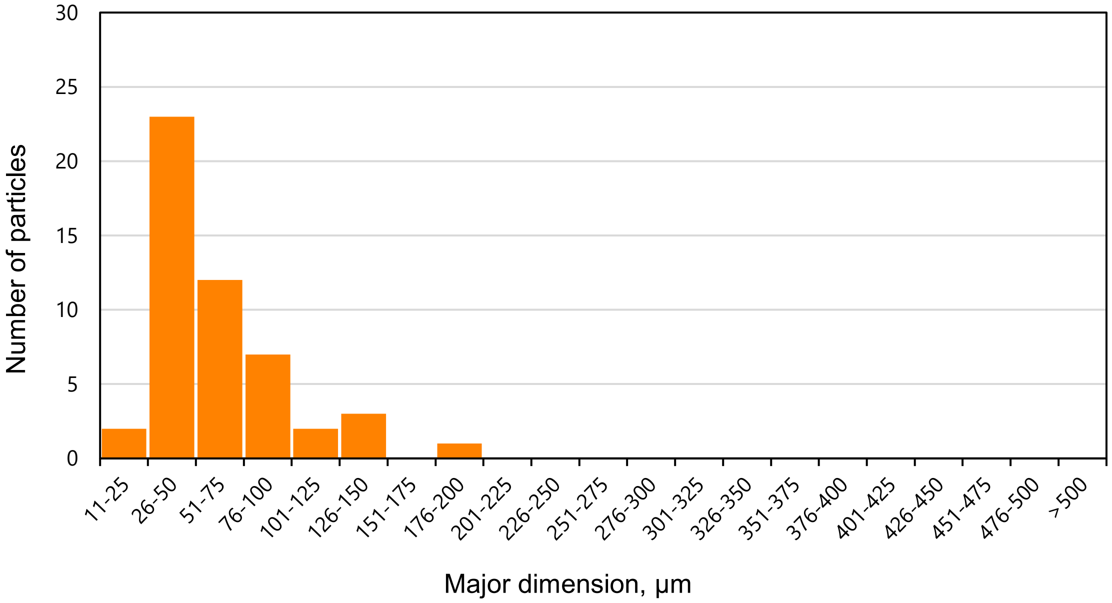

Figure 8. Size distribution of MP particles detected in snow samples from Kouvola.

Samples from the ditch water before and after the reed filter were taken in late May when the snow piles were finally melting (Table 2). Additional laboratory analyses of the ditch water were performed once a month from December to June (Table 3).

Table 2. Microplastic concentrations in snow, snow meltwater and in ditch water before and after the reed filter. The concentration in snow has been calculated from the measured water content of the snow samples (55%).

Unit	Snow	Meltwater	Ditch water before reed filter	Ditch water after reed filter
MPs per m^3 of snow or water	4,620*	8,390*	362	1,060
µg per m^3 of snow or water	558*	1,010*	7.4	132

* mean of two samples

Table 3. Results from additional ditch water analyses before and after the reed filter, sampling from December 2020 to June 2021.

	Results of ditch water analyses on various sampling dates							
Date of sampling	9.12.	18.1.	10.2.	24.3.	14.4.	4.5.	26.5.	16.6.
Flow rate after filter, $L \cdot sec^{-1}$	0	0	0	0	5	12	12	12
Days from start of water flow					0	20	42	63
Thickness of ice in ditch, cm	2	10	20	26	0.5	0	0	0
Temperature before, °C	0.4	0.0	0.0	0.0	1.7	7.1	12.3	15.4
Temperature after, °C	0.6	0.0	0.0	0.0	1.6	6.7	11.7	15.3
pH before	6.9	6.7	6.7	6.5	6.8	7.2	7.2	7.1
pH after	6.9	6.6	6.8	6.6	6.7	7.1	6.8	7.0
Turbidity before, FNU*	8.9	32	18	30	7.1	11	5.0	5.7
Turbidity after, FNU	9.1	70	18	49	9.1	9.2	4.6	5.0
Total susp. solids before, $mg \cdot L^{-1}$	6.0	12	17	14	2.4	5.2	5.9	6.2
Total susp. solids after, $mg \cdot L^{-1}$	4.0	52	16	20	3.2	5.2	5.6	4.0
Conductivity before, $mS \cdot m^{-1}$	23.3	29.0	30.9	28.9	29.0	26.5	16.4	13.7
Conductivity after, $mS \cdot m^{-1}$	23.2	29.9	34.9	32.5	26.4	26.8	17.9	16.4
Zinc before, $\mu g \cdot L^{-1}$	11	<20	7	19	9	5	5	3
Zinc after, $\mu g \cdot L^{-1}$	11	59	2	54	14	4	6	3
Total sulphur before, $mg \cdot L^{-1}$	2.6	2.5	3	3	1.4	1.2	<1	<1
Total sulphur after, $mg \cdot L^{-1}$	2.7	2.7	5.8	3.3	2.1	1.2	<1	1

* FNU, formazin nephelometric unit

The ditch water remained at least partially frozen until late April. In later months, water flow was observed in the ditch, but the water was very cold (Table 3). The common reed filter started to retain suspended solids when the water temperature had increased above 12°C (Figure 9). At the end of the observation period in June, 35% of total suspended solids in the ditch water was retained by the filter. By then, an active biofilm had most probably developed on the reed material, restricting particle passage. As the MP sampling of ditch water was carried out on May 20, the performance of the filter was not yet optimal for MP retention. It was concluded that a period of conditioning for biofilm formation is necessary for optimal operation of the filter. Therefore, the efficiency of the reed filter in MP removal needs to be further studied and more samples taken at various time points. It is probable that the reed filter system is better suited for ambient temperature stormwater treatment than for cold snow meltwaters.

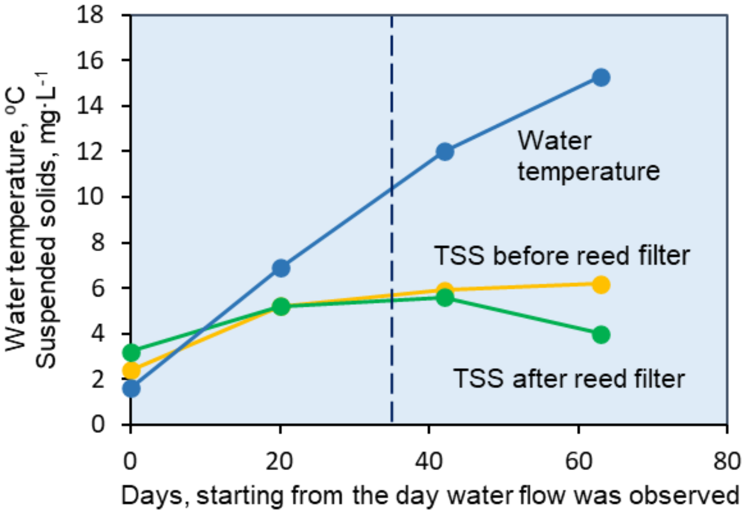

Figure 9. Temperature and concentrations of total suspended solids (TSS) in the ditch water in spring 2021. The dashed line indicates the time of microplastics sampling.

In conclusion, the reed filter is easy and cheap to build and maintain, and it is locally adaptable. Local conditions also influence the removal efficiency and operating time of the reed filter. The other reed filters in Kouvola have operated well for about two years before any need for changing the reed material.

2.4. Pilot 2: Snow melting and filtering unit (Clewat/Luke)

2.4.1. Description

During typical winter conditions in all cities across Finland, as in other Nordic countries, huge amounts of urban snow are ploughed from the streets and transported to snow collecting sites. In some cities the situation is even worse if snow is dumped directly into the Baltic Sea, as in Helsinki. During a typical winter, ca. 50,000 truckloads of snow (and up to 300,000 truckloads of snow with heavy snowfall) are transported to snow collecting sites and even one fifth is dumped untreated into the sea (Mäkipere 2022).

A cleantech company, Clewat Ltd, has addressed this problem by developing a snow treatment unit (https://clewat.com/en/snow-control/). The system is centered around an ISO-sea shipping container (length 12 m / 40 ft) that houses the technology necessary to pump sea water onto snow, melting and filtering it before releasing it into the sea. In Clewat's solution, snow melting process uses the power of flowing water and seawater temperature, or alternatively waste heat from the district heating network. This leads to a more sustainable process, both environmentally and economically, than in other methods used for snow melting when fossil fuel is used.

The actual purification step is performed by filtration. The snow and water passing through the process is filtered and the macro and micro litter in the snow meltwater is collected in the process with a combination of a coarse steel filter system and a denser filter cloth. The treated meltwater can either be led to the sea (or other waterway) or to a wastewater treatment plant (WWTP) via the sewer system. The snow treatment unit can be placed either on land or floating in the sea (Figures 10 and 11).

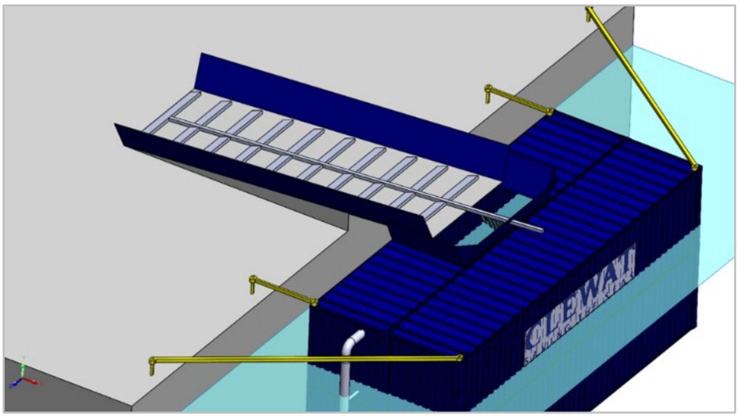

Figure 10. Clewat's snow melting and filtering unit. Source: Clewat Ltd.

