

3 WORK PACKAGE 3

Resume

In the Wondelgem district in Ghent, at a distance of approximately 500 meters from the port area, there was a tar and carbon-black factory in the past. As a result of industrial processes and calamities, the soil has become contaminated with various hydrocarbons. A large amount of residual contamination has been left behind, with the contaminated groundwater flowing into the Lieve canal. As a result, the surface water does not meet the quality requirements and there is an ecological risk. The aim of work package 3 is to structurally improve surface water quality with a sustainable and nature-based measure. This measure has taken shape in a reactive mat, filled with adsorbent materials of natural origin, the Natural CatchTAUW. This reactive mat has three nature-based pillars:

1. The natural drainage capacity of the canal as the driving force;
2. The use of natural materials as adsorbent and passive adsorption;
3. A biologically active zone at the interface of mat and surface water for aerobic decomposition.

After a preliminary study, design and construction on the bottom of the Lieve, the reactive mat based on green adsorbent was monitored for 2 years in the context of RESANAT. It follows that a reactive mat in the form of a Natural CatchTAUW can significantly improve the quality of surface water. Moreover, it appears to be the most sustainable solution compared to alternatives such as excavation and (limited) groundwater extraction. Finally, the study showed that a number of critical factors must be met to successfully use a reactive mat over the long term.

3.1 INTRODUCTION

3.1.1 General problem statement & solution

Work package 3, the development and application of the reactive mat, focuses on the situation where there is a negative influence on draining surface water quality due to long-term inflow of contaminated groundwater. The situation can even deteriorate further by removing dredged material to improve water drainage in the context of climate adaptive measures. The consequence of this is the possible occurrence of human and ecologische risico's en het niet voldoen aan de Kaderrichtline Water.

Examples of locations where this can occur are: Residual

- contamination at industrial locations and brownfields;
- Chemical dumps;
- Agricultural areas (pesticides, phosphate).

The experimental design was based on the possibility of achieving a significant improvement in water quality by applying a water-permeable geotextile construction filled with adsorption material to the water bottom; the reactive mat (for an impression please refer to Figure 1 Figure 17). The reactive mat has three nature-based principles:

- The natural inflow of contaminated groundwater: No pump is needed; The
- adsorption of contaminants to a natural (green) material; The
- biological degradation at the aerobic/anaerobic interface on the mat (micro-habitat).

The advantages of this approach are the relatively low operating costs (cost-effectiveness) and the low environmental footprint (a passive, long-term operating system). This avoids the use of classic active remediation techniques with more intensive use of energy and raw materials.

The technology is being tested with a pilot project at a location in Ghent, Flanders.

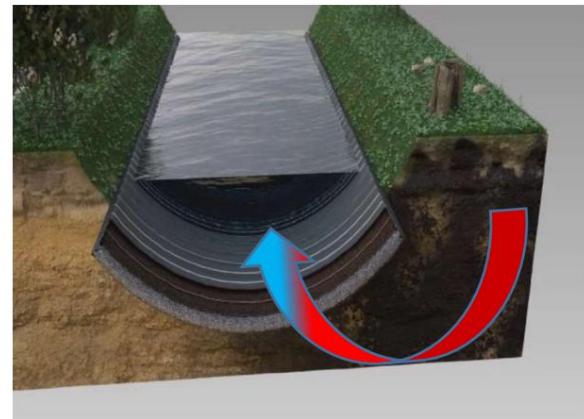


Figure 17. Impression of reactive mat and operation

3.1.2 General framework work package 3

This technique fits within a number of frameworks: global, European and national.

First of all, the concept fits within the Sustainable Development Goals of the United Nations, in particular:

- SDG 3 - Good Health and Well-Being: preventing humane SDG risico's.
- 6 - Clean Water and Sanitation: improving water quality by reducing pollution;
- SDG 12 -
- Responsible Production and Consumption: 1) minimizing the use of fossil fuels, materials (incl. production) and chemicals and waste production; 2) (re)use of natural resources;
- SDG 13 - Climate action:
- the reactive mat enables the redevelopment of streams, ditches and canals, which improves the drainage of the immediate environment; SDG 14 - Life
- below water: protection of aquatic life through elimination and/or control van onacceptabele ecologische risico's.

Furthermore, the international standard ISO 18504 for Sustainable Remediation now exists, where the definition of sustainable remediation is:

"Elimination and/or control of unacceptable risks in a safe and timely manner whilst optimizing the environmental, social and economic value of the work. For the reactive mat, this applies to the environmental value ('Planet') and the economic value ('Prosperity') van het werk zijn geoptimaliseerd ten opzichte van conventional remediation techniques (demonstrable as part of WP6).

Within the EU, the Water Framework Directive applies, which aims to guarantee the quality of surface and groundwater in Europe. With the reactive mat, the surface water quality is greatly improved, which means that exceeding standards is eliminated or minimized. This is tested against the maximum acceptable environmental quality standard (MAC-MKN) and the annual average environmental quality standard (JG-MKN) that have been established in Vlaam II - General environmental quality standards for lakes and rivers (Appendix 2.3.1 art. 3) and in the stainless steel search system of the RIVM.

The application of this technique fits within EU regulations and the national and regional environmental policy of the Netherlands and Flanders respectively. The question is whether this technology is available in every land inzetbaar is. De techniek betreft immers een 'end-of-pipe' maatregel en is risico-based. Not all EU countries have a soil policy that is risk-based for historical contamination.

3.1.3 Research location

The research location is located in Ghent, in the Wondelgem district, at a distance of approximately 500 meters from the port area. As a result of the industrial distillation of tar and the production of carbon black and asphalt in the past by Lumco, including a disaster with one of the storage tanks, the soil on a site immediately east of the Lieve Canal has become contaminated with aliphatic and mono- and polyaromatic hydrocarbons, in particular benzene, C6-C10 (light fraction of mineral oil) and several PAH components. These substances were part of the production process as raw materials.

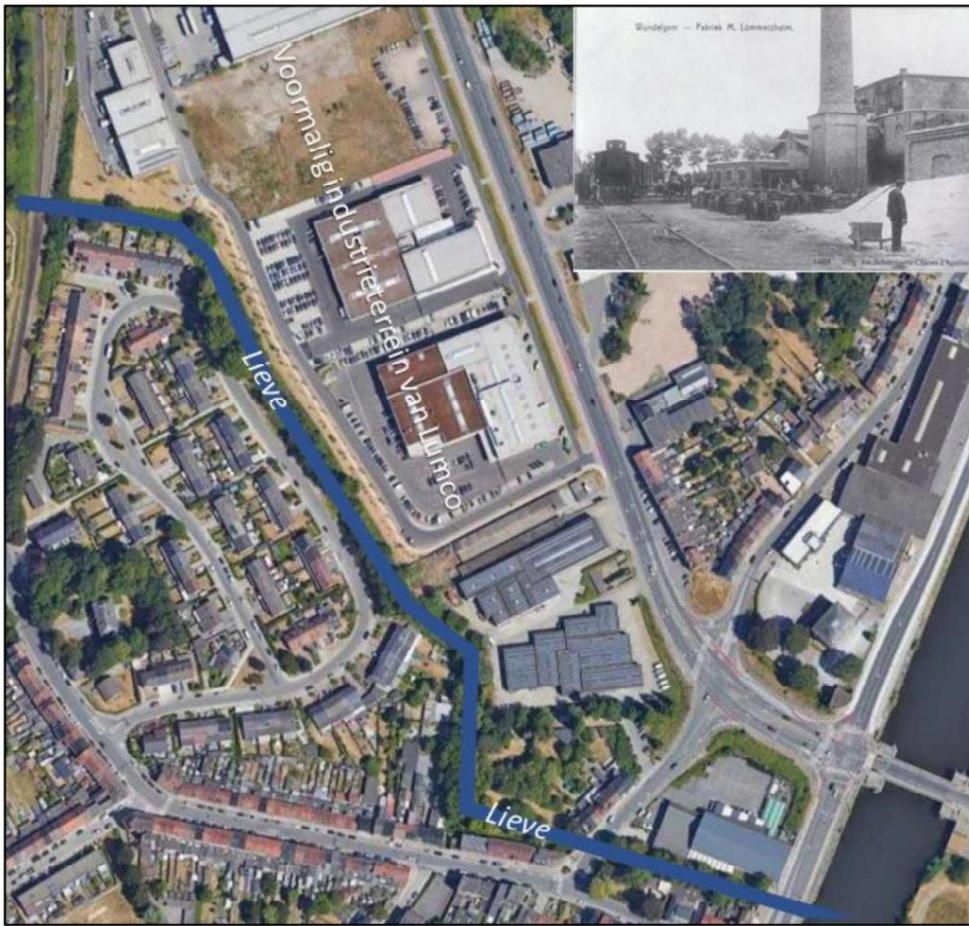


Figure 18. Location of the research location: the Lieve and the former Lumco site

Despite remediation by excavating part of the soil contamination, which was carried out partly with a view to the redevelopment of the former industrial estate, there is residual contamination in the soil with pure product spots and contaminated groundwater. Both the waterbed (sediment) and the surface water became contaminated through direct contact with pure product and through migration of the shallow groundwater contamination to the canal. The surface water has been affected over a length of almost 600 meters. Residents were asked to avoid contact with the water and the banks of the Lieve at a distance of 200 meters. Research also showed that there was an ecological risk.

After the removal of the heavily contaminated sediment from the Lieve in 2019 in the context of water management (climate adaptation), the discharge and drainage capacity of the canal has increased. The result was a further increase in pollutant concentrations in the canal due to an increase in the inflow of contaminated groundwater, with PAH exceeding the environmental quality standard for surface water by up to 300 times.

Since this situation largely meets the problem definition as outlined in section 3.1.1, this location seems suitable for the design and use of a reactive mat. The social and environmental problem is evident and the situation in spatial, hydrological and organizational terms is extremely suitable for testing these techniques. *ek. De enige 'maar' is the presence of residual pure product in the bed and banks as the reactive mat primarily targets contaminants in solution, in view of the adsorption mechanism, the adsorption capacity and the desired lifespan of the reactive mat.*

This technical lifespan ultimately determines sustainability (including cost-effectiveness). Yet there is decided to choose this location and this is partly due to the possibility at this location to demonstrate the working principle of a reactive mat in the short term. After all, RESANAT has a limited duration.

3.2 DESIGN

3.2.1 Conceptual model of the pilot

3.2.1.1 Terrain characteristics

Based on several site visits and field research (see section 3.2.1.2), the site can be described as follows. See also the schematization drawn up by TTE in Figure 19.

The bottom east of the Lieve consists of fine silty sand to a depth of approximately 5 to 6 m below ground level, with moderate sand alternating with loamy layers underneath. The groundwater level is present at a depth of 1.5 to 2.5 m below sea level, depending on seasonal fluctuations.

Over the years, the Lieve became clogged due to the formation of a thick contaminated sludge layer. This layer was removed in 2019 in the context of remediation and water management (climate adaptation). The difference in head between the shallow groundwater and the current surface water of the Lieve, after clearing, is usually 0.2 to 0.3 m and indicates a flow direction from the groundwater to the surface water. It can be deduced from this that the shallow groundwater contamination flows from the former industrial estate (source zone) to the Lieve (receptor). The depth to which the Lieve drains groundwater is assumed to be approximately 6 m below ground level. The deeper groundwater flows in the opposite direction (and is tackled via a separate remediation track).

On the paved areas of the adjacent car companies (lease/sales), rainwater is collected in a shallow system and discharged directly into the Lieve, without coming into contact with the soil and groundwater contamination. In the event of heavy precipitation, this can lead to rapid dilution of the pollution in the Lieve.