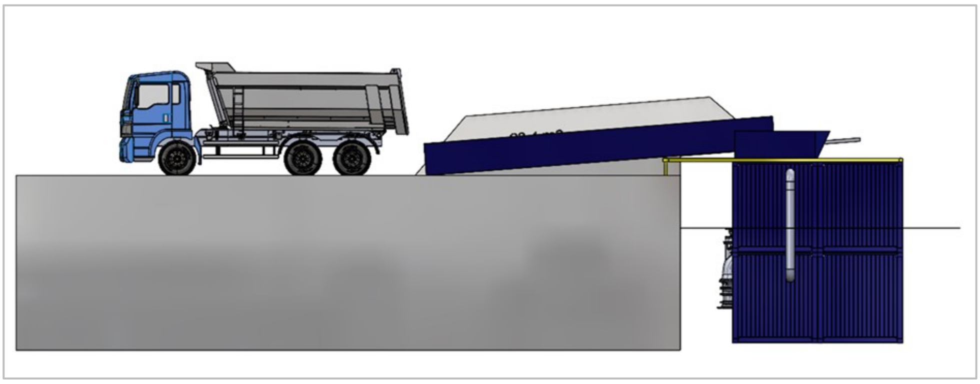

Figure 11. Trucks can empty the snow load directly to the snow melting unit. Electric conveyor transports the snow to the unit. Source: Clewat Ltd.

One unit can treat 10 truckloads of snow (150 m^3) per hour. Depending on the amount and dirtiness of the snow, 0–2 service breaks (less than 1 hour) are needed per day. Thus, the maximum capacity of one unit is 70 truckloads of snow (1,050 m^3), when used 8 hours per day. To be able to treat all the snow in Helsinki otherwise dumped directly into the sea (10,000 truckloads) over three months, i.e. 110 truckloads per day, two snow treatment units would be needed.

The electricity consumption of the unit is mainly caused by the water pumps because the melting action is based on the kinetic energy of the sea water sprayed on the snow entering the unit. The electricity consumption of the unit is ca. 12 kWh per truckload of snow.

The amount of litter and other impurities in the snow depends on the area snow has been collected from as well as age and composition of the snow. Clewat performed a pilot test in Helsinki in February-March 2021 when ca. 1,000 truckloads of snow were treated (Figure 12). One truck load contained in average 30-50 kg of coarse gravel and macro litter, of which ca. 1 kg of floating litter, and 10 L of fine sand and micro litter. Thus, together with the 10,000 truckloads of untreated snow, ca. 10 tons of floating garbage is entering the sea. Until now, this has been only partly removed with barriers mounted around the sea area where snow is being dumped.

Figure 12. Clewat tested a pilot-scale snow treatment unit in Helsinki in winter 2021. Photo: M. Vahvaselkä.

2.4.2. Experimental plan and sampling

Urban snow contains various impurities, but the focus was MPs from road traffic, i.e. small particles released from car tires and road surface. However, there is very little information available on the particle size of the MPs from road traffic.

To help Clewat further develop its now treatment system, Luke's project team conducted with Clewat a pilot test to find out the particle size range of the MPs in urban snow, and according to that select an optimal mesh size for the filter cloth to catch the fine fraction. The mesh size is a compromise between MP removal efficiency and the capacity in the snow treatment.

Snow for the pilot experiment was collected from a snow collecting site in Kokkola in February 2020. Originally the snow had been collected from the city center of Kokkola 3-4 weeks before. Part of the melted snow was filtrated through a Clewat prototype unit with mesh sizes of 50 or 150 µm and part of the snow was left untreated. The analysis of the untreated meltwater provided data for the original MP concentration and the particle size distribution in urban snow. Respectively, the analysis of the treated meltwater provided data for the efficiency of the filtration system. All samples were further filtrated through the AAU's UFO system to recover the solid fine fraction in meltwater. The samples were pretreated by NORCE and analyzed by AAU.

2.4.3. Results and discussion

After melting and filtering of the snow samples, high amounts of solid material depositing at the bottom of the snow containers were observed. The concentrations of this solid material in the two snow samples taken were highly variable, 16.8 and 3.3 kg dry matter per m^3 of snow.

This corresponds to 33.6 and 6.5 kg dry matter per m^3 of meltwater. The solid materials consisted mainly of coarse gravel and sand with various inorganic and organic macro litter particles (Figure 13).

Figure 13. Solid materials found in Kokkola snow samples. Photos: M. Vahvaselkä.

In untreated snow samples, only very low concentrations of MPs were detected and after subtraction of the MP values of the snow container blank, the MP values of the samples were zero (Table 4). Relatively small volumes of snow meltwater (55–65 L) were filtered through the UFO system due to technical difficulties. This could have reduced the accuracy of the results. However, MPs were detected in meltwater treated with the pilot filtering system and the efficiency of different mesh sizes can be compared. According to the filtering experiments, the mesh size of 50 µm in the filter cloth was suitable, as major part of snow-originated MP particles were removed then (Table 4). The results of pilot 1 also support this conclusion (Figure 8). The most abundant polymer types in Kokkola snow samples were PP, PE and polyvinyl acetate.

Table 4. Microplastic concentrations in snow, in untreated snow meltwater and in meltwater filtered through filter cloth with 150 µm or 50 µm mesh size. The concentration in snow has been calculated from the water content of the snow samples (50%).

Unit	Snow	Untreated meltwater	Meltwater filtered through 150 µm	Meltwater filtered through 50 µm
MPs per m^3 of snow or water	0.0	0.0	2,400	180
µg per m^3 of snow or water	0.0	0.0	84.8	67.7

In conclusion, the Clewat snow melting and filtering process has several advantages: it is based on sustainable snow melting technology, the unit can be operated both on land and floating on water and as a decentralized system it reduces snow transport distances. The mesh size of 50 µm seems to be efficient in MPs removal.

2.5. Pilot 3: Constructed wetland system for wastewater effluent (GIWK)

2.5.1. Description

Modern WWTPs with primary and secondary treatment processes can remove MPs in wastewaters, but given the large volumes discharged constantly, they still represent a significant source of MPs to the aquatic environment (Sun et al. 2019). Therefore, MP-targeted tertiary treatment technologies at the WWTPs are essential to be developed. Recent years have brought interest in more nature-based solutions, such as constructed wetland technology (Zhou et al. 2022).

A pilot-scale constructed wetland installation was investigated by GIWK to assess its ability to remove MPs from the final effluent of the Wschód WWTP in Gdansk, Poland. The pilot was based on an existing pilot-scale constructed wetland system developed during another international BSR Interreg project "International Water management" (IWAMA). The system required some technical work to adapt to the FanpLESStic-sea project purposes.

The pilot plant has been designed as a two-stage hybrid system and consisted of two types of wetland beds that differ in their operating conditions and characteristics: horizontal flow (HF-CW) and vertical flow constructed wetland (VF-CW).

The wastewater stream entering the WWTP contains only a small proportion of industrial wastewater (approx. 10%), which is a unique aspect of separated wastewater handling in Gdansk and presents a perfect opportunity to gain knowledge on domestic sources of MPs.

The Gdańsk "Wschód" WWTP where the pilot study was conducted is located approximately 3.5 km from the Baltic coastline (Figure 14).

Figure 14. Location of the constructed wetland pilot station for effluent wastewater treatment: final effluent channel of the wastewater treatment plant (A), pilot station (B). Photos: GIWK.

The pilot station was implemented and operated in 2021. The analyzed pilot was a representation of a hybrid two-stage constructed wetland system, as it consisted of two types of wetlands that differ in their operating conditions and characteristics, combined into one serial system (Figure 15).

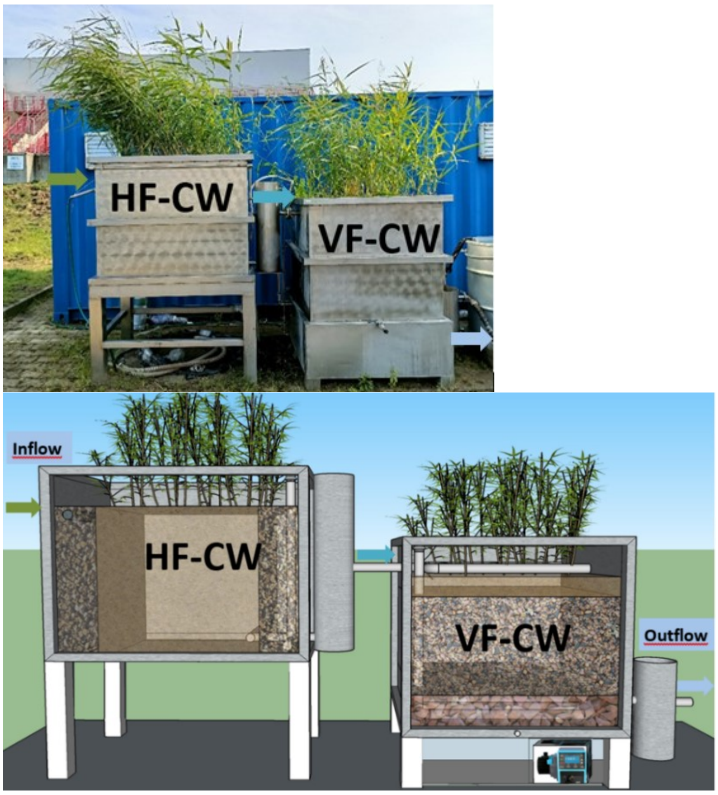

Figure 15. Overview of the pilot station: horizontal flow constructed wetland (HF-CW) followed by vertical flow constructed wetland (VF-CW) working in series. Photo: GIWK.

The constructed wetland units were planted with the most popular wetland vegetation, common reed (*Phragmites australis*).

The treated wastewater from the final effluent channel was directed to the inlet of the pilot station at flow rates between 15–20 L·$^{-1}$.

The 1st stage HF-CW: horizontal flow constructed wetland

The first stage wetland bed was built in the form of a cube-shaped tank made of AISI 304 stainless steel with the following dimensions:

- Length 120 cm
- Width 80 cm
- Working depth (filled with filter material) 80 cm
- Total depth 100 cm
- The slope of the tank bottom towards the outlet 1%.

Characteristics of the filtering material in the HF-CW bed (Figure 16):

- Inlet-drainage layer: gravel of granulation 16–32 mm, width 80 cm, length 20 cm, depth 80 cm.
- Main layer: sand of granulation 2-8 mm, width 80 cm, length 80 cm, depth 80 cm.
- Outlet-drainage layer: gravel with a granulation of 16–32 mm, width 80 cm, length 20 cm, depth 80 cm.
- The permeability of the filter layer was approximately kf ≈ 1 m/s.

The layout of the individual layers of the filter beds is shown in Figure 16.

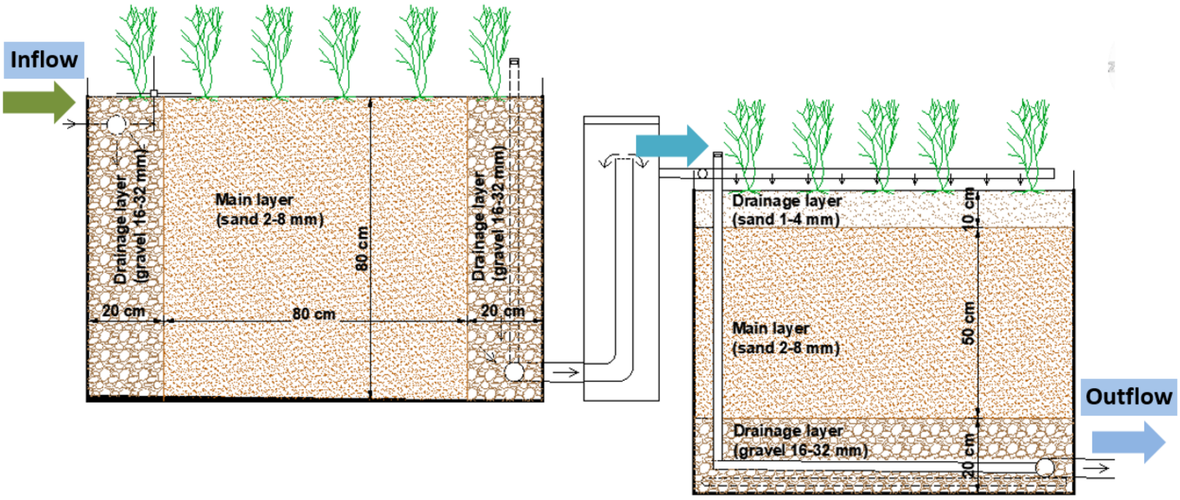

Figure 16. Cross-section of the constructed wetland pilot system. Structure of wetland beds shown, with layers of wetland matrix indicated.

Wastewater distribution in the HF-CW bed was performed by means of a 74 cm long, 1 inch diameter perforated stainless steel pipeline, laid horizontally in the upper part of the bed, at a distance of 5 cm both from the edge of the tank and the filter surface. There were two rows of 15 holes with a diameter of 5 mm in the distribution line. The perforations were regularly spaced at 5 cm intervals on both sides of the pipe along its length in order to distribute the sewage evenly over the entire bed width.

The outlet of wastewater from the HF-CW was operated by means of perforated 74 cm long pipe, 1 inch of diameter, laid at the bottom of the bed in the drainage layer at a distance of 5 cm from the edges of the tank. The drainage pipe was connected to the well that connected both wetland tanks.

Perforation of the drainage pipe: drilled holes with a diameter of 4 mm. The holes were located at the top and the sides of the pipeline, three rows of 15 holes regularly spaced along the pipe at 5 cm intervals.

Air venting of the effluent drainage was accomplished through a 1-inch diameter vertical pipe section connected to the ends of the drainage pipe. The vent pipe was located in the middle of the drainage pipe. The end of the pipe was 10 cm above the surface of the bed.

The 2nd stage VF-CW: vertical flow constructed wetland

The second stage wetland bed was built in the form of a cube-shaped tank made of AISI 304 stainless steel with the following dimensions:

- Length 100 cm
- Width 100 cm
- Working depth (filled with filter material) 80 cm
- Total depth 100 cm
- The slope of the tank bottom towards the outlet is 1%.

Characteristics of the filtering material in the VF-CW bed (Figure 16):

- Inlet-drainage layer: sand of granulation 1–4 mm, width 100 cm, length 100 cm, depth 10 cm.
- Main layer: sand of granulation 2–8 mm, width 100 cm, length 100 cm, depth 50 cm.
- Outlet-drainage layer: gravel with a granulation of 16–32 mm, width 100 cm, length 100 cm, depth 20 cm.
- The permeability of the filter layer was approximately kf ≈ 1 m/s.

The layout of the individual layers of the filter bed is shown in Figure 16.

The wastewater inflow to the VF-CW was carried out by gravity and performed by means of two 94 cm long, 1 inch diameter perforated stainless steel distribution pipelines, laid 3 cm above the wetland surface. Two rows of 19 holes of 5 mm diameter were made in each pipe. The holes were regularly spaced at 5 cm intervals on both sides of the line along its entire length. In order to evenly distribute the sewage on the surface of the bed, the pipes were placed at equal distances from each other and from the tank walls.

The effluent from the VF-CW was collected via four 90 cm long, 1 inch diameter steel drainage pipes evenly distributed over the entire bottom surface. The distance between drainage pipes was 25 cm. They were connected to a final collecting pipe with a diameter of 1 inch, which directed the treated wastewater to a final well. Perforation of the drainage pipes: 4 mm diameter holes. Positioning of the holes at the top and at the sides: three rows of 18 holes in each pipe, regularly spaced along the entire length at 5 cm intervals. The slope of the drainage pipes was 1% in the outlet direction.

Ventilation of the drainage pipes was realized through a 1 inch diameter vertical pipe connected to the final drainage pipe. The vent pipe had its end 10 cm above the bed surface.

2.5.2. Experimental plan and sampling

To determine the MPs removal efficiency of the constructed wetland pilot, samples were taken from the WWTP effluent (pilot inlet) and from the pilot effluent. The samples for MP analyses were collected with the use of the AAU filtering unit. The required amount of water for the sampling process was stored in steel tanks, 200 L of volume each.

The samples were collected after approximately 3 months of continuous operation, when the wetlands were fully developed (between September 29 and October 15, 2021). The samples were taken sequentially: on the first day at the outflow of WWTP and on the following day at the outflow of the pilot station, and three samples were taken from both locations. The samples were pretreated by Latvian Institute of Aquatic Ecology (LIAE) and analyzed by AAU.

Additionally, between September and October 2021, five series of laboratory analyses on basic pollutant parameters were performed and the wastewater samples were taken at the inlet of the pilot station, at the outlet of HF-CW and then at the outlet of VF-CW. The following parameters were investigated:

- total suspended solids, TSS
- organic and mineral suspended solids
- chemical oxygen demand, COD
- biochemical oxygen demand, BOD_5

- total nitrogen, TN; ammonium-nitrogen, N-NH_4; nitrites, N-NO_2 and nitrates, N-NO_3
- total phosphorus, TP

2.5.3. Results and discussion

The results of MP analysis, total MP concentrations in the inlet and outlet of the constructed wetland pilot system and MP removal efficiency, are presented in Table 5.

Table 5. Average microplastic concentrations in the inlet and outlet of the constructed wetland pilot.

Unit	Inlet	Outlet	Removal efficiency, %
MPs·m^{-3}	8,140	5,550	31.8
µg·m^{-3}	1,830	459	74.9

In Table 6, the results of the other laboratory analyses from the pilot study are presented.

Table 6. The inlet and outlet wastewater quality and removal efficiency in the wetland pilot.

Parameter	Inlet concentration, mg·L^{-1}	Outlet concentration, mg·L^{-1}	Removal efficiency, %	Mass removal rate*, g·m^{-2}·d^{-1}
Total suspended solids, TSS	12.00	5.32	53.9	2.871
Inorganic suspended solids	3.88	3.14	19.1	0.303
Organic suspended solids	8.08	2.18	69.9	2.550
Chemical oxygen demand, COD	34.92	21.40	37.9	5.679
Biochemical oxygen demand, BOD_5	2.40	0.48	80.0	0.776
Total nitrogen, TN	8.76	4.76	52.7	1.512
Ammonium-nitrogen, N-NH_4	<0.5	<0.5	-	-
Nitrite-nitrogen, N-NO_2	0.041	0.014	71.6	0.012
Nitrate-nitrogen, N-NO_3	6.63	3.47	57.0	1.181
Total phosphorus, TP	0.34	0.19	43.2	0.065

* the formula for mass removal rate is presented in Section 2.6.2.
<, concentration below detection limit

There were large variations in the MP concentrations of both the inlet and outlet samples. Further, polyurethane clearly dominated in the MP samples, possibly as a contaminant from the pilot. The probable source was several pipeline components in the pilot station equipment. The properties of this material and its specific density should be considered in this case.