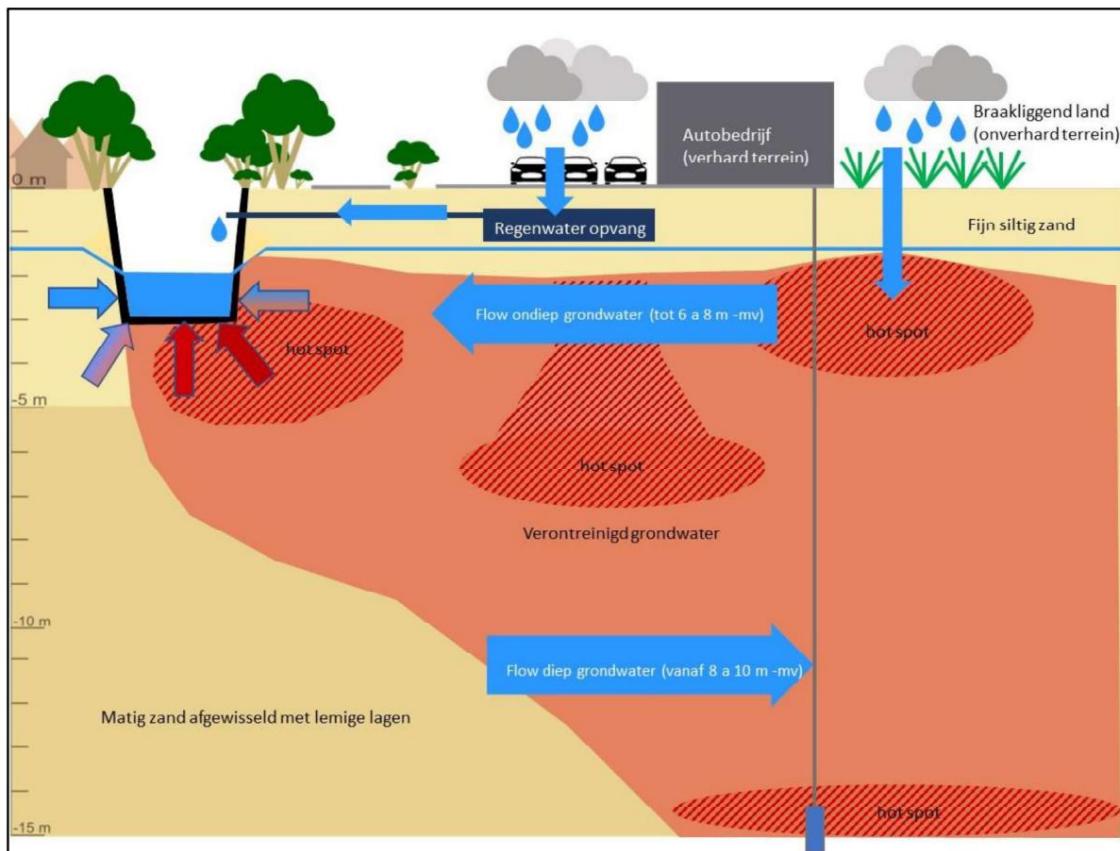


Figure 19. Schematic representation of the soil contamination situation and the Lieve

3.2.1.2 Specific contamination situation

To determine the initial contamination situation, the consortium conducted a field study into the location-specific conditions at the Lieve location, near the former industrial estate. First of all, measurements were carried out along the eastern banks of the Lieve over a length of approximately 150 meters by Witteveen+Bos with EnISSA-OIP and -MIP to a depth of 8 m-mv, whereby not only the contamination situation but also the soil structure was determined. Based on these results, fixed monitoring wells were installed by TAUW and samples of groundwater and surface water were taken and analyzed, both before and after sediment removal. Finally, iFLUX used samplers and sensors to determine the water flux and contamination flux from the inflow of contaminated groundwater into the surface water.

The EnISSA-OIP(UV) measurements showed that pure product is very likely present in the soil on the eastern bank in the OIP5 OIP8 section (see photo below Table 1). On the upstream north side, OIP-0 and on the south side OIP-10 appeared to limit soil contamination.

The monitoring wells PB20, PB50, PB90 and PB100 were installed by TAUW in October 2019 at OIP-2, OIP-5, OIP-9 and OIP-10 respectively. Table 3.1 contains the groundwater concentrations as measured in March 2020 (after clearing and prior to the construction of the reactive mat) for some relevant contaminants in the east bank of the Lieve.

It follows that there is indeed no longer any groundwater contamination at PB100 and that the highest concentrations occur at PB50. This includes 38,000 µg/l benzene, 60,000 µg/l C6-C10 and 280 µg/l acenaphthene. The groundwater concentrations at PB50 have increased significantly compared to the situation prior to the removal of the sludge from the Lieve as a result of the increased drainage effect.

Before and after dredging, the horizontal groundwater flux and mass flux were determined by iFLUX in November 2019 and March 2020. For this purpose, measurements were carried out with iFLUX samplers in monitoring wells PB20, PB50, PB90 and PB100 at 2 depths each.

It follows that the horizontal flow of groundwater prior to clearing is on average 5.75 cm/d (range <1-13 m/d), and after clearing it is 10.5 cm/d (range 9-12 m/d). This directly demonstrates that the Lieve drains better after clearing and that the water flux since clearing has also been more homogeneously distributed over the entire length of the research route.

The horizontal mass flux in the groundwater has also increased. For example, on site PB50 has increased by a factor of 15 for benzene and by a factor of 8 for acenaphthene. It is also striking that, in contrast to before dredging, a relevant mass flux of mineral oil (C6-C40) was measured after dredging. Horizontally speaking, significantly more contamination is moved towards the Lieve in the groundwater package at 3-5 m below ground level compared to the situation prior to the clearing.

The initial surface water concentrations in the Lieve were determined (after clearing and prior to the installation of a reactive mat) in February, March and June 2020. The analysis results from March 2020 were presented in Error! Reference source not found. It follows that the largest increase in concentrations from upstream to downstream in the Lieve is measured at measuring point 203 for BTEX, naphthalene and C6-C10. For PAH this already seems to be the case at measuring point 202 and there continues to be a gradual increase over the period up to 207.

Maart 2020	PB 20 (3,2-5,2 m -mv)	PB 50 (3,15-5,15 m -mv)	PB 90 (3,2-5,2 m -mv)	PB 100 (2,4-4,4 m -mv)
Benzeen	15	38.000	100	< 0,2
Tolueen	15	11.000	1,2	< 0,5
Ethylbenzeen	5,5	1.100	8	< 0,5
Xylenen	9,9	4.600	3,9	< 0,5
Naftaleen	240 / 270	6.100 / 7.200	13 / 16	0,14 / 0,2
Acenaatteen	1,1	280	41	0,1
C6-C10	99	60.000	130	< 10



Table 1: Groundwater concentrations in the eastern bank of the Lieve after clearing in March 2020 (in µg/l)

	201	202	203	204	205	206	207	208
Benzeen	<0,2	<0,2	180	140	100	83	75	3,5
Tolueen	<0,5	<0,5	56	30	20	16	16	8,2
Ethylbenzeen	<0,5	1	6,1	6,9	7	5,9	5,4	3,2
Xylenen	<0,5	1,7	27	23	21	17	16	9,3
Nattaleen	0,2	12	46	57	60	54	53	26
PAK (16 EPA)	0,66	25	57	77	86	80	93	79
Acenafteen	0,12	3,9	3,2	6,3	7,5	9,4	10	15
C6-C10	<10	<10	280	210	160	130	120	61

Table 2. Surface water concentrations in the Lieve after clearing in March 2020 (in µg/l)



If we then test the maximum concentrations measured in the period February June 2020 against the quality standards from the European Water Framework Directive for surface water (EQS values), it is clear that there are exceedances for several substances, with the PAH compounds phenanthrene, pyrene and acenaphthene exceed by a factor of more than 100 (see Table 3). This leads to the need for measures.

Stof	Concentratie max. (µg/l)	Kwaliteitsnorm (µg/l)	Overschrijdingsfactor
Anthraceen (3-ring)	4,1	0,1 *	41
Fenantreen (3-ring)	25	0,1 **	250
Fluorantreen (4-ring)	8,5	0,12 *	71
Pyreen (4-ring)	4,4	0,04 **	110
Benzo(a)anthraceen (4-ring)	0,52	0,3 **	1,7
Benzo(k)fluorantheen (5-ring)	0,063	0,017 *	4
Benzo(g,h,i)peryleen (6-ring)	0,044	0,0082 *	5
Benzo(b)fluorantheen (5-ring)	0,14	0,017 *	8
Acenafteen (3-ring)	18	0,06 **	300
Fluoreen (3-ring)	14	2 **	7
C6 - C10 (vluchtige m. olie)	280	200 ***	1,4
Benzeen	180	50 *	3,6
Xylenen (som)	27	40 *	0,7
Nattaleen (2-ring)	91	130 *	0,7

* MAC-MKN; ** JG-MKN; *** SME Decree 1994

Table 3. Testing maximum surface water concentrations in the first half of 2020 against quality standards (EQS values)

Finally, the measured influx, by using vertical flux samplers in the waterbed, is included in Table 4. This has led to an illuminating insight into the pollution loads that the canal receives daily (up to a maximum of 100 mg/m² of water sediment per day) and the distribution of the incoming loads over the canal route.

The preliminary research shows that measures must be taken to protect surface water quality over a canal section of approximately 110 meters and an area of 660 m². Sensory observations during the field work after clearing the Lieve show that there is still residual free product present locally in the waterbed: thin oil films have been observed on the water surface.

	Segment 1	Segment 2	Segment 3
Benzeen	0,00	11,8	0,00
Xylenen (som)	0,17	20,2	0,04
Naftaleen	2,36	28,4	0,35
Fenantreen	7,93	17,8	5,17
Pyreen	2,21	4,59	4,83
Acenaatteen	4,98	7,24	2,24
C6-C10	0,00	3,02	0,00

Table 4. Measured influx of contamination into surface water after clearing (in mg/m² per day)

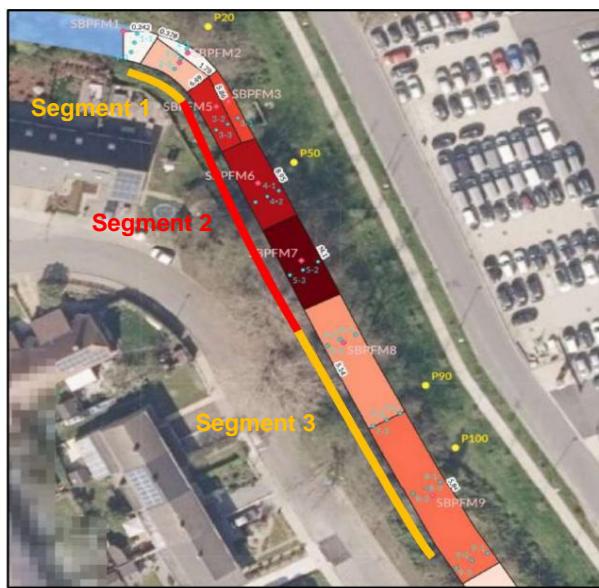


Figure 20: Designation of segments De Lieve

3.2.1.3 External factors

Communication

process With regard to permission for the use of the reactive mat and the green maintenance of the bank (for the accessibility of the reactive mat), we deal with the City of Ghent and Farys as owner and manager of the watercourse.

The residents on the west bank of the Lieve near the research project were periodically informed about the work and progress via resident letters.

Location developments

Since the second quarter of 2021, a new 3rd car company (lease/sales) has been established on the previously undeveloped part of the Lumco site north of the research route.

The new pavement may influence the geohydrology by reducing the water flux and thus the pollution flux. This is a point of attention.

3.2.1.4 (Technical) design and layout of the system

Literature research into green adsorption materials

Based on a literature study, TAUW examined the suitability of natural and/or secondary materials for use in the reactive mat as an adsorbent for the inflowing contamination. The following material requirements were taken into account:

- It must be reasonably
- inert; It must have a significant adsorption capacity for the contaminant in question;
- The specific weight (g/m³) must be in balance with the adsorption capacity, such that the thickness of the reactive mat can be
- limited; The permeability must be higher than that of the natural water bottom;
- It must be cheaper than high-quality (commercial) adsorption materials;
- The material must be less harmful to the environment than high-quality (commercial) adsorption materials (carbon footprint, renewability, local availability).

Based on these requirements, we have made an initial selection of materials for testing in the laboratory:

- Crushed hazelnut shells;
- Biogranulate from thermal sludge dryer (wastewater treatment plant residual product); Pulverized coal sludge
- (residual product of drinking water extraction); Biochar (pyrolyzed residual wood); Pine bark (fine fraction); Sieved white peat/sod peat.

Laboratory research on green adsorption materials

TAUW's test laboratory initially conducted research into the adsorption capacity of the aforementioned materials. This was determined on the basis of shaking tests. Several batches were used, consisting of 1 liter bottles each containing a fixed amount of contaminated groundwater from the location in Ghent and different amounts of adsorption material (variable L/S ratio). The batches were shaken on a shaking machine in a horizontal position for 72 hours. The shake flasks were then left upright for several hours to allow the adsorbent to settle. The supernatant liquid was then poured gently over a metal sieve to retain the floating parts.

Om de bewerking voor alle monsters gelijk te houden, is dit proces ook gevuld voor de blanco's. De decanted liquid, the eluate, has been sent to the AL-West laboratory for analysis for BTEX, PAH and C6-C10.

This resulted

- in: Hazelnut shells adsorb the pollutants to a limited and highly variable extent.
- Biogranulate appears to add contamination in the form of C6-C10 and to emit a significant stench. Moreover, the adsorption capacity for BTEX was too limited.
- Pulverized coal sludge appeared to adsorb maximally. However, an additional permeability test revealed a k value of 0.015 m/d. This is too low to be applied in the Lieve. After all, the permeability of the waterbed is between 0.5 and 5 m/d.
- Biochar is highly adsorbent for all pollutants up to a high L/S ratio. At L/S ratios up to approximately 230, all substances are adsorbed for 95 to 100%. At an L/S ratio of approximately 570, most substances are adsorbed for 85 to 97% and benzene and C6-C10 for 68 to 73%.
- Pine bark adsorbs the pollutants to varying degrees. Benzene, xylenes and C6-C10 are adsorbed to less than 50% at almost all L/S ratios. Good results are only achieved for naphthalene and acenaphthene (83-88%).
- Sod peat (a type of peat) adsorbs pollutants on average more than 6% better than pine bark. Although benzene and C6-C10 are adsorbed for less than 50%, the score for ethylbenzene, naphthalene and acenaphthene is 86-95%. The results are less good and more variable than for biochar.