The presence of polyurethane could have distorted the values and resulted in MP removal efficiency of 32% for quantitative determination of MPs, and in higher removal efficiency, 75% on average, in terms of total mass of MPs.

The average inlet concentrations of pollutants at the pilot station constitute and represent the composition of the Gdansk WWTP final effluent (treated wastewater). It can be seen that the quality of the wastewater applied to the wetland pilot station is characterized by low concentration values (i.e. total nitrogen, COD and suspended solids at the level of 8.8 mg·L^{-1}, 34.9 mg·L^{-1} and 12.0 mg·L^{-1}, respectively). Ammonium nitrogen was not present in the influent to the constructed wetland system (results below the limit of quantification) and did not appear in any sample at the subsequent treatment steps. Regarding the results, particularly worth mentioning is the mass removal rates for total nitrogen (1.51 g·m^{-2}·d^{-1}) and phosphorus (0.065 g·m^{-2}·d^{-1}). The highest removal efficiencies were obtained in case of BOD$_5$, nitrogen compounds (TN, N-NO$_2$ and N-NO$_3$) and total suspended solids.

2.6. Pilot 4: Constructed wetland system for stormwater (GW)

2.6.1. Description

The pilot station of GW was established to verify the efficiency of MP removal from urban stormwater. The pilot is an artificial wetland (constructed wetland), using Nature Based Solutions in the form of aquatic plants (common reed) and filtration beds (gravel of suitably selected grain size) (Figure 17). The pilot station is located about 800 meters from the place where stormwater from a stormwater collector is directed to the sea in Gdansk, Poland (Figure 18). The stormwater collector, on which the pilot was installed, discharges stormwater from a catchment area of approximately 1,740 hectares (i.e. 17.4 square kilometers). It is a highly urbanized catchment area.

Figure 17. Pilot station for the stormwater treatment. Photo: GW.

The pilot has been fully operational from September 2020. However, for the winter season (from mid-November, after sampling) it was stopped, because the water could freeze in the water pipes. Its work was continued in April 2021. The amount of water treated during 10 months of operation is about 110 m^3 (average flow rate 5–50 L·h^{-1}).

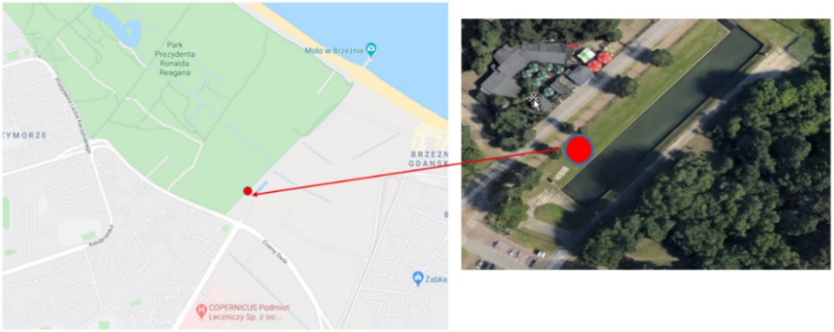

Figure 18. Location of the pilot station, about 800 meters from the place where stormwater from a stormwater collector is directed to the sea, in Gdansk, Poland. Photo: GW.

Stormwater from the stormwater collector is directed to the pilot station, that consists of five steel tanks (including a multi-stage wetland system) constituting elements of the filtration system through which stormwater supplied to the system gradually flows. The first tank contains probes that are used to measure basic parameters of water flowing into the station (pH, temperature, oxidation-reduction potential (redox), conductivity, turbidity, and dissolved oxygen). It also plays the role of a sedimentation tank. Two more tanks are filled with a filter bed in which the common reed (*Phragmites australis*) has been planted. Tank No. 2 is a bed with vertical flow (VF-CW), and Tank No. 3 with horizontal flow (HF-CW). The order of these two tanks can be changed by opening or closing the corresponding valves. After passing through the subsequent filter beds, the water goes to tank No. 4, which acts as a cleaning pond with a variable depth filter bed. The last, fifth tank stores purified water and, like tank No. 1, is equipped with a measuring system (Figure 19).

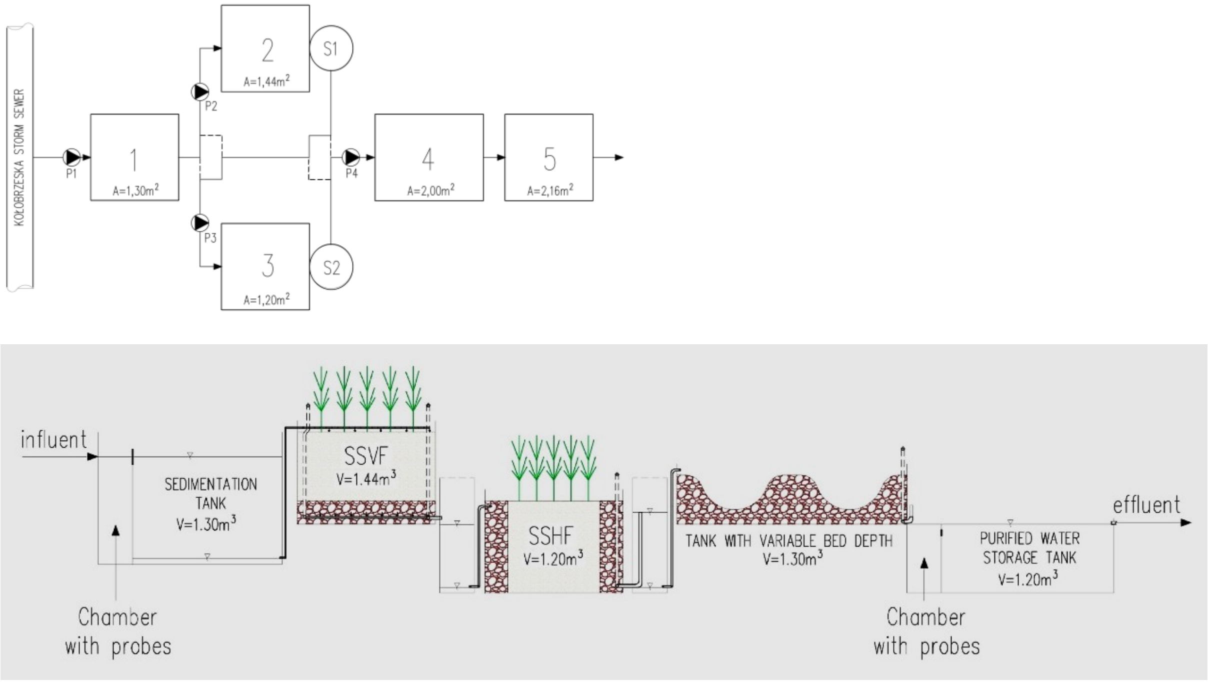

Figure 19. Technological scheme of the wetland system (fractional-pilot installation). 1, sedimentation tank; 2, 1st stage bed with subsurface vertical flow (SSVF); 3, 2nd stage bed with subsurface horizontal flow (SSHF); 4, reservoir with variable bed depth; 5, purified water storage tank; S1 and S2, water collecting wells after SSVF and SSHF beds; P1-P4, piston pumps.

2.6.2. Experimental plan and sampling

To verify the MP removal potential of the constructed wetland system, samples from the inflow and the outflow of the pilot installation were taken. The first 4 samples (2 from the inflow and 2 from the outflow of the pilot system) were collected in October 2020. The sampling was repeated in September 2021.

Microplastics are a mixture of contaminants. They can adsorb many harmful substances on their surface, and they contain many additives and harmful compounds themselves. For this reason, beside the online measurements of the basic water parameters, the stormwater samples from the pilot station were collected and analyzed for the additional parameters. The results shown in Tables 7–13 were obtained from sampling series done from May 2021 to November 2021.

The following parameters were analyzed:

- Biochemical oxygen demand, BOD_5
- Chemical oxygen demand, COD
- Total organic carbon, TOC
- Total suspended solids, TSS
- Petroleum substances
- Metals (Zn, Cd, Cu, Ni, Pb, Hg)
- Total phosphorus, TP
- Total nitrogen, TN
- Ammonium-nitrogen, $N\text{-}NH_4$; nitrites, $N\text{-}NO_2$; nitrates, $N\text{-}NO_3$
- Phthalates (DEHP, BBP, Dicyclohexyl phthalate, Diethyl phthalate, DIBP, Dimethyl phthalate, DBP, DNOP, DPP, Di-n-propyl Phthalate
- Polycyclic aromatic hydrocarbons (PAHs): acenaphthene, acenaphthylene, anthracene, benz[a]anthracene, benzo[a]pyrene, benzo[b]fluoranthene, benzo[g,h,i]perylene, benzo[k]fluoranthene, chrysene, dibenz[a,h]anthracene, phenanthrene, fluoranthene, fluorene, indeno[1,2,3-c, d] pyrene, naphthalene, pyrene

In order to assess the efficiency of the removal of selected pollutants, Mass Removal Rate (MRR) was used, based on removed loads of pollutants (Jakubowicz et al. 2022):

$$\mathbf{MRR = (C_{in} \cdot Q_{in}) - (C_{out} \cdot Q_{out})/A\ ,\ [g \cdot m^{-2} \cdot d^{-1}]}$$

where:

C_{in} – pollutant concentrations in the inflow $[g{\cdot}m^{-3}]$

Q_{in} – inflow to the bed $[m^{-3}{\cdot}d]$

C_{out} – pollutant concentrations in the outflow $[g{\cdot}m^{-3}]$

Q_{out} – outflow from the bed $[m^{-3}{\cdot}d]$

A – total area of beds $[m^2]$

The removal efficiency (%) of MPs, heavy metals and polycyclic aromatic hydrocarbons concentrations from stormwater was calculated using the formula:

$$\eta = L_i - L_e / L_i \cdot 100\%, [\%]$$

were:

L_i – pollutant mass loading inflow

$L_i = C_{in} \cdot Q_{in} / A$, $[g \cdot m^{-2} \cdot d^{-1}]$

L_e – pollutant mass loading outflow

$L_e = C_{out} \cdot Q_{out} / A$, $[g \cdot m^{-2} \cdot d^{-1}]$

2.6.3. Results and discussion

The results for total MPs and for individual polymer types from the inlet and outlet of the constructed wetland pilot are presented in Tables 7 and 8, respectively.

Table 7. Microplastic concentrations in the inlet and outlet of the pilot station with removal efficiency.

Unit	Inlet	Outlet	Removal efficiency, %
MPs·m^{-3}	2,320	263	89.6
µg·m^{-3}	387	28.6	93.2

Table 8. The concentrations of individual plastic polymer types in the inlet and outlet of the pilot station with their removal efficiencies and mass removal rates from one series of measurements.

Polymer	Inlet concentration, µg·m^{-3}	Outlet concentration, µg·m^{-3}	Removal efficiency, %	Mass removal rate, µg·m^{-2}·d^{-1}
Polyethylene	101	3.17	97.1	5.65
Polypropylene	70.5	0.45	99.4	4.05
Polyester	94.9	23.6	77.2	4.23
Polyamide	9.4	0.84	91.8	0.50
Acrylic	0.65	0.0	100	0.04
Polyvinyl chloride	0.56	0.0	100	0.03
Polystyrene	3.7	0.0	100	0.21
Polyurethane	1.5	0.08	95.2	0.08
Alkyd	105	0.0	100	6.05

The results of other analyses are shown in the Tables 9–13.

Table 9. The range values of laboratory analyses results (TSS, COD, BOD_5, TN, N-NH_4, N-NO_3, N-NO_2, TP and TOC) with the removal efficiencies and mass removal rates from four measurement series.

Parameter	Inlet concentration, $mg \cdot L^{-1}$	Outlet concentration, $mg \cdot L^{-1}$	Removal efficiency, %	Mass removal rate, $g \cdot m^{-2} \cdot d^{-1}$
Total suspended solids, TSS	5.6–72.0	<2.0–3.4	96–100	0.80–9.33
Chemical oxygen demand, COD	13–39	5–20	56–76	0.83–3.48
Biochemical oxygen demand, BOD_5	<3.0–4.0	<3.0	100	0.42–0.57
Total nitrogen, TN	<0.5–2.13	<0.5–1.32	0*–100	0.00*–0.21
Ammonium-nitrogen, N-NH_4	<0.5–0.50	<0.5	100	0.001–0.030
Nitrite-nitrogen, N-NO_2	<0.003–0.12	<0.003–0.004	63–100	0.0002–0.009
Nitrate-nitrogen, N-NO_3	<0.05–0.50	<0.05–0.80	0*–100	0.00*–0.03
Total phosphorus, TP	<0.003–0.35	<0.003–0.027	82–100	0.020–0.042
Total organic carbon, TOC	4.40–9.81	3.50–7.9	24–66	0.12–1.14

* an increase in the concentration of a given element after the purification process was observed in some series
<, concentration below the limit of quantification

Table 10. The range values of heavy metals concentrations in the inlet and outlet of the pilot station with the removal efficiencies and mass removal rates from four measurement series.

Metal	Inlet concentration, $mg \cdot m^{-3}$	Outlet concentration, $mg \cdot m^{-3}$	Removal efficiency, %	Mass removal rate, $mg \cdot m^{-2} \cdot d^{-1}$
Zinc	86–262	52–96	0*–88	0.00*–22.4
Cadmium	<0.6–0.6	<0.6	100	0.09
Copper	24–83	<0.0019–44	26–100	1.85–7.16
Nickel	3–6	1–4	36–83	0.00–0.60
Lead	<0.006–28	<0.006	100	0.00–4.01
Mercury	<0.000010–0.15	<0.000010–0.07	44–98	0.00–0.02

* an increase in the concentration of a given element after the purification process was observed in some series
<, concentration below the limit of quantification

Table 11. The range values of detected polycyclic aromatic hydrocarbons concentrations in the inlet and outlet of the pilot station with the removal efficiencies and mass removal rates from four measurement series.

Compound	Inlet concentration, $\mu g \cdot m^{-3}$	Outlet concentration, $\mu g \cdot m^{-3}$	Removal efficiency, %	Mass removal rate, $\mu g \cdot m^{-2} \cdot d^{-1}$
Benzo(a)pyrene	<0.002–0.035	<0.002	100	0.31–5.01
Benzo(b)fluoranthene	<0.005–0.0055	<0.005	100	5.15
Phenanthrene	<0.005–0.084	<0.005	100	0.22–8.42
Fluoranthene	<0.005–0.1	<0.005–0.01	92–100	0.27–13.1
Pyrene	<0.005–0.12	<0.005–0.015	89–100	0.20–15.4

<, concentration below the limit of quantification

Table 12. The range values of microbial contamination in the inlet and outlet of the pilot station with the removal efficiencies from three series of measurements.

Microorganism	Inlet concentration, cfu*·100 mL^{-1}	Outlet concentration, cfu·100 mL^{-1}	Removal efficiency, %
Escherichia coli	6,100–11,000	5–620	91.7–99.9
Enterococci	15,000–39,000	340–460	97.7–98.9

* cfu, colony forming units

Table 13. The values of detected phthalates in the inlet and outlet of the pilot station.

Compound	Sampling date	Inlet, $\mu g \cdot L^{-1}$	Outlet , $\mu g \cdot L^{-1}$
di-2-ethylhexyl phthalate, DEHP	August 27, 2021	<1.3	2.9
DEHP	November 22, 2021	3.4	<1.3
Diisobutyl phthalate, DIBP	November 22, 2021	<0.6	2.25

<, concentration below the limit of quantification

The stormwater directed to the pilot station was characterized by a variable load of specific contaminants. The multistage constructed wetland system enabled partial or complete removal of specific substances and emerging pollutants.

The removal efficiency of the total number of MPs particles was 89.6%, and 93.2% in case of their mass reduction (Table 7). As shown in Table 8, the largest weight share in the total mass of MPs was represented by PE, PP, PES and alkyd. The reduction efficiency achieved at the pilot station for all detected MPs was over 77%. The PE reduction was on the level of 97.1% and MRR was equal to 5.65 $\mu g \cdot m^{-2} \cdot d^{-1}$. The PP reduction was at the level of 99.4%, while the MRR amounted to 4.05 $\mu g \cdot m^{-2} \cdot d^{-1}$. A slightly lower reduction was achieved for PES, respectively: 77.2% and MRR=4.23 $\mu g \cdot m^{-2} \cdot d^{-1}$). In case of alkyd, efficiency was 100% and MRR was equal to

6.05 µg· m^{-2}·d^{-1}. This data was obtained from the analysis of samples collected in 2020 and will be verified with the data obtained from the sampling done in 2021, which will be delivered in 2022. Recently, Chen et al. (2021) studied the removal of MPs from wastewater in constructed wetlands of different configurations. The MP removal efficiency was 81.6% in surface flow constructed wetlands. In horizonal subsurface flow constructed wetlands, the removal efficiency was 100%. Physical filtration and biofilm development on the surface of gravel particles were considered as the major mechanisms involved in MP retention.

In Table 9, the range values of laboratory analyses results (TSS, COD, BOD_5, TN, $N\text{-}NH_4$, $N\text{-}NO_3$, $N\text{-}NO_2$, TP and TOC) with the removal efficiency and load removal rate from four measurement series were shown. High efficiency was achieved in reducing three pollution indicators from the basic group: BOD (100%), COD (in the range of 56-76%) and total suspended solids (in the range of 96%-100%). Nutrients were present in the stormwater generally in low concentrations. The total phosphorus was effectively removed in the range of 82-100%. In case of the total nitrogen (TN) a variable efficiency of reduction was observed. In three measurement series it ranged from 44% to 100%, but the increase in total nitrogen after the purification processes was observed for the samples collected on November 21, 2021. It may be related to the increase in nitrate nitrogen as well as the distribution of biomass in the form of deposits lying on the surface as remains of plant matter (typical especially in autumn), susceptible to biodegradation, while considering that total nitrogen is the sum of nitrogen organic, ammonium, nitrate and nitrite. Issues related to nitrogen transformations would, however, require more results to evaluate the observed changes more reliably. For the nitrate nitrogen, in the two last test periods, i.e. November 17, 2021 and November 22, 2021, an increase was observed after purification processes. Accurate analysis of changes in nitrogen forms is not possible due to the insufficient number of measurement results. However, this increase could be related to the lower activity of microorganisms responsible for denitrification processes connected with water temperature, i.e. transformation of nitrate nitrogen to molecular nitrogen or nitrogen gas form. Denitrification is most effective in the temperature range from 15 to 35°C. Last two measurement series were conducted in November and the water temperature was around 5°C.

Based on the laboratory tests, it was observed that metals such as copper, cadmium, nickel and mercury were effectively reduced, and their reduction ratio was in the range of 26–100% (Table 10). For the zinc concentration, the reduction in the three measurement series was observed, except in one series conducted in August, when an increase after treatment processes was observed. This situation needs further research, especially in terms of processes occurring in a bed with subsurface horizontal flow, because in all three series an increase in the zinc concentration was observed after stormwater had passed through this deposit.