Figure 21. The three best tested adsorption materials

Calculations for design

Based on the results of the adsorption tests in the laboratory and the vertical flux measurements, calculations were carried out for the expected life of the reactive mat at a thickness of 30 cm. A maximum thickness of 30 cm of the mat is a requirement for water-bearing capacity of the Lieve. The lifespan of the mat, based solely on adsorption, and therefore without taking biological degradation into account, is partly determined by the requirements (standards) that apply to the most critical contamination in surface water.

The calculations have been carried out for the fluxes that are representative of the 3 distinct segments (see Figure 20).

PAH are decisive for segment 1. Biochar achieves the highest yield of 97% over 9 years for phenanthrene and 90% over 16.5 years for acenaphthene.

Benzene, C6-C10 and PAH are decisive for segment 2. Biochar achieves the highest efficiency of 75% for benzene for 16.5 years, 73% for C5-C10 for 100 years, 96.5% for phenanthrene for 17 years and 90% for 11 years for acenaphthene.

Segment 3 is characterized by little to no inflow via the groundwater from BTEX and C6-C10. So here we only focus on PAH. For this purpose, turf peat is sufficient as a lower-quality and cheaper alternative to biochar. The return on this is 85% over 12.5 years for acenaphthene; the lifespan for phenanthrene and pyrene could not be calculated given the high adsorption at all L/S ratios of 98-100% (expectation > 15 years).

Design

Finally, the design of the reactive mat construction was worked on in close consultation between the manufacturer of the required geotextile fabric, Envisan (Jan de Nul) as contractor and TAUW as environmental advisor, supported by a student from TU Twente. The design procedure was complex due to the many product requirements.

Aspects that play a role are the weight of the mat (both dry and wet), the lifting capacity of the equipment, the tendency of the adsorption material to (initially) float up, the type and amount of ballast to withstand (initial) upward pressure, the method of filling the geotextile construction, the sealing of the construction after filling, the recyclability of the mats, the durability of the geotextile, the method of anchoring, ensuring a homogeneous distribution of the adsorbent and the prevention of preferential flow of groundwater via the seams. After an initial prototype, it was ultimately decided to work with 4 different sizes of mat elements, varying from 3 to 5 meters wide and 6 to 7 meters long, taking into account the varying width of the Lieve, bends and spatial nuisance caused by trees. In addition to the simplicity of filling, lifting and installation, working with elements has the advantage that they can be easily replaced, once loaded with contaminants, or removed when no longer needed. Each element consists of a double layer of fabric (top and bottom layer), divided into multiple compartments, comparable to a down-filled winter coat. Most compartments are filled with adsorption material, and some are filled with ballast material to counteract buoyancy. The transition between the individual mat elements is provided with impermeable foil strips to prevent short circuits of contaminated groundwater between the elements.

Soil remediation

In April 2020, an independent soil remediation expert was commissioned by OVAM to deliver the soil remediation project for the preconditions and principles, the substantiation of the choice of the remediation variant with reactive mats, the elaboration of the construction and activities requiring a permit (Second phased soil remediation project De Lieve in Ghent, Watercourse and left bank De Lieve downstream railway Ghent, Part of pilot test placement of reactive mats). On April 30, 2020, this remediation project was approved by OVAM as the licensing authority.

3.2.2 Follow-up and process evaluation

3.2.2.1 Specific remediation objectives

The formal objective is to comply with the environmental quality standards for surface water (European Water Framework Directive) or at least not to negatively affect the quality of the inflowing surface water. The results to be achieved in the soil remediation project after carrying out the soil remediation works are listed in the following Error! Reference source not found. shown (table from the April 2020 soil remediation project). The initial maximum values mentioned in this table relate to the concentrations as measured prior to the clearance of the sludge from the Lieve. These are not representative of the baseline situation after clearing and prior to the installation of reactive mat. These are considerably higher. Reference is made to paragraph 3.2.2.2 (including the expected end result on this basis).

Referentie sanering: Pilootproef plaatsing reactieve maten						
Medium	Parameter	Top (m-mv)	Basis (m-mv)	Eenheid	Initiële max. waarde	Te verwachten eindresultaat waarde*
Oppervlakte- water	naftaleen			µg/l	9,1	2
	Benzo(a)pyreen				0,1	0,00017
	fenantreen				4,3	0,1
	fluorantreen				2,1	0,0063
	benzo(a)antraceen				0,36	0,3
	benzo(b)fluorantreen				0,19	0,00017
	benzo(k)fluorantreen				0,08	0,00017
	Benzo(ghi)peryleen				0,05	0,00017
	Indeno(1,2,3-cd)pyreen				0,06	0,00017
	acenafteen				1,4	0,06
	pyreen				1,1	0,04
	benzeen				12	10

Table 5: Results to be achieved from the soil remediation works (remediation objective)

* The expected end result value here means the basic environmental quality standard for surface water in accordance with Appendix 2.3.1 of Vlaam II (average environmental quality standard for rivers and lakes, JG-MKN)

1) De waarden genoemd onder de kolom 'Initiële max. waarde' is gebaseerd op analyses van het surface water prior to the clearance of the sludge from the Lieve. These are not representative of the baseline situation after clearing and prior to the installation of reactive mat (see section 3.2.2.2).

It must also be taken into account that the Lieve upstream can also show slightly increased concentrations compared to the environmental quality standard. The quality of the incoming surface water must not be negatively influenced. In such cases, the target is taken as the average inflowing concentration + 10% (X + 10%).

3.2.2.2 Hypothesis & measurement strategy

3.2.2.2.1 Hypothesis

As stated in section 3.2.1.4, a certain purification efficiency is expected from the reactive mat based on the laboratory study. For the guide parameters it is: Acenaphthene: 90%

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- Phenanthrene: 97%
- Benzene: 75%
- C6-C10: 73%.

The maximum surface water concentrations measured in one of the measuring points 203, 205, 206 or 207 during the baseline situation after clearing and prior to the construction of the slab (an average of the baseline measurements in February, March and June 2020) are included in Error! Reference source not found. The table also includes the environmental quality standard. It follows that a number of PAH, despite the expected high purification efficiency, will probably not meet the 3.5). BTEX is expected to comply with the environmental milieukwaliteitsnorm (benoemd als 'te bereiken resultaat' in het saneringsplan, conform tabel quality standard MAC-MKN, but the JG-MKN can be permanently exceeded by benzene. The derived environmental quality standard will be achieved for C6-C10.

Parameter	Baseline concentration ($\mu\text{g/l}$, max) 11.2	Expected concentration with mat ($\mu\text{g/l}$, max) 1.12 0.22	Environmental quality standard ($\mu\text{g/l}$)
Acenafteen	(n=3) 7.3	41	0.06 (JG-MKN)
Phenanthrene	(n=3) 165		0.1 (JG-MKN)
Benzene	(n=3)		10 (JG-MKN) 50 (MAC-MKN)
C6-C10	267 (n=3)	72	200 (SME, 1994)

Table 6: Expected results of the soil remediation works

3.2.2.2.2 Measurement strategy

Surface water quality The zero situation of the surface water quality after the clearance of the Lieve and prior to the construction of the reactive mat has been recorded on the basis of 3 measurements during the first half of 2020. After the construction of the reactive mat, periodic measurements (3 to 4 times a year) are carried out. and depending on interim results) sampling of the surface water. Samples are taken at 4 measuring points above the mats (203, 205, 206 and 207), a measuring point on the upstream side of the mat construction (201) and a measuring point on the (far) downstream side of the mat construction (208). The surface water samples are analyzed for:

- THEN
- C5-C10
- BTEX
- Phenol index (indicator for aerobic breakdown of aromatics).

In the field, the surface water is measured for:

- Temperature (T), conductivity (EC) and acidity (pH)
- Redox potential (Eh) and oxygen (O₂).

Groundwater quality

The zero situation of groundwater quality is recorded at the same times as for surface water.

After the installation of the reactive mat, groundwater samples are taken approximately twice a year (the groundwater quality is expected to be fairly constant).

Samples are taken from 4 monitoring wells on the banks of the Lieve (PB20, PB50, PB90 and PB100).

The groundwater samples are analyzed for:

- THEN
- C5-C10
- BTEX
- Fenolindex.

In addition, the groundwater in the field is measured at:

- Temperature (T), conductivity (EC) and acidity (pH)
- Redox potential (Eh) and oxygen (O₂).

Micro-organisms

To determine the activity of specific micro-organisms at the aerobic/anaerobic interface on the mat, surface water samples are taken against the mat surface at 3 times during the pilot test. These water samples are analyzed, via DNA extracts, for the total Eubacteria and sulfate-reducing bacteria and 20 functional genes that are relevant to the biodegradation of various petroleum-related components are also measured via QuantArray®-Petro, an advanced qPCR method.

Flux

measurements Both prior to and immediately after the clearance of the Lieve, horizontal water and mass flux measurements were carried out by iFLUX in the monitoring wells PB 20, 50, 90 and 100 to determine the flow direction and velocity of the groundwater and contamination towards the Lieve at 3-5. m-mv (see section 3.2.1.2).

In addition, after clearing and prior to the construction of the mat construction, vertical water and mass flux measurements were carried out through the waterbed, which provide a picture of the actual influx of contamination, on the basis of which the mat dimensions and expected lifespan can be calculated and a zero situation for the mass flux has been established.

During the pilot test, vertical flux measurements are carried out on the mat construction when surface water concentrations increase. The location of the flux measurements was chosen based on the location of the concentration increase in the surface water and the measurements carried out with the digital iFLUX flow sensor. Based on the mass flux measurements, it can be determined whether and to what extent there is breakdown through the mat in question and whether there is saturation of the mat. When saturated, the mat must be replaced.

Log

To assess the measurement and analysis results, the following parameters were also measured, queried and recorded in a logbook:

- Weather type during sampling;
- Amount of precipitation in the week prior to sampling (weather archive Ghent - Meteoblue);
- Water level of both groundwater and surface water in m TAW;
- Flow direction and speed of the surface water (simply determined by putting out a half-filled bottle and recording the distance and time travelled);
- Sensory perception of any presence of oil films on surface water;

These parameters are important in the interpretation of measurement and analysis results.

Periodic inspection of mat construction and surroundings, and maintenance The partners Envisan and iFLUX, the parties that carry out environmental guidance and field work on behalf of OVAM and Farys / City of Ghent periodically visually assess the situation at the mat construction. This concerns:

- Presence of broken tree branches and illegal dumping in the Lieve and obstructive or harmful vegetation on the banks of the Lieve;
- Destruction, floating or shifting of the canvas;
- Presence of sludge on the cloth;
- Presence of floating layer of oily products on surface water.

Farys is responsible for the maintenance of the greenery on the banks (at least annually, preferably biannually for accessibility), broken tree branches and illegal dumping.

Envisan is responsible for the maintenance and repair of the mat construction.

3.2.2.3 Process evaluation

Implementation of a reactive mat in the

Lieve The adsorption tests and the measured influx made it clear that biochar is required for segments 1 and 2 (see Figure 20) and that turf peat can be used for segment 3, with a more limited influx. The choice of turf peat instead of biochar in segment 3 was made to test and compare the effectiveness of several green adsorption materials in practice. In addition, the costs for turf peat are lower than biochar, so that the cost-efficiency of several materials can also be compared.

A special geotextile construction has been designed to keep the adsorption material in the desired location on the waterbed of the Lieve. This construction must meet a number of requirements: safe, replaceable, easy to fill, submersible, easy to attach, affordable and reliable.

In addition, the construction must comply with the shape and dimensions of the Lieve. To meet the requirements can meet the requirements, after intensive consultation about several embodiments, it was decided to work with separate mat elements that, placed in series, form the total construction.

The mat elements consist of a double-layered cloth: a strong woven outer part for strength and a fine (non-woven) inner part that retains the fine adsorbent particles. This construction was custom-made by an experienced Dutch geotextile manufacturer and is UV-resistant. Each mat element consists of several compartments (see 1st image of Figure 2222) to ensure a homogeneous distribution of the adsorption material.

One compartment on either side has a liquid-tight finish so that it can be filled with ballast material, so that the mat does not float up. An impermeable foil flap is applied to one side of a mat element that is pulled over the next mat element to prevent short-circuit flow of groundwater between two mat elements. Finally, the mats are equipped with lifting loops.

The empty mat elements were transported to the location in September 2020. These were filled on site by contractor Jan de Nul/Envisan with the adsorption material (biochar or turf peat) and ballast material (fine gravel). The compartments were then sewn shut with a so-called sewing alder and the mats were hoisted into the canal and attached to the banks (see 2nd and 3rd image of Figure 22). The mats filled with biochar were used over a channel length of 65 meters (segment 1 and 2, northern part, mat 1-16) and the mats filled with turf peat were used over a length of 45 meters (segment 3, southern part, mat 17 -27). The total length of the construction is therefore approximately 110 meters. The mats are mainly located on the canal bottom with a small folding area on the banks. The mats are anchored to the bank with loops and pins.

Figure 23 shows the entire trajectory and the 27 individual mat elements can be distinguished (shaded in red).



Figure 22. Filling and applying the reactive mats in the Lieve



Figure 23. Route and location of the mat elements in the Lieve

The following emerged from the design-related preliminary research, the design process and the construction:

The flux

- measurements with the vertical flux samplers in combination with the adsorption capacity tests in the laboratory provide relevant input for the final design (mat thickness and service life); Close consultation
- between environmental advisor, contractor and producer is essential for a feasible custom design of an innovative construction; Furthermore, the design and
- construction of a reactive mat is not possible without knowledge of the specific location characteristics (slope angle, channel dimensions over the entire route, water depth, vegetation/trees, accessibility, bank completion, etc.); Filling the compartments in
- the mats under gravity using a ramp met platform (een 'ramp') verliep goed, maar was arbeidsintensiever en kostte meer tijd dan thought in
- advance; Biochar can easily be atomized. Filling during a period with wind is therefore difficult. Moistening can help prevent atomization but makes it more difficult to fill the compartments;

The upward force

- of the adsorbent provides buoyancy. To compensate for this, ballast material is applied. In the case of some mat elements, more ballast material was required than previously calculated to prevent floating. This has been dealt with by additionally providing one or two of the compartments per mat with an impermeable tube with ballast. The adsorbent content per mat therefore varies from 76 to

87%.

3.3 RESULTS

3.3.1 Monitoring results and interpretation

3.3.1.1 Introduction

This is in line with the measurement strategy as set out in section 3.2.2.2.2. After recording the baseline situation (February June 2020) and the construction of the reactive mat construction (September October 2020), 8 measuring rounds were carried out with regard to the surface water, 4 measuring rounds with regard to the groundwater, 3 measuring rounds with regard to micro-organisms and 2 flux measurement rounds on the mat elements.

For the location of the monitoring wells and surface water measuring points, please refer to Figure 24.

The periodically carried out field measurements, sampling and chemical analyzes are reported in various reports

- from: RSK (surface water and groundwater):
- appendix 3.1; Avecom (qPCR)
- analyses): appendix 3.2; iFLUX (flux measurements): appendix 3.3.

Progress reports with interim evaluations have also been periodically drawn up by TAUW (not included in this report). The quantitative results of all measurements and chemical analyzes relating to groundwater and surface water are included in table form in Appendix 3.4, as well as the logbook (situation description at the time of the measurement rounds).

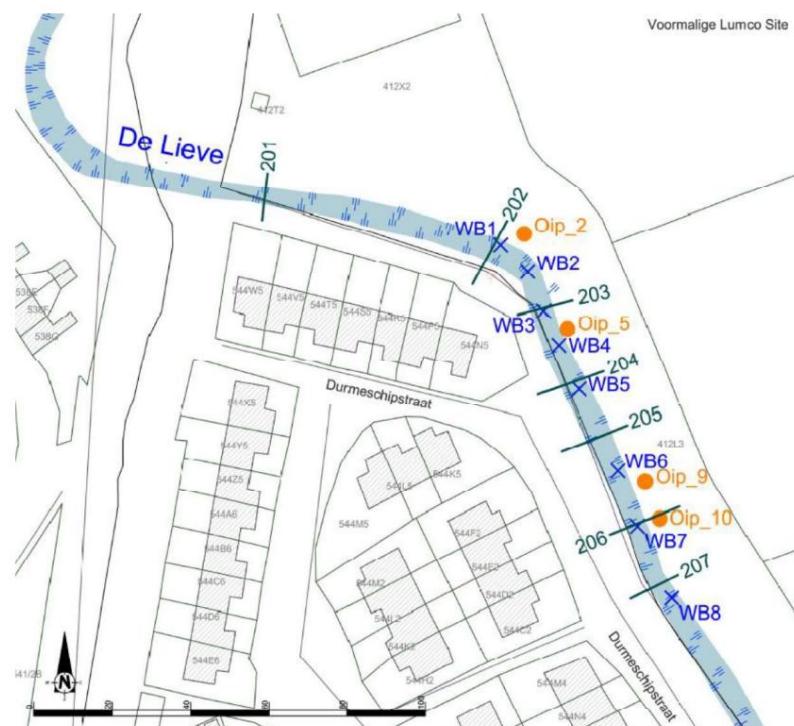


Figure 24. Location of monitoring wells (OIP2/PB20; OIP5/PB50; OIP9/PB90; OIP10/PB100) and surface water measuring points (201-207; measuring point 208 is located 460 meters downstream of 207)

The following section 3.3.1.2 first discusses the general picture: what was the effect of the reactive mat on surface water quality? The subsequent section 3.3.1.3 includes a graphical representation of the development of critical parameters in the surface water with respect to time and space and zooms in further on the causes, by making a connection with the groundwater quality, the groundwater type, head differences, microorganisms and degradation parameters, site-specific conditions and the physical condition of the reactive mat construction.

3.3.1.2 Effect on surface water quality

In general, the quality of the surface water has improved considerably after the installation of the reactive mat construction with the green adsorbent (Natural CatchTAUW).

An efficiency of 80 to 99% was achieved for a longer period of time (5 of 8 measurements) for PAH (lower limit determined by acenaphthene), volatile mineral oil (C5-C10) and BTEX. An exception to this is benzene with an efficiency of 70-80%. Efficiency in % is expressed as $100 \cdot (1 - Ct/C0)$, where:

- Ct = the concentration in the surface water at time t , and
- $C0$ = the concentration in the zero situation (i.e. without mat construction).

For PAH, based on the laboratory tests (see section 3.2.1.4), a yield of 85-97% was expected (lower limit determined by acenaphthene). For benzene and C5-C10 this was approximately 75%. Benzene was also expected to adsorb the least strongly due to the lowest organic matter partition coefficient in water (kom or koc). The expected returns therefore correspond relatively well with the measured returns in De Lieve.

Furthermore, it can be stated that the biochar mat elements generally show a higher efficiency for BTEX and C5-C10 than peat (= turf peat). For PAH, the yield of biochar and peat is comparable.

In the 2nd year after the installation of the reactive mat construction, there are clearly two intermediate periods (a total of 3 measurements) with a clear decrease in the purification efficiency compared to the efficiency as outlined above. These concentration increases in surface water are further discussed and explained in the following paragraphs.

3.3.1.3 Graphic processing and interpretation

3.3.1.3.1 Surface water

General

Table 7 lists the general conditions at the Lieve during the measurement rounds. It follows, among other things, that the direction of flow of the surface water is always towards the harbor (ring canal), at a speed of 23-100 m/h. In the week prior to sampling, cumulative rainfall never exceeded 12 mm, which means that dilution as a result of precipitation or as a result of rainwater from the overflow is generally limited. It is also noticeable that oil films are occasionally observed on the water surface (this will be discussed in more detail later in the text).

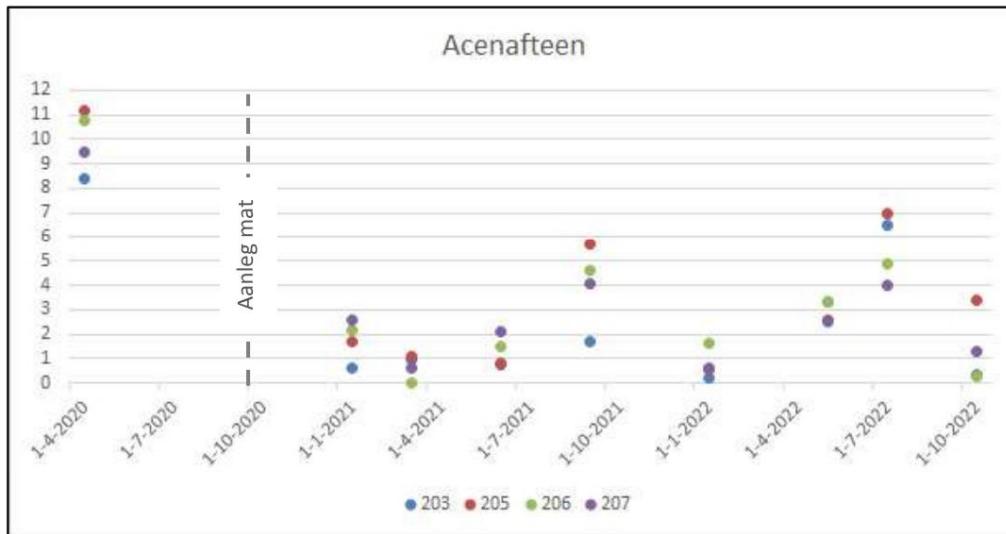
Datum	Flow direction	Weather during sampling	Precipitation prior week (mm)*	Other
3-2-2020	.	Cloudy*	.	.
30-3-2020	.	Clear*	0	.
4-6-2020	.	Cloudy and light rain*	0	.
5/11-1-2021	Towards harbour; light current	Dry and cloudy	12	Oil films between MP 206 and 207
26-3-2021	.	Partly cloudy and a shower*	2	.
2-6-2021	No current	Dry and cloudless (sunny)	7	.
27-9-2021	Towards harbour; light current approx. 100 m/h	Cloudy and partly rain	1,5	No oil film observed
6-1-2022	Towards harbour; approx. 100 m/h	Sunny, dry and windless	3,5	Small oil stains at 205 and 208
17-5-2022	Towards harbour; approx. 23 m/h	Sunny and dry	1	.
12-7-2022	.	Sunny and dry	0	.
26-10-2022	Towards harbour; approx. 43 m/h	Partly cloudy and dry	5,5	bulging mats, oil stains at 203/205