Polycyclic aromatic hydrocarbons (PAHs), the source of which in rainwater may be pollution from the atmosphere (incomplete combustion products, car exhaust fumes) were present in the rainwater in small concentrations, but their content in the water was efficiently reduced (89–100%) after passing through the hydrophyte system (Table 11).

The pilot station proved to be particularly effective in removing microbial contamination. Bacteria (*E. coli* and Enterococci), especially after heavy rains, were found in quite large numbers in rainwater. Over 98% reduction in their presence was achieved at the pilot station (Table 12).

Analyses for phthalates presence in stormwater were carried out, including a total of 10 phthalates, DEHP, BBP, Dicyclohexyl phthalate, Diethyl phthalate, DIBP, Dimethyl phthalate, DBP, DNOP, DPP, Di-n-propyl Phthalate. In the majority of samples, no phthalates were detected, except in individual cases, identified as certain episodes, shown in Table 13. On August 27, 2021 the presence of DEHP (di-2-ethylhexyl phthalate) was detected and on November 22, 2021 the presence of diisobutyl phthalates. The presence of these substances in the final tank may indicate the occurrence of suffusion (a phenomenon opposite to sorption), i.e. washing out these substances from the deposits, where they were previously deposited in the sorption process. Phthalates, including especially DEHP, are commonly used as target plasticizers flexibilization of PVC, and may be present in toys for children, carpets, window joinery, packaging etc. The analysis of samples from November 22, 2021 showed the presence of DEHP in the amount of 3.4 $\mu g \cdot dm^{-3}$ at the inlet to the station and after the purification processes there was a complete reduction of this substance (100%). Undoubtedly the migration of phthalates in the environment requires further studies, taking into account the sources of their occurrence, and the distance they have to travel before they end up in the stormwater system or surface water.

3. Environmental impact

3.1. Environmental impact assessment

Life cycle assessment (LCA) is a widely used method to quantify the environmental impacts of a product or service along its life cycle and can help limit burden shifting between life cycle phases or impacts. Historically impacts due to the presence of plastics, macro or micro, in nature and in contact with the fauna and flora, have not been modelled and considered within the LCA framework. In 2017, the Medellin Declaration on Marine Litter in Life Cycle Assessment and Management (Sonnemann ja Valdivia 2017) prompted for further researcher into the field and several researchers have taken on the challenge. Since then, work on the impact assessment of MPs has been ongoing, e.g. (Saling et al. 2020) have proposed characterization factors for MP debris in the marine environment and (Salieri et al. 2021) have investigated the contribution to freshwater impacts. The modelling of the impacts of MPs in snow melts and stormwaters in urban and peri-urban environments has not yet been tackled but due to the interconnectedness of waterways, many MPs generated in cities and towns will end up eventually in seas and oceans.

The goal of the environmental assessment performed in the FanpLESStic project is to understand the impacts generated by the construction and use of the different MP removal systems for snow melt and stormwaters. Due to lack of reliable data both on the amount of MPs removed and their impacts, we do not consider the question "what is more impactful, leaving MPs in stormwaters or installing the removal systems?" Rather, we assess the removal systems based on the functional unit "1 m^3 of water treated".

For each removal system, the boundaries of the studied system are presented in their respective sections and, as much as possible, they include the core processes necessary for the removal and the direct upstream and downstream processes. In each case, the system does not consider the end-of-life of the MPs and any other debris that is collected. Indeed, currently the pilots considered have not yet implemented discarding measures that will ensure that the MPs are not re-released into nature. A previous FanpLESStic project report, "Existing and emerging technologies for microplastics removal" (Vahvaselkä & Winquist 2021), discusses potential approaches for the final disposal of captured MPs and the materials used for the capture. The methods that appear viable for the end-of-life of the MPs from the pilots include incineration, thermolysis/pyrolysis, and chemical recycling (Zhang et al. 2021).

3.2. Pilot 1: Common reed filter (Luke)

The system boundaries considered for the common reed filter are presented in Table 14. The lifetime of a single filter construction (and the bundles included within) is considered to be two winters, which corresponds to the treatment of 220,000 m^3 of snow with a density of 400 kg per m^3 resulting in 88,000 m^3 of water.

Table 14. Common reed pilot - processes within the system boundaries in orange cells.

Upstream	Core	Downstream
Growing of reeds	Building of bundles	Destruction of reed filter, micro-plastics and other waste gathered
Harvesting of reeds	Transport of bundles to location and building into the filter	
Transport of snow to the site	Removal of the filter	

The growing of reeds and the End-of-Life (EoL) of the filter are excluded. The first one due to the fact the reeds used in the pilot are perennial plants, meaning that they do not require active planting or maintenance actions, such as fertilization or weeding. The EoL is currently unknown and is not considered in any of the pilot assessments (cf. Section 3.1.). While reeds are biomass and thus store carbon, it is unlikely that the carbon would be sequestered for a long period of time (>20 years) as the bundles should be disposed of once they have collected the MPs and other debris.

The environmental impacts generated by the construction of the machinery used for the processes included in the system is excluded. Indeed, the tractors and trucks are used year-round for different tasks and only a minimal portion of the impacts can be attributed to the building and use of the reed filter. The fuel and other consumables used to gather the raw material and build the bundles/filter are within the system. The transportation of the snow to the snow collection site is outside the boundaries because the snow would be transported whether the pilot exists or not.

The most important impacts come from fuel and influence Climate Impact. It is necessary for the harvesting of the raw material as well as transport of the filter to the site and its correct placement. Green House Gas emissions depend on the fuel and machinery used. Overall, these emissions are only expected to take place once every 2 years and treat 92,000 m^3 of water, resulting in very low FU emissions. As described in Section 2.3.3., further studies are necessary to understand when the filter becomes active after its placement. Moreover, reeds are efficient at removing nutrients and this can result in eutrophication control, which is beneficial in the long term.

3.3. Pilot 2: Snow melting and filtering unit (Clewat/Luke)

The system boundaries considered for the snow melting and filtering unit are presented in Table 15. The system is centered around an ISO-sea shipping container that houses the technology; it is estimated that each unit can treat 94,500 m^3 of snow with a density of 400 kg per m^3 resulting in 37,800 m^3 of water. The lifetime of a unit is expected to be 10 years, with limited need for maintenance and cleaning.

Table 15. Snow melting and filtering pilot – processes within the system boundaries in orange cells.

Upstream	Core	Downstream
Transportation of snow to the site	Energy for water circulation and snow feeding	Destruction of microplastics and other waste gathered
Filter meshes and nozzle raw materials	Maintenance and cleaning chemicals	
Pumps and connections		

Due to the long lifespan of each unit, the impacts associated with the raw materials and the manufacturing are not within the boundaries. The choice ISO-sea shipping container also means that containers can be repurposed as snow treatment units at the end of their lifespan as shipping containers, if their structural integrity is intact. The EoL impacts are not considered as explained in Section 3.1.

The aim is to place the units at existing snow collection sites, thus there would be no need for extra transportation of the snow compared to what is done today. Thus, the transportation is excluded. Moreover, the units will be built in such a way that the trucks are able to dump the snow directly onto conveyors to be treated within the unit. The main processes studied for this pilot are thus the consumables, maintenance and energy inputs necessary for the treatment of the snow.

The most important impacts are expected to be from the energy that is used for the movement of the snow within the unit and the pumping and circulation of the water for snow melting. The water will be collected from the sea and is expected to be above freezing temperatures. In case of extreme weather, some heating may be provided to avoid the snow freezing and damage to the unit. Regular maintenance of the unit will ensure a long lifespan and can require chemical inputs, although most is expected to be done through mechanical means. The marine environment is sensitive to chemical inputs and thus appropriate preparations must be chosen (e.g. biodegradable, non-toxic for marine life). The MPs and other debris are collected through meshes that will have a shorter lifespan than the unit, the raw materials and energy inputs for their production and transport can add up.

3.4. Pilot 3: Constructed wetland system for wastewater effluent (GIWK)

The system boundaries considered for the third pilot are presented in Table 16. The structure is considered to be made up of two sections where the water would flow naturally from the main WWTP. The flow rates are reported to be between 15–20 $L \cdot h^{-1}$, resulting in the annual treatment of 131 to 175m^3 of water at pilot level and with potential for higher treatments when scaled-up. The treatment should be installed as a continuation of an existing WWTP, thus not requiring the use of extra land.

Table 16. Constructed wetland pilot – processes within the system boundaries in orange cells.

Upstream	Core	Downstream
Sand and gravel extraction and transport	Energy for water circulation (pumping if no natural flow – not expected)	Destruction of microplastics and other waste gathered
Connections (pipes)	Maintenance	

At pilot scale, the set up is housed in stainless steel basins but can be expected to be housed in permanent structures when scaled up with lifespans that exceed 10 years. Thus, these structures are outside the system boundaries. The presence of reeds on the surface is not considered as they are perennial plants that do not require extra inputs for growth and are currently not expected to be actively harvested and used elsewhere. The EoL impacts of the MPs collected and any other debris are not considered as explained in Section 3.1.

The water to be treated is expected to flow from the main collection area without the need for extra pumping to achieve a good flow rate. The basins are connected using pipes, these are within the system boundaries and have an expected lifespan below that of the main basins. Regular maintenance will also increase overall lifespan, but no chemical use is expected beyond that for cleaning testing apparatus. The filtration is done using gravel and sand sections, which are expected to last several years but would need replacement if too many MPs and debris impede good functioning and water flow.