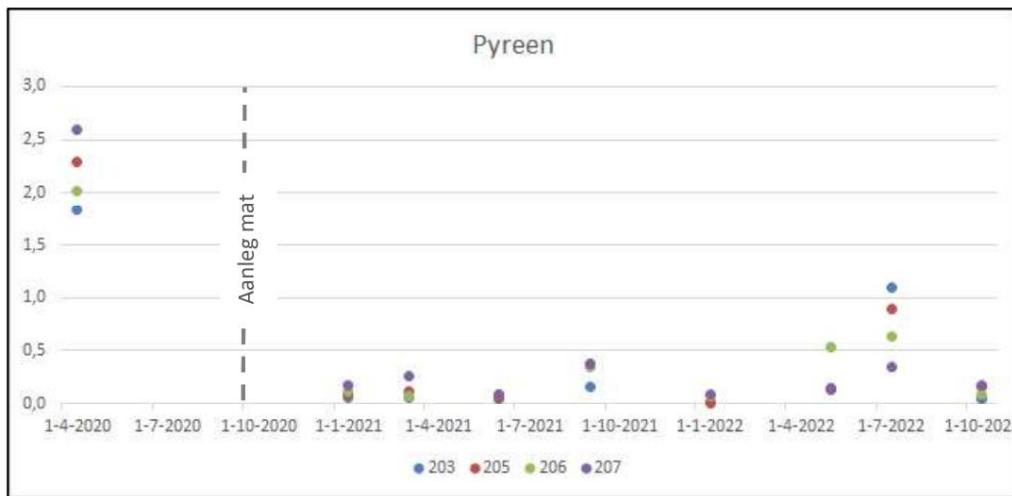
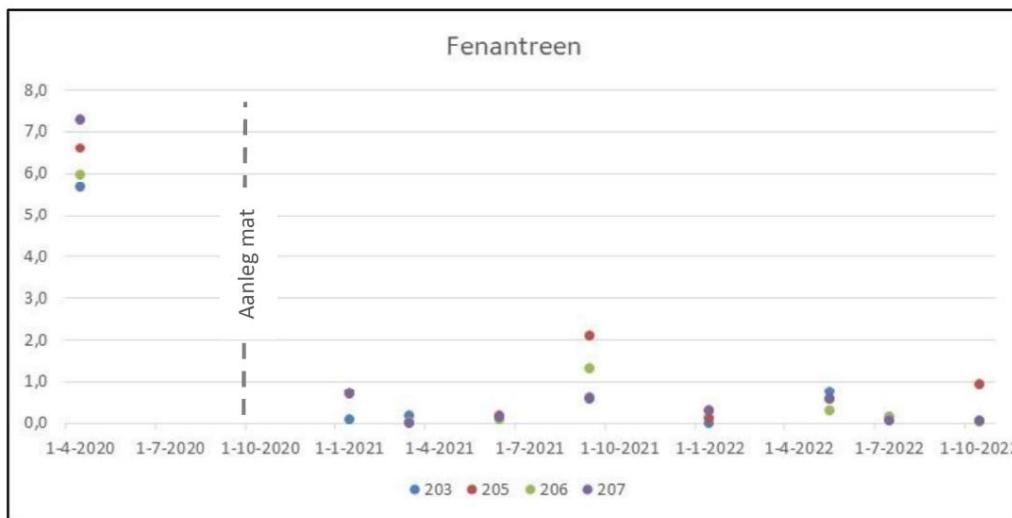
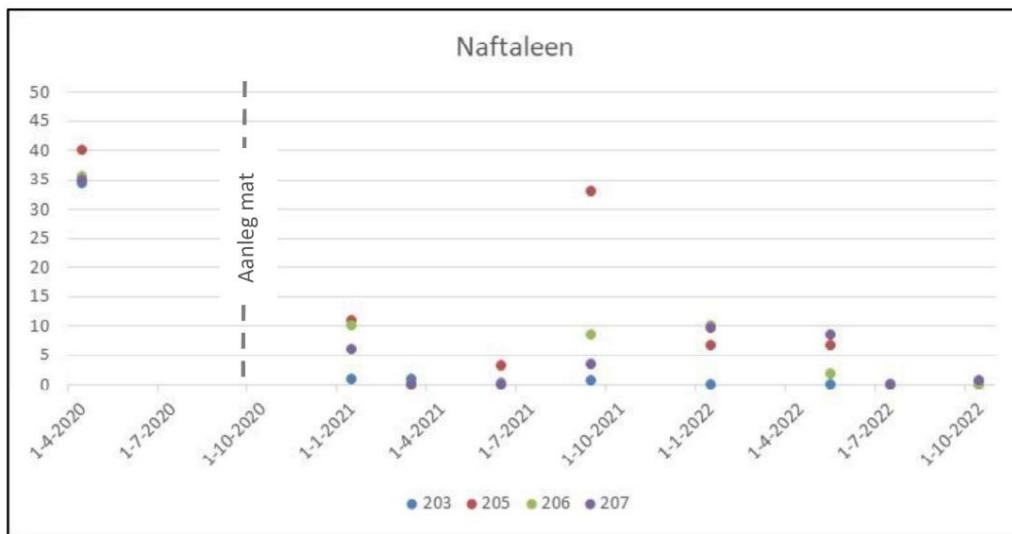
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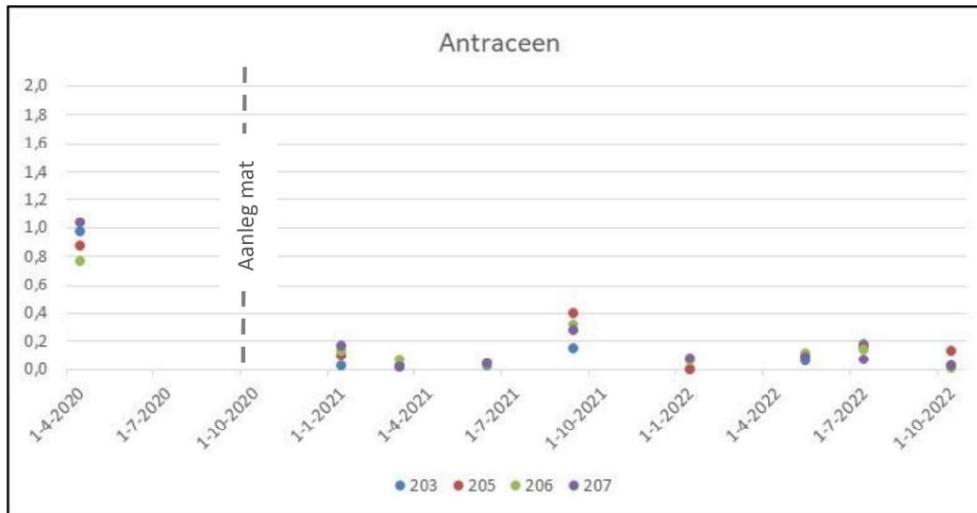
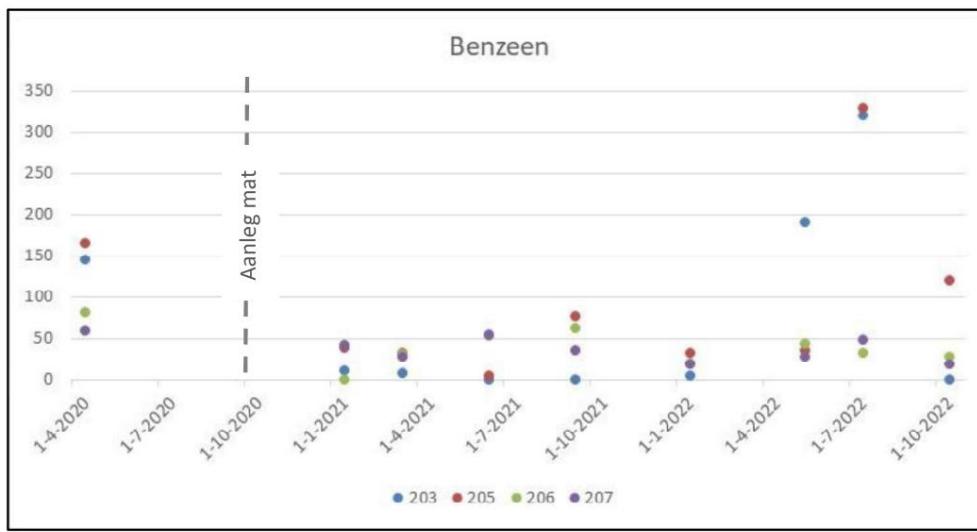
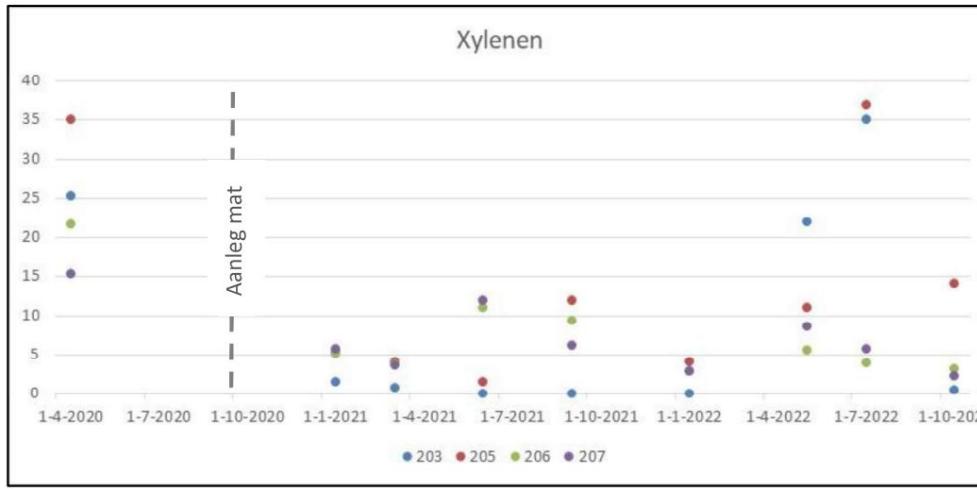
Table 7. Logbook regarding the situation at the Lieve during measurement rounds

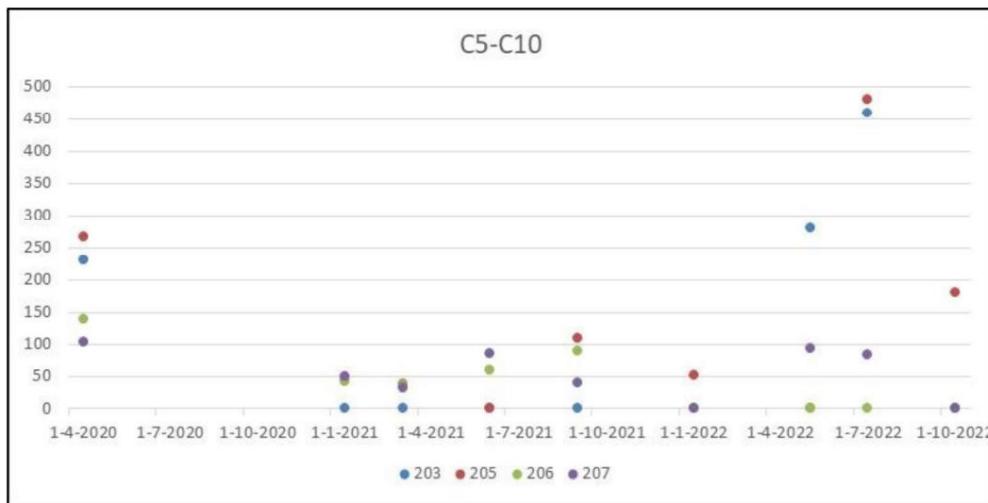
Pollution

In Figure 25 to Figure 32 the concentration ($\mu\text{g/l}$) of the normative and critical contaminants in the surface water above the mat construction are shown as a function of time (critical contaminants are defined as substances that occur in groundwater in high concentrations compared to the environmental quality standards of surface water and/or their high mobility. Measuring points 203 and 205 are located above the mats filled with biochar. Measuring points 206 and 207 are located above the mats filled with peat. The zero situation is always depicted on the far left of the figures: the average concentration of 3 measurements in the period February-June 2020. This is the reference situation without a reactive mat.

Figure 25. Acenaphthene ($\mu\text{g/l}$) in surface water per measuring point over time

Figure 26. Pyrene ($\mu\text{g/l}$) in surface water per measuring point over timeFigure 27. Phenanthrene ($\mu\text{g/l}$) in surface water per measuring point over timeFigure 28. Naphthalene ($\mu\text{g/l}$) in surface water per measuring point over time

Figure 29. Anthracene ($\mu\text{g/l}$) in surface water per measuring point over timeFigure 30. Benzene ($\mu\text{g/l}$) in surface water per measuring point over timeFigure 31. Xylenes ($\mu\text{g/l}$) in surface water per measuring point over time

Figure 32. C5-C10 ($\mu\text{g/l}$) in surface water per measuring point over time

In Error! Reference source not found. is the average purification efficiency of the 4 measuring points (203, 205, 206 and 207) included per substance per measurement round.

	5-1-21	26-3-21	2-6-21	27-9-21	6-1-22	17-5-22	12-7-22	26-10-22
Acenafteen	82%	93%	87%	61% ↓	93%	70%	43%	87%
Pyrene	95%	94%	97%	86% ↓	97%	89%	64%	95%
Phenanthrene	92%	99%	98%	82% ↓	97%	91%	98%	96%
Naphthalene	81%	99%	98%	70% ↓	82%	88%	100%	99%
Anthracene	88%	96%	96%	68% ↓	96%	90%	84%	95%
Benzene	75%	73%	59%	54% ↓	80%	37%	-36%	66%
xylene	80%	86%	66%	70%	89%	50%	25%	82%
C5-C10	75%	81%	67%	63% ↓	90%	37%	-17%	78%

Table 8. Average purification efficiency (n=4) per substance per measurement round

Explanation

Orange: drop below 50% efficiency

Red: decrease to a negative return, concentration > zero situation

Figure 25 to Figure 32 and Table 7 show that a drop in returns can be seen at two points in time. This concerns September 27, 2021 and May 17 and July 12, 2022 consecutively. On September 27, 2021, there is a yield of 54-70% for benzene, xylenes and C5-C10 and for PAH from 61-86%. The loss of yield in the second period (May-July 2022) is more serious: for benzene, xylenes and C5-C10 a yield remains of -25% to -36% (concentrations partly higher than the zero situation) and for acenaphthene and pyrene of 43 and 64%.

The cause of the decrease in efficiency (increase in concentration in surface water) for all substances in September 2021, which may have cautiously announced itself as early as June 2021 for non-PAH substances, turned out to be a short-circuit flow of contamination via the seam between 2 mat elements, at the water outlet and the connection of the structure to the concrete of the water outlet. Based on visual inspection, it was found that the waterproof flap over the seam of two mat elements and the connection to the outlet had shifted, probably due to the flow of abundant rainwater from the water outlet. In December 2021, the geotextile was first properly laid again, extra waterproof foil was applied and then permanent ballast was placed on the connections in January 2022 to prevent shifting.

Flux measurements in November 2021 showed that the mats were not saturated and penetration of contamination through the adsorption material was not an issue (see [Figure 32](#) in this paragraph). As a result of the presence of pure product in the water bottom directly under the mat construction and its escape into surface water, it appears that short-circuit current has major consequences (see also Figure 33).



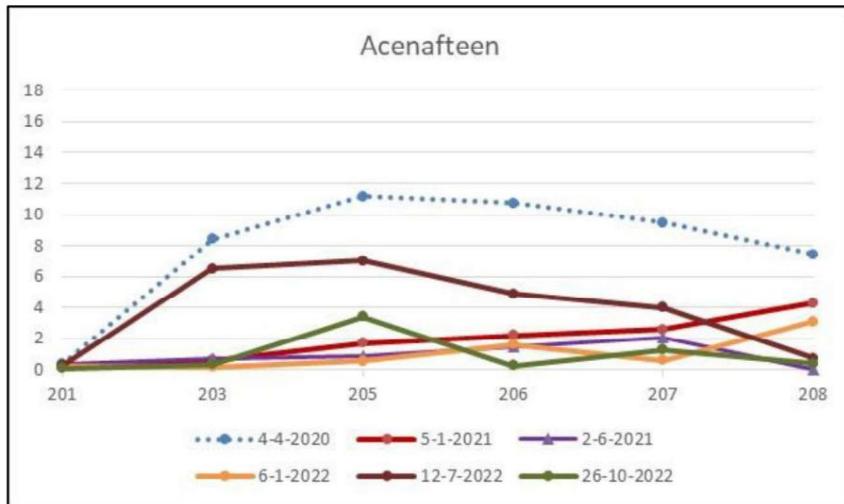
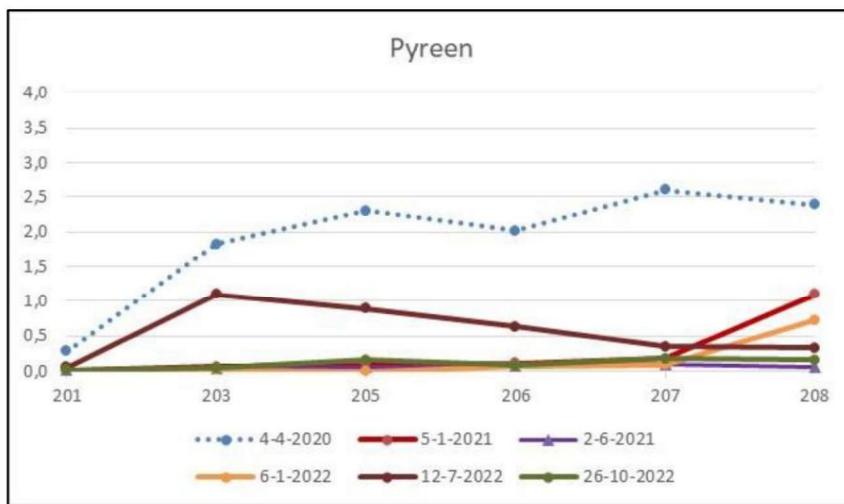
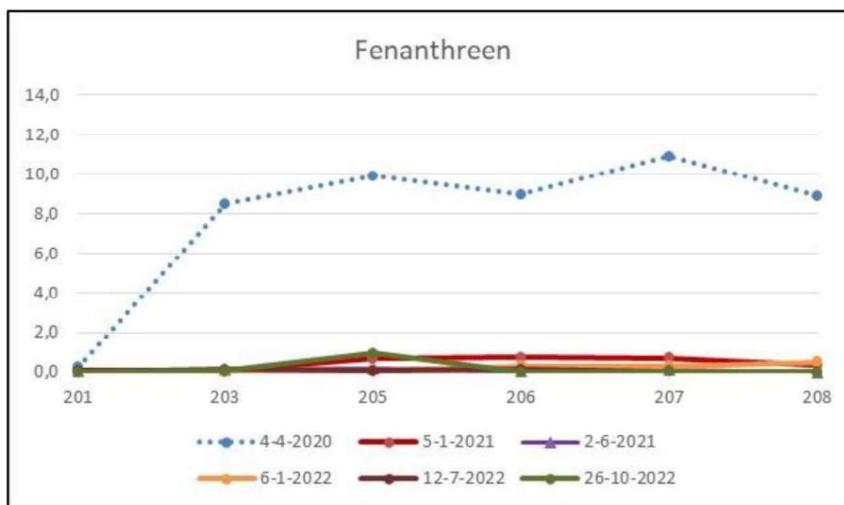
Figure 33. Location of short-circuit current at the end of 2021 and observation of pure product

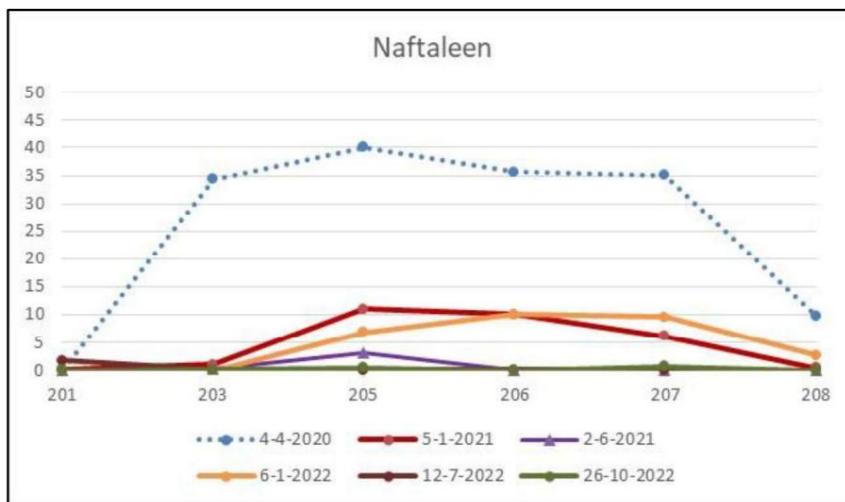
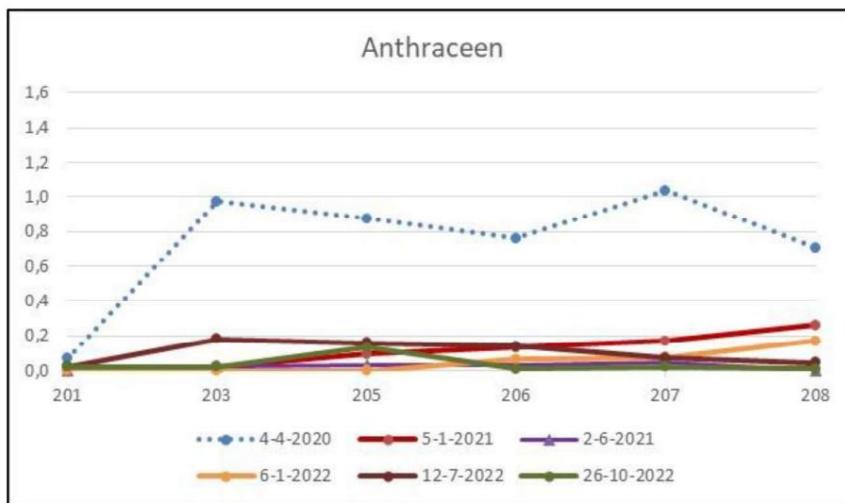
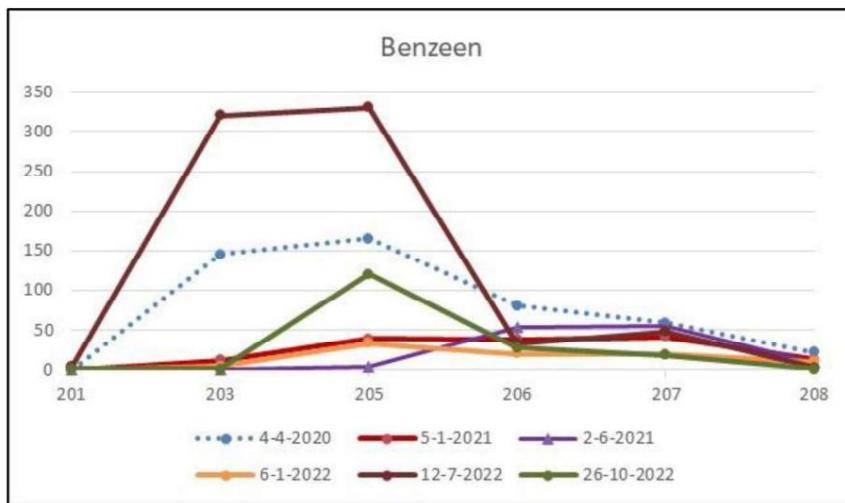
That the local adjustment to the mat construction has the desired effect is evident from the measurement on January 6, 2022, which again shows an expected return.

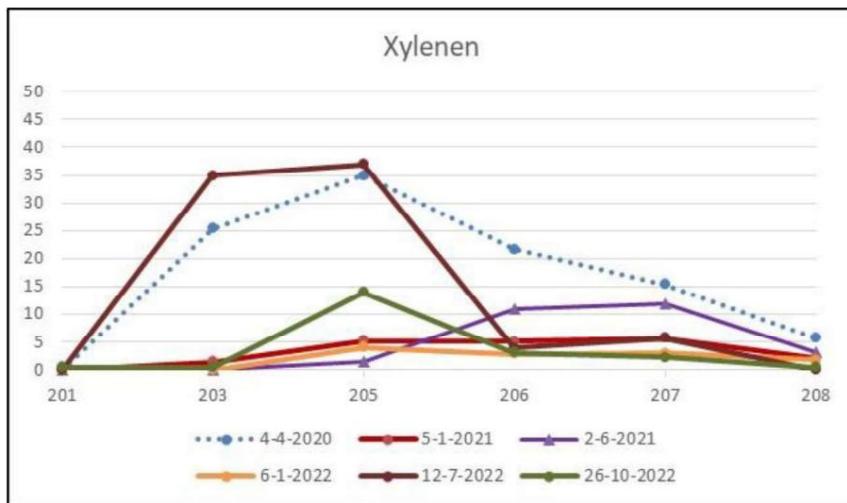
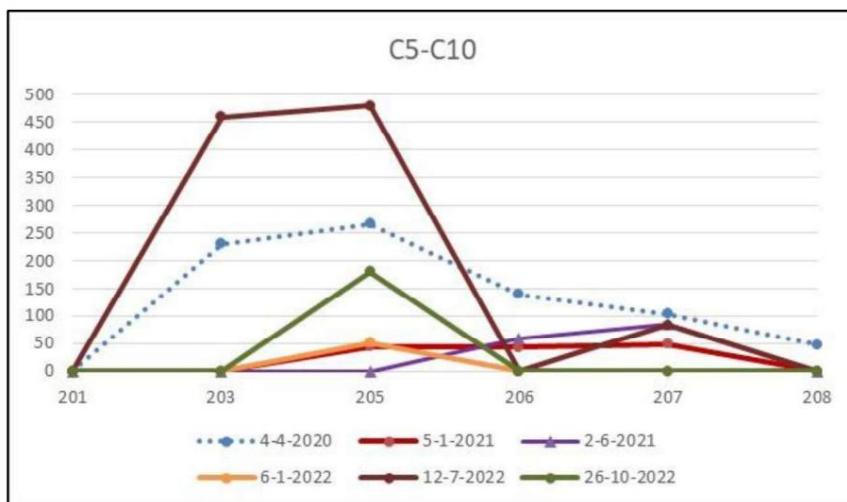
The loss of return during the second period appears to be more complex to explain. An inspection was carried out in the Lieve by Envisan and although the mat still connects well to the water outlet, it appears that pure product and gas bubbles are released when walking on the mat and that there is still movement in the mat elements (particularly mats 8 and 9 near the overflow). The gas (methane gas, carbon dioxide and hydrogen sulfide) is formed by biological activity in the waterbed under the mat construction and is temporarily trapped in the geotextile by upward pressure. It has been noted that the release of pure product takes place across the entire width upon entry, not just at the banks.

At the same time, this cannot be the only explanation, since this time concentrations of some substances are even measured in the surface water that are higher than during the zero situation without a reactive mat and we also see changes in the composition of both oppervlaktewater als grondwater (zie kopje 'Watertype' en paragraaf 3.3.1.3.2 'Grondwater'). Dit has to do with the more extreme precipitation deficit in this period, resulting in a temporarily higher vertical upward flux (seepage) of more contaminated deeper groundwater and pure product, and a reduced inflow of shallow groundwater (originating from the depth of the monitoring filters up to 5 m -mv). This will be discussed in more detail later in the text.

Figure 34 to Figure 41 shows the spatial concentration development ($\mu\text{g/l}$) over the entire monitored stretch of the Lieve, i.e. upstream of the mat construction (measuring point 201), at the location of (measuring points 203, 205, 206 and 207).) and downstream of the mat structure. For readability in the graph, the distance between the measuring points has been chosen to be the same, given the large distance of the other measuring points to measuring point 208. The entire measuring route has a length of approximately 610 meters, with measuring points 201, 203, 205, 206 and 207 cover the first 150 meters. The average reference or zero situation was established on April 4, 2020 (the dashed blue line).