The main impacts are associated with the extraction and transport of the gravel and sand, due to their weight. These types of materials should be acquired, as much as possible, locally to where the filtration is required. This is also true for the connecting pipes. It is also recommended that regular light maintenance is performed to increase the lifespan of these parts that can resource and energy heavy during the production phase. Energy use is minimal in the pilot and expected to be nil when the pilot is scaled up.

3.5. Constructed wetland system for stormwater (GW)

The system boundaries considered for the fourth pilot are similar to those presented in Table 16, with only gravel necessary for the filtration beds. The pilot has a larger area but is still connected to an existing structure for stormwater treatment. From 43 to 438 m^3 of water are currently treated per year at pilot level.

The most important impacts are, like for the third pilot, linked to the gravel extraction and transport, if the surrounding structures are considered to have a lifespan of over 10 years. Regular maintenance will increase this lifespan and will also decrease the changes necessary to pipes and other connectors. If the constructed wetland is built as a continuation of an existing structure, the water flow can be done without the need for extra energy input for pumps.

It is important to note that during the piloting stage, there was no filtration during the winter because of water freezing and, thus, limited water flow. This type of event must be monitored closely as the lifespan of the system can be shortened if e.g. water freezes in the pipes, increasing the overall environmental impact.

3.6. Conclusions

The present environmental impact assessment considers the causes for the environmental hotspots for each of the pilots. At the time of writing, no data was available on the MP removal rates per FU thus a quantitative “efficiency” comparison is not possible. Table 17 presents the main environmental hotspots and how they could be addressed.

Table 17. Main environmental hotspots for the studied pilots.

Pilot	Main environmental hotspot	Potential to lower impacts	MP removal efficiency
Common reed filter	Fuel for harvesting and filter transport	Efficient machinery and low-emission fuels	Improves when the filter matures (surfaces covered with biofilm), expected to be Medium
Snow melting and filtering unit	Energy for snow and water circulation, raw materials and energy for production and transport of meshes	Use of renewable energy and long-lasting meshes	Depends on the mesh size selected for the filtering unit, expected to be High
Constructed wetland system for wastewater effluent	Extraction and transport of sand and gravel, production of pipes	Use of local production and regular maintenance to increase lifespan	Expected to be High
Constructed wetland system for stormwater	Extraction and transport of gravel, production of pipes	Use of local production and regular maintenance to increase lifespan	Expected to be High

4. Techno-economic feasibility

4.1. Pilot 1: Common reed filter (Luke)

Both the investment and operating costs for a common reed filter are low because they are limited to building, renewing, and disposing of the filter structures. The cost for collection, transportation and piling of the snow and the required land area are not taken into consideration. The energy needed for snow melting comes from the sun in spring and early summer.

The total building cost for a common reed filter is 2,000 € covering both the material costs and machinery and working costs for one day. Manually collected common reed price is ca. 800 $€·ton^{-1}$ for small quantities. Lifetime is expected to be from two to three years. The investment cost calculated per year is thus only 1,000 € for treatment of 110,000 m^3 of snow (2021), corresponding to 46,000 m^3 of snow meltwater. The suggested disposal method for the common reed filter is to lift the filter on the shore on wooden pallets to dry and then transport it to a local waste incinerator for burning. Thus, disposing costs would include transport cost and gate fee to the waste incinerator.

In a previous study, common reed filter was shown to remove suspended solids and nutrients from the stormwater. Thus, the benefits of this technology are not limited for removal of macro- and microplastics, but it also improves the overall water quality.

4.2. Pilot 2: Snow melting and filtering unit (Clewat/Luke)

Clewat Ltd is both providing the technology as a service as well as selling the snow melting and filtering units. The price for the snow treatment as a service is between 21–22 € per truck load.

The investment cost is 1.8 milj. € for one snow melting and filtering unit built in an ISO container including the electric conveyor for filling the unit. The investment cost is high due to all the automatization, pumps, and other electric devices. The lifetime of this unit is expected to be at least 10 years. To be able to treat all the snow in Helsinki otherwise dumped directly into the sea two to ten snow treatment units would be needed depending on the amount of snow fall.

Operating costs for the snow melting and filtering unit are:

- electricity for pumps and other devices including the conveyor belt (12 kWh per truck load)
- no costs for additional heating since sea water is planned to be used as such and the melting power comes from the power of flowing water
- maintenance and repairing ca. 5% of investment cost
- cost for an operator.

On the other hand, snow treatment in snow melting and filtering units can also save costs. The units can be placed in several places offering a decentralized treatment network. The floating treatment unit could be placed even in harbor areas that are used in summertime for boating, because snow treatment unit can be transported away after winter period. This avoids unnecessary traffic from transporting snow for long distances. In addition, less expensive land area in urban environments is needed for snow piling. The total cost of the treatment is also affected by the recycling possibilities of gravel and plastic part. If gravel can be purified from other impurities, it can be reused. The remaining litter could be burned for energy.

4.3. Pilot 3: Constructed wetland system for wastewater effluent (GIWK)

Constructed wetlands require maintenance to keep balance with the nutrients and other wastewater components. For the plant growth they need renewing and nutrients. Wetlands are able to effectively purify wastewater. The wetlands should be constructed so that they are easy to maintain. Part of the vegetation and sediment material with accumulated nutrients and impurities must regularly be removed (Jiang & Chui 2022).

The basic design rule is that plants should have time to take up the nutrients and harmful compounds biologically after they are retained in soil matrix. The water flow should be less than 0.1 $m \cdot s^{-1}$ and the living biomass should be more than 10 $kg \cdot m^{-2}$ (Stottmeister et al. 2003, Langergraber et al. 2019).

The constructed wetland pilot in Poland was built in 2017 during the "IWAMA" project. The total cost of the system including pipelines and armature (without the cost of pumps) was 17,500 € + adaptation works for MP pilot ca. 3,000 €.

A peristaltic pump of maximum capacity of 60 $L \cdot h^{-1}$ was used. In the pilot study, with the already installed system, the investment cost of one pump was 1,500 € to transport the wastewater from the final effluent channel to the pilot station. If the topography of the land area had been favorable for a gravity-flow system, no wastewater pumping would have been needed.

The main operating cost for constructed wetland systems comes from dredging in 5-10 years intervals and annual cutting, transportation, and handling of biomass. The cost of one treated cubic meter of wastewater is ca. 10 € in this pilot scale including investment cost and operating cost.

Investment could be divided only to 10-15 years since this area is under development and new and more effective solutions are appearing during this time-period. The annual operating cost would be 5% of all investment cost with a flow rate of ca. 20 $L \cdot h^{-1}$ (200 $m^3 \cdot y^{-1}$). In a 1,000 times larger constructed wetland system the cost is estimated to be 100 times lower per treated wastewater m^3.

After the pilot tests, maintenance work consisted of the emptying of the tanks for winter season and cutting of common reed. As a summary, the main cost comes from building, monitoring, and maintenance of units, where building have the biggest share. The flow rate of the wastewater effluent can be regulated according to the pilot capacity. This system could also be connected to the overflow situations at the WWTP.

The pilot system was also designed to treat impurities other than MPs and therefore, only about 10–20% of the costs should be allocated to MP removal. Then, the cost of MP removal in a large scale (e.g. 1 hectare) constructed wetland system would be only at the magnitude of 0.01 $€ \cdot m^{-3}$ with other benefits gained sharing a major part of the treatment cost (Murali 2021).

4.4. Pilot 4: Constructed wetland system for stormwater (GW)

As stormwaters can come with up to 50 mm·h^{-1} rainfall, the rainwater systems can easily overflow or become dry. Since the pilot system also include the gravel tanks it operates semi-mechanically with biological system. In heavy rainfall the mechanical filtration dictates the purification speed and after rain the relative impact of biological processes becomes greater (Hazelton & Murphy 2021).

Soil material and plants must be renewed periodically for efficient operation, otherwise the soil becomes too dense to catch suspended solids and biomaterial and it will start to leak. The maximum flow rate should always be less than 0.1 m·s^{-1} for biological systems to operate without flushing of the soil material and nutrients or ripping the plants away (Rahman et al. 2020).

Investment cost of the constructed wetland pilot of GW was quite high, 120 k€, including tanks, pipes, other equipment, and installation work. In this pilot a large pool area was used as a water reservoir. The lifetime estimation for this kind of filtration pilot material would be 5-10 years and after this time period the material must be emptied and renewed. Equipment lifetime in this pilot, even when operating outdoors, is estimated to be up to 15-20 years.

In this pilot, the flow rate varied from 5 to 50 L·h^{-1} being typical for stormwaters. That was far less than estimated permeability and therefore the treated waste cost became very high. However, this indicated that biological part of the process became more efficient.

Total cost in this pilot would be 300 €·m^{-3} including energy and operating expenses. The operating cost of combined constructed wet land pilot system was estimated to be in total less than 10 €·m^{-3}. The evaluated electricity consumption of pilot station was about 650 kWh per month, and the cost of electricity was then 100 € per month representing only 1% of investment or operating costs.

As the calculated total treatment cost for pilot scale was 300 €·m^{-3} for treated stormwater, upscaling up to 10,000 folds is essential to have the size of pools and treatment areas perhaps in hectare scales. The cost must be decreased to less than 0.3 €·m^{-3} by increasing size, using filtration pools and gravel walls instead of metallic structures.