Figure 34. Acenaphthene ($\mu\text{g/l}$) in surface water over the entire measuring rangeFigure 35. Pyrene ($\mu\text{g/l}$) in surface water over the entire measuring rangeFigure 36. Phenanthrene ($\mu\text{g/l}$) in surface water over the entire measuring range

Figure 37. Naphthalene ($\mu\text{g/l}$) in surface water over the entire measuring rangeFigure 38. Anthracene ($\mu\text{g/l}$) in surface water over the entire measuring rangeFigure 39 . Benzene ($\mu\text{g/l}$) in surface water over the entire measuring range

Figure 40 . Xylenes ($\mu\text{g/l}$) in surface water over the entire measuring rangeFigure 41. C5-C10 ($\mu\text{g/l}$) in surface water over the entire measuring range

The concentration development over the entire measuring route shows

- the following: At measuring point 201, upstream of the reactive mat construction, only PAH is found in slightly elevated concentrations during the entire measuring period. This means that a limited or negligible part of the contamination, prior to the influence by the former Lumco site, is present in the surface water of the Lieve.
- The graphs show at a glance that there has been an improvement in water quality compared to the situation without a mat, with the exception of the period around July 12, 2022.
- It is also notable that on July 12, 2022, the concentration of benzene, xylenes and C5-C10 at the measuring points 203 and 205 (biochar mats) is higher than during the zero situation.
- The surface water quality at downstream measuring point 208, just before the Lieve enters the harbor water (the ring canal), is continuously better in the situation with the reactive mat than in the situation without the reactive mat. Nevertheless, fluoranthene (0.47 $\mu\text{g/l}$), pyrene (0.16 $\mu\text{g/l}$) and acenaphthene (0.38 $\mu\text{g/l}$) still exceed the EQS standard here in October 2022 (0.12, 0.04 and 0.04 respectively). 0.06 $\mu\text{g/l}$ with a factor of 4 to 6.

Fluxmetingen

After the clearance of the Lieve, iFlux carried out vertical flux measurements through the waterbed and through the mat construction at three moments:

- Initial measurement in February 2020 without mat construction (baseline measurement);
- In November 2021 and July 2022: 2 'mat' flux samplers t.h.v. meetpunten 203 en 205.

With regard to the construction and location of the mat-flux sampler, reference is made to Figure 42. The samplers are placed on the biochar mats using a reinforced construction. A week after installation, these were collected again and the sorbent materials from the flux samplers were analyzed for tracers and contaminants and the flux direction and size were determined.

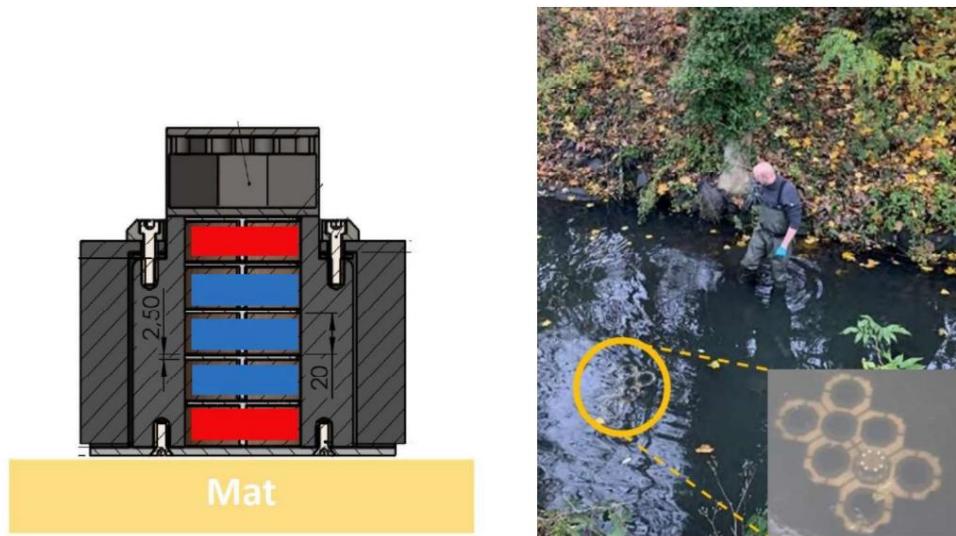


Figure 42. Mat-flux sampler (red: sorption mass flux; blue: sorption and tracers water flux) and location in the Lieve

For the relevant reports from iFLUX, please refer to appendix 3.3.

The water flux measurements always show an upward flux, or an inflow of groundwater via the waterbed to the surface water:

- Zero measurement (without mat): maximum 0.73 cm/d
- November 2021: 0,7-1,0 cm/d
- July 2022: 1.56 cm/d (only measuring point 203; 205 has risen above the water surface)

Table 9 includes the mass flux of substances that have been detected in levels above the reporting limit.

	Benzeen (mg/m²/d)	Naftaleen (mg/m²/d)	Acenafteen (mg/m²/d)
Nulmeting 2020	11,8	28,4	7,24
November 2021	0,25	<0,06	<0,06
Juli 2022	0,63	0,20	0,13

Table 9. Vertical mass flux results for substances above the reporting limit

It can be deduced from the results in table 9 that the initial mass flux as determined during the baseline measurement prior to the mat construction will not be approached in November 2021 and July 2022 in the situation with the mat construction. In other words: the reactive mat elements are not yet saturated. However, the mass flux increases slightly in July 2022 compared to November 2021 for benzene, naphthalene and acenaphthene, respectively. Although this concerns only 2 measurements in the time after installation of the reactive mat, but at the location of the highest inflow of contamination. This supports the hypothesis that the fluctuations in surface water concentrations are 'caused by local short-circuit currents (see pollution section; after all, the measured fluxes through the mat show that there is no saturation of the mat elements and the associated breakdown to high concentrations in the surface water.

Water

During sampling, the conductivity and redox potential of the surface water were measured, among other things. The results are included in Figure 43 and Figure 44.

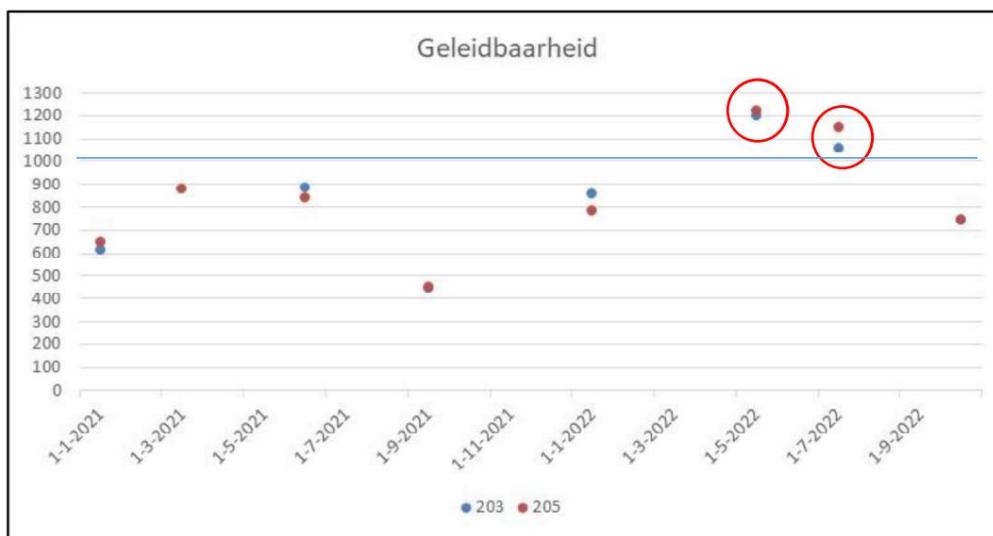


Figure 43. Conductivity ($\mu\text{S}/\text{cm}$) in the surface water above the biochar mats (measuring points 203 and 205)

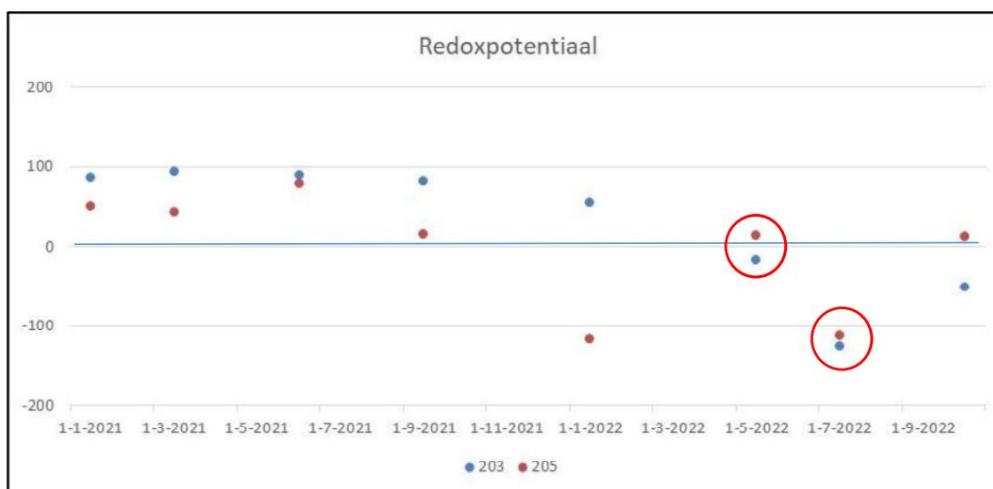


Figure 44. Redox potential (mV) in the surface water above the biochar mats (measuring points 203 and 205)

It follows that the conductivity of the surface water will increase and the redox potential will decrease (reducing iron to sulphate) during the period May-July 2022, in which the concentration of contaminants in the surface water increases sharply. At the same time, the shallow groundwater is becoming less anaerobic, peaking on May 17, 2022. This is shown in Table 10.

	11-1-2021	2-6-2021	6-1-2022	17-5-2022	26-10-2022
Redox (mV)	-188	-104	-57	-11	-125

Table 10. Average redox potential groundwater (pb 20, 50, 90 and 100)

It follows that during that period there is an inflow of a different type of (ground)water into the Lieve. This probably concerns groundwater that seeps up vertically from the highly contaminated soil under the Lieve instead of (shallow) groundwater that is supplied from the direction of the bank (which we monitor). The difference between the groundwater in the bank and the surface water level in the Lieve shows that the Lieve is temporarily not or hardly fed by this groundwater (see section 3.3.1.3.2). Inflow from a more vertical direction with higher concentrations or even pure product explains the aforementioned observation that a surface water concentration was observed for some substances in the period May-July 2022 that is higher than during the zero situation without a mat (obviously in combination with short-circuit flow).

Biological

degradation Water samples taken from the mat surface at measuring points 203 and 205 were analyzed for a number of functional genes that code for specific enzymes for the degradation of BTEX, PAH and aliphatics. This was carried out for the measurement rounds in January 2021, January 2022 and May 2022. The results from January 2021 and May 2022 are included in Figure 45.1 and 45.2 (measurement point 203) and Figure 47.1 and 46.2 (measurement point 205).

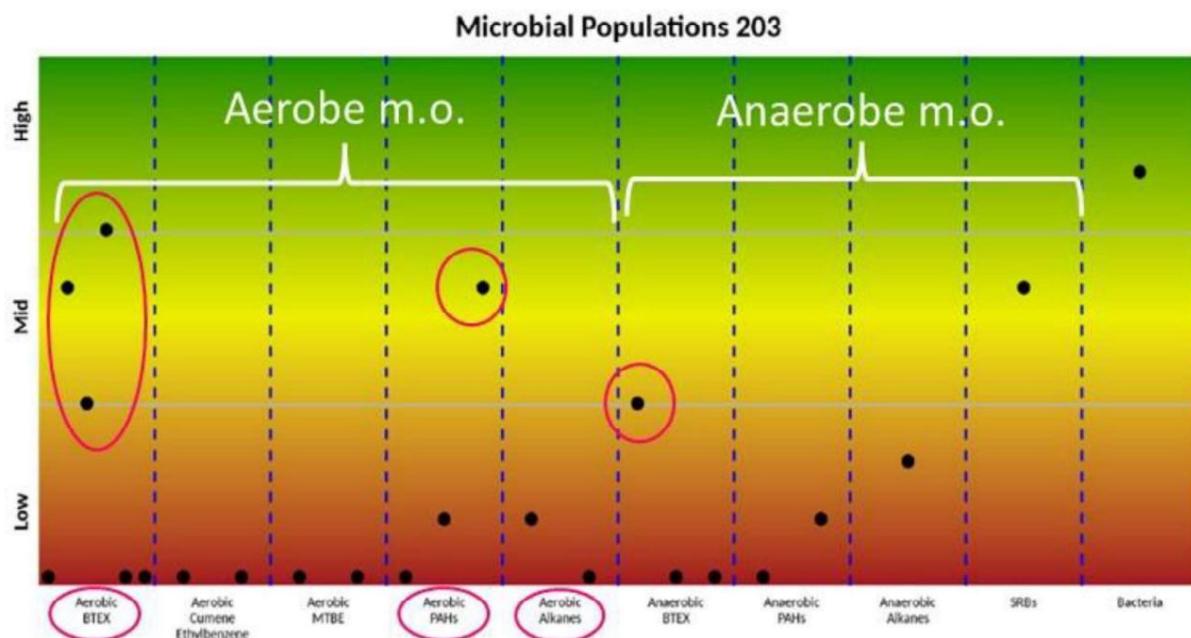


Figure 45.1 Results January 5, 2021 measuring point 203 DNA analysis / qPCR

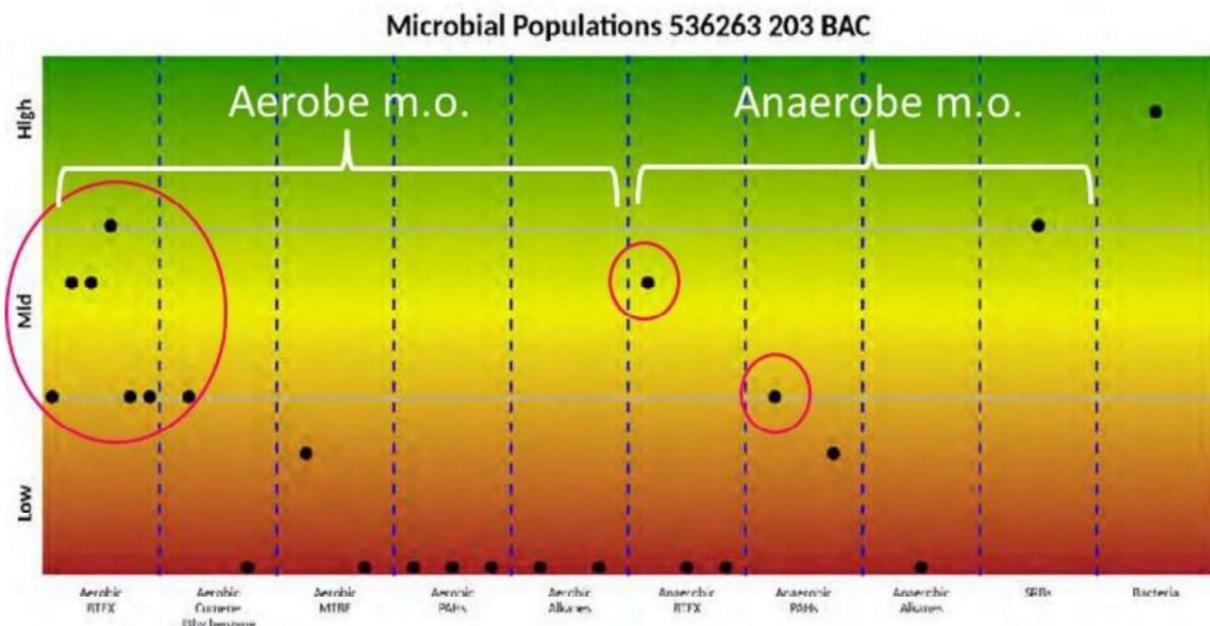


Figure 46.2 Results May 17, 2022 measuring point 203 DNA analysis / qPCR

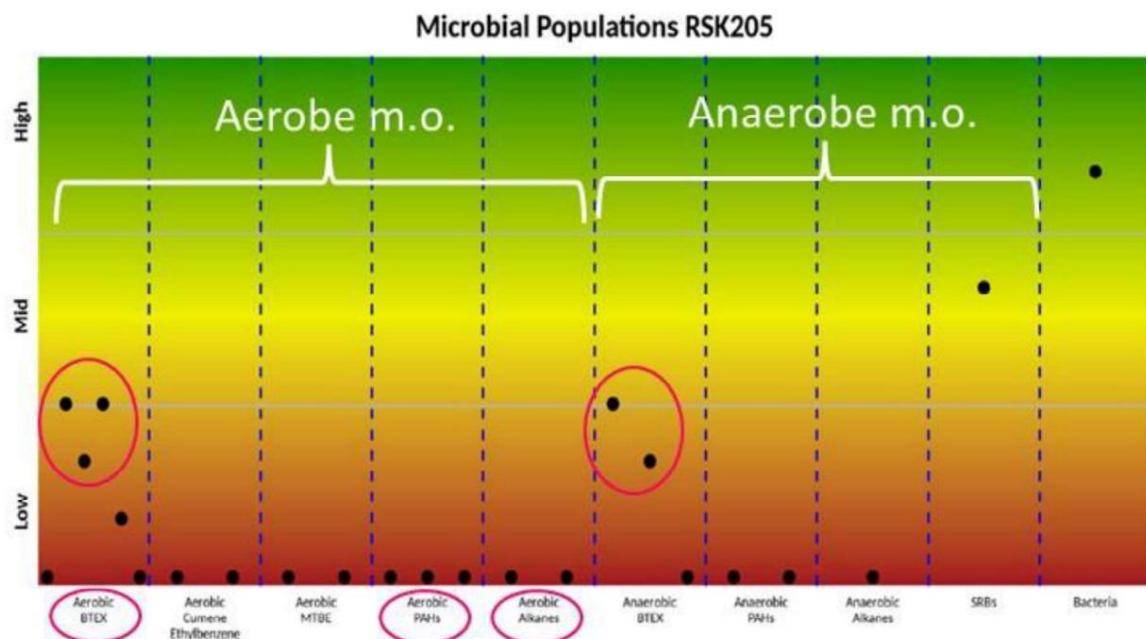


Figure 47.1 Results January 5, 2021 measuring point 205 DNA analysis / qPCR

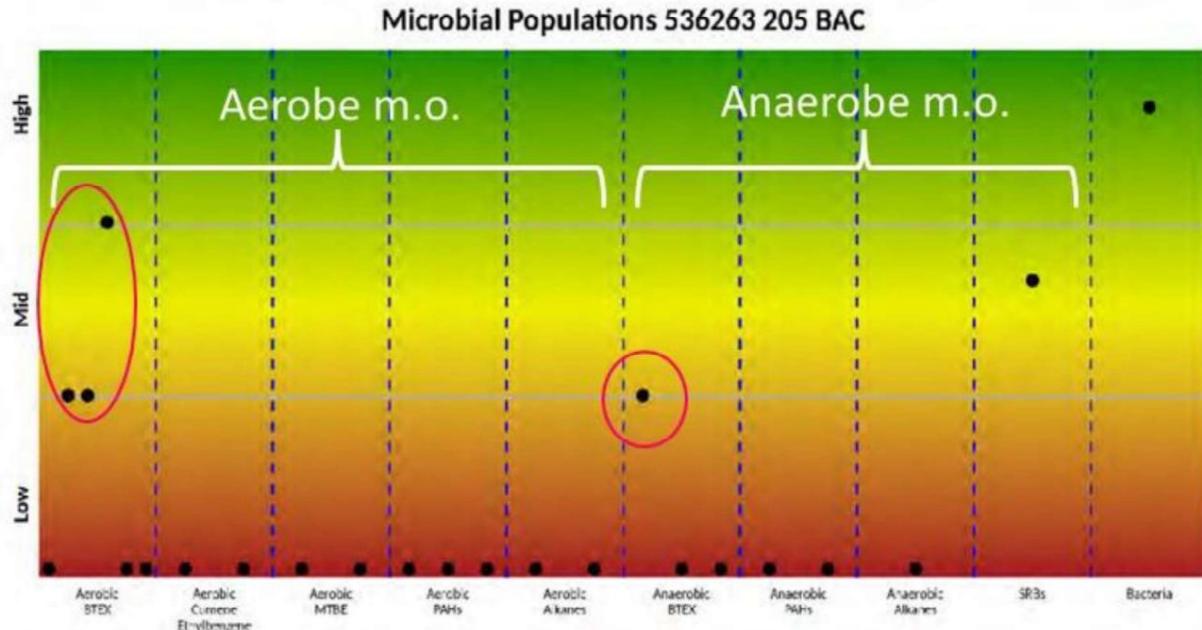


Figure 48.2 Results May 17, 2022 measuring point 205 DNA analysis / qPCR

In the figures, the y-axis shows the extent to which specific micro-organisms occur:

- Low: $<1 \times 10^3$ cells/ml;
- Medium: $1 \times 10^3 - 1 \times 10^5$ cells/ml;
- High: $>1 \times 10^6$ cells/ml.

The x-axis shows the specific micro-organisms, grouped by specific degradation, respectively:

Aerobic BTEX,

- ethylbenzene, MtBE, PAH and alkanes degraders;
- Anaerobic BTEX, PAH and alkane decomposers; Sulfate
- reducing bacteria; Total bacteria count.

The results show the following:

- Aerobic BTEX degraders were found in both measuring points 203 and 205 in generally moderate numbers.
- Aerobic PAH decomposers were only detected in a moderate number in January 2021 at measuring point 203. This could be explained by the fact that PAH are allowed to pass through the mat to a very limited extent.
- Aerobic alkane decomposers are only detected in a low number in January 2021 in measuring point 203.
- Anaerobic BTEX degraders are present in low to moderate numbers at both measuring points.
- Anaerobic PAH degraders were only found at measuring point 203 in May 2022. This may be related to an increase in PAH in surface water in May 2022.
- Sulfate-reducing bacteria are present in moderate numbers.
- The total number of bacteria increased approximately by a factor of 18: in 203 from 3.5×10^6 to 5.8×10^7 and in 205 from 8.3×10^5 to 1.6×10^7 cells/ml.

It can be concluded that in general both the aerobic and anaerobic BTEX degraders are active on and near the mat surface. This makes it clear that both aerobic and anaerobic conditions occur at the groundwater/surface water interface and that degradation of BTEX takes place. The numbers of PAH degraders and alkane decomposers found are nil or low.

The following should be noted here. The total number of bacteria shows that there is a significant increase in activity in May 2022. This can be associated with an increase in contamination concentrations in surface water. It is unclear exactly which bacteria they are, as the lab cannot specify all decomposers (not all genes/enzymes are known). In other words: there may be a higher degradation activity/capacity in May 2022 than is currently apparent from the DNA results.

Another indicator of the microbial degradation of BTEX is the phenolic index. The progression of this is included in Figure 49, which shows that during the high concentrations in the surface water on July 12, 2022, the phenol index is indeed much higher.

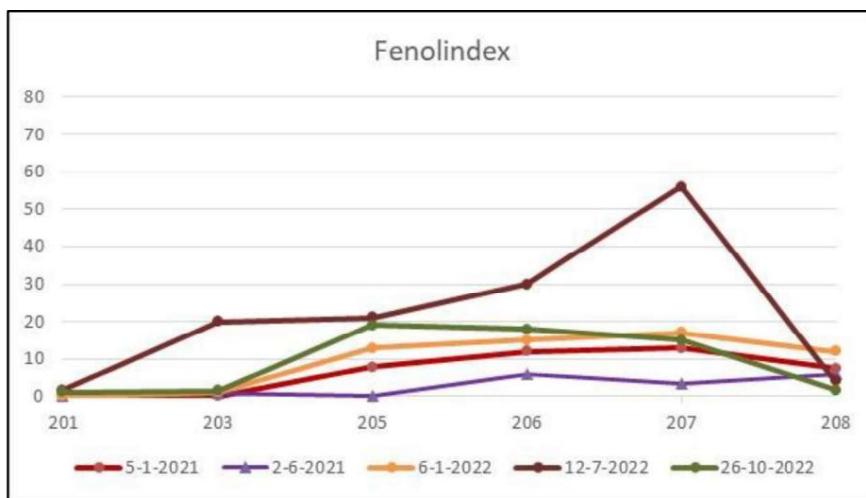


Figure 49. Phenol index ($\mu\text{g/l}$) over the measurement range at different times

3.3.1.3.2 Groundwater

Contamination

Figures 50 to 51 show the concentration ($\mu\text{g/l}$) of the normative and critical contaminants in the groundwater in monitoring wells 20, 50, 90 and 100 at different times.

(Overview plan: see Figure 24)

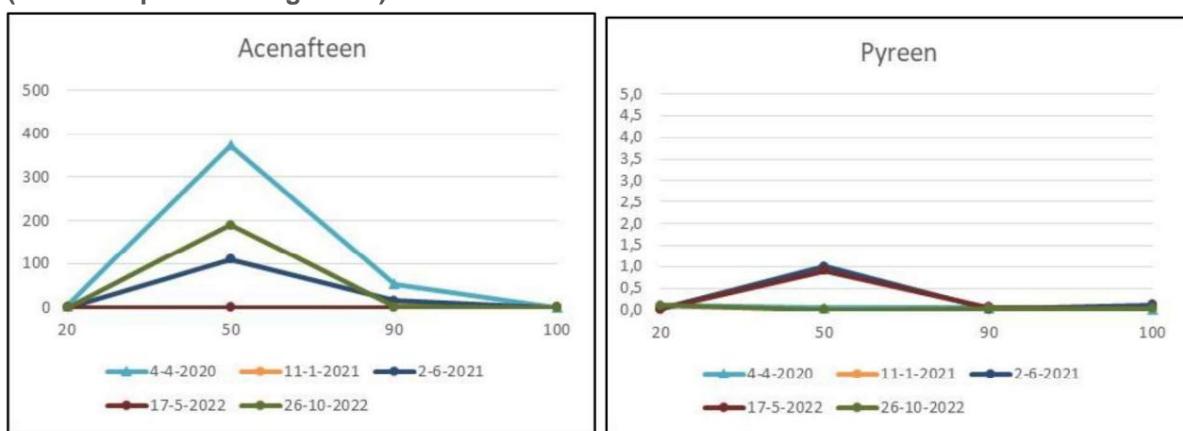