As a summary, constructed wetlands provide a feasible option in proper scale to prevent stormwater damages and retain MPs as well as other pollutants. The main investment cost comes from the required pool area, especially near city centers if naturally occurring park lakes are not available. The investment cost for preparation of filtration beds, pumping, vegetation, i.e. plants and planting work, in constructed wetland areas should to be less than 50 €·m^{-2} (Xi et al. 2022).

4.5. Cost efficiency and business potential

Cost-efficiencies of the pilot technologies were estimated based on the results of the pilot experiments and costs of the technologies and are summarized in Table 18. With most of the tested technologies, the characterization of the MP removal mechanism and efficiency would still need further testing. The only technology providing explicit removal was snow treatment unit when correct mesh size is used. It also provides possibilities for other savings related to snow transport and storage and thus, can be considered as cost-effective.

Table 18. Summary of the estimated cost-efficiency of the full-scale systems based on the pilots tested.

System	Investment cost	Operational costs	MP removal efficiency
Common reed filter	Low	Low	Improves when the filter matures (surfaces covered with biofilm), expected to be Medium
Snow melting and filtering unit	High	Medium	Depends on the mesh size selected for the filtering unit, expected to be High
Constructed wetland system for wastewater effluent	High + land area needed to be included in urban planning	Low	Expected to be High
Constructed wetland system for stormwater	High + land area needed to be included in urban planning	Low	Expected to be High

As with decentralized snow treatment, the business potential in MP removal can be found by combining the various benefits of different technologies and not only by focusing on MP removal. Common reed filter improves the overall stormwater quality and decreases nutrient run off to water ways. Wastewater treatment with constructed wetland system could remove also other emerging contaminants than MPs, such as pathogens and pharmaceuticals. Stormwater treatment with constructed wetland system, on the other hand, could provide additional water sources for certain uses (irrigation, algae production, recreational) when the required quality is met. Feng et al. (2022) also pointed out in their review that stormwater treatment for reuse would solve three problems at the same time, namely environmental pollution, flooding due to limited capacity of the stormwater system, and limited availability of fresh water.

4.6. Locally adapted investment plans and proposals

The pilot experiments were conducted for meltwater of urban snow (pilot 1), urban snow (pilot 2), wastewater (pilot 3), and stormwater (pilot 4). The pilot experiments were customized to solve a local problem, but the results can be applied to similar use elsewhere. The pilot descriptions in this report, including the LCA and techno-economic assessment of each pilot, will help FanpLESStic-sea project partners and other stakeholders in Microplastic Alliance around the Baltic Sea to assess the suitability of the specific technology for the application in question.

Pilot 1: Common reed filter (Luke)

The Common reed filter was used for treatment of snow meltwater. Due to the late build-up (November 2020), the maturation and microfilm formation, which seemed to occur mainly when water temperature was above 12°C, did not have enough time before MP sampling (May 2021). In similar experiments earlier, significant removal of suspended solids could be shown. Even in this experiment, suspended solids were removed by 35% on later sampling date (June 2021). The technology has potential also for MPs removal although additional research is still needed. Moreover, in addition to treatment of snow meltwater, the technology can also be applied to stormwater treatment. Stormwater treatment might even be more efficient due to the ambient temperatures and thus shorter maturity time needed.

The common reed pilot was built in collaboration with the city of Kouvola and Kestävästi luonnosta -cooperative (https://kestavastiluonnosta.fi/), which are both still interested in further collaboration. The pilot experiment got a lot of publicity when it was presented in the television news (https://yle.fi/uutiset/3-11894065). Luke presented the pilot experiment at a stormwater management webinar in September 2021 organized by the Stormwater division of the Water association Finland (https://www.vesiyhdistys.fi/hulevesijaosto/). Many participants got interested about the technology and further collaboration. Luke is actively looking for suitable funding to carry on research and development of this technology.

Pilot 2: Snow melting and filtering unit (Clewat/Luke)

The hometown of the company Clewat Ltd (www.clewat.com) is Kokkola by the Gulf of Bothnia, the most northern part of the Baltic Sea. In Kokkola, the urban snow is collected to a snow dumping site on the shore, from where the meltwaters are running to the sea. Clewat started to develop and test the snow melting and purification unit in Kokkola during winter 2020. After further development, the snow treatment unit was tested in Helsinki in collaboration with Stara Ltd and the city of Helsinki during winter 2021. They are now considering either investing or buying the technology as a service from Clewat Ltd. In addition to Helsinki, Clewat has offered their technology also to Oslo and Trondheim.

Luke helped Clewat to maximise the MP removal efficiency for their treatment unit. However, first MP analysis results were available first in the end of 2021 and the rest in early 2022. Despite the lack of the MP analysis results, Clewat has been able to commercialize its technology. This is because the pilot removes also macroplastics (e.g. cigarette filters) and other litter from melting snow, which is also important to prevent from entering the sea. Macroplastic is even a source for further MP pollution.

Pilot 3: Constructed wetland system for wastewater effluent (GIWK)

The project of the pilot station was elaborated within the scope of the BSR Interreg project "International Water Management" in which GIWK took part in period 2016-2019. The station was built by an external contractor in 2017. In the FanpLESStic-sea project, the adaptation work at the pilot station was also carried out with the help of a subcontractor. Due to the COVID pandemic and the risk of corona virus contamination in the wastewater, the pilot studies on constructed wetland treatment could be started first in the third year of the FanpLESStic-sea project. Moreover, due to technical challenges at the beginning of the start-up period, it was possible to operate the system for less than three months before the samples were collected. In this period, it was not possible to carry out tests under different operating conditions, i.e. variable hydraulic load, variable pollutant load, aerobic conditions in the wetland beds, variable wetland water table level, and wastewater recirculation mode. The above-mentioned analyses are necessary for estimating implementation on a larger scale. Due to the longer adaptation time of constructed wetland systems to subsequent changes in operation, these studies require longer course of action so that all the assumptions could be met. Thus, further research should be carried out to confirm the reduction of MPs and the suitable operation conditions in constructed wetland pilot system.

As a water and wastewater company, GIWK is responsible for modernizing the infrastructure and the technology, and thus is interested in planning a large-scale facility as part of an additional, final treatment step of Gdansk WWTP effluent which is directed to the Gdansk Bay. GWIK is going to analyze a possible investment in the close surroundings of the WWTP. Moreover, there has been a growing interest towards Nature Based technologies in the city of Gdansk. It is already used, among others, in the city's rain gardens. Also, Gdansk University of Technology (GUT) specializes in constructed wetland systems for stormwater and wastewater treatment. The city therefore has a scientific support for future investments.

Pilot 4: Constructed wetland system for stormwater (GW/GUT)

The pilot station was designed in collaboration of GW and Gdansk University of Technology, built by a subcontractor, and funded by the FanpLESStc-sea project. First results of the pilot performance are very promising. However, the role of the plants is still not well known, as the size of the removed particles can be below the detection limits of analytical methods. Further research should be carried out to confirm or exclude the reduction of MPs in sorption and bioaccumulation processes. GW is searching actively new research funding and has even tried twice to get the subsidy from the LIFE Programme for this purpose without success unfortunately.

The pilot station has obtained a lot of publicity since it is situated next to a popular outdoor route. It can be seen through the fence and GW has placed information boards near the pilot station. In addition, a video has been published from the pilot station (https://www.youtube.com/watch?v=0vduujjC7no). There is growing interest in stormwater treatment using Nature Based solutions in Gdansk. The city of Gdansk has reserved a place for stormwater treatment using wetlands in the municipal spatial development plan.

5. Conclusions and recommendations

Microplastics are transported to the sea both in stormwaters and in treated wastewaters. In Finland and other Nordic countries, urban snow is even creating additional problems. The FanpLESStic-sea project piloted promising, locally adaptable, and cost-effective technologies for treatment of stormwater, urban snow meltwater, and treated wastewater. The main findings, conclusions and recommendations are as follows:

- Common reed is harvested for nutrient up-take from lakes and sea bays to mitigate eutrophication. In the present and in previous local projects, harvested common reed has proved to be a versatile and cost-effective filtering material for stormwaters.
- Common reed filters could mitigate both MP pollution and nutrient run-off but are better suited for stormwater treatment in ambient temperatures than for treatment of very cold snow meltwater due to the important biofilm formation during warmer periods.
- Snow melting and filtering technology by Clewat Ltd. was demonstrated to be very efficient in MP removal when proper mesh size for the fine filter was used. In addition, it removes other litter found in urban snow, e.g. gravel and sand, cigarette filters and debris of plastic packaging materials.
- Snow melting and filtering technology solves the urgent problem of dumping urban snow into the sea. The unit can be operated both on land and floating on water and as a decentralized system it reduces snow transport distances.
- Constructed wetland systems piloted for treatment of WWTP effluent and urban stormwaters were efficient in removal of MPs, suspended solids, nutrients, and other pollutants.
- Vegetation in constructed wetlands is known to be important for removal of nutrients and other pollutants. However, the role of common reed vegetation for MP removal remained uncertain in this project. At least the rhizome forms a filtering matrix, but the possible up-take of nano- and microscale plastics by plants was not examined.
- Pilot-scale testing is necessary to proof the functionality of the developed technologies in real conditions close to full-scale applications.
- Especially for nature-based solutions, long time pilot experiments are essential to enable the stabilization of the systems and to study the biological mechanisms, e.g. biofilm formation (common reed filter) and nanoplastic up-take by vegetation (constructed wetlands).
- Standardized protocols for MP sampling, sample preparation and analytical methods suitable for various MP types, e.g. tyre and road wear particles, should be further developed.
- The economic feasibility of the various MP removal systems comes from combining MP removal with other benefits, e.g., removal of nutrients and other contaminants, savings in logistics costs, preventing flooding and providing additional sources for fresh water.

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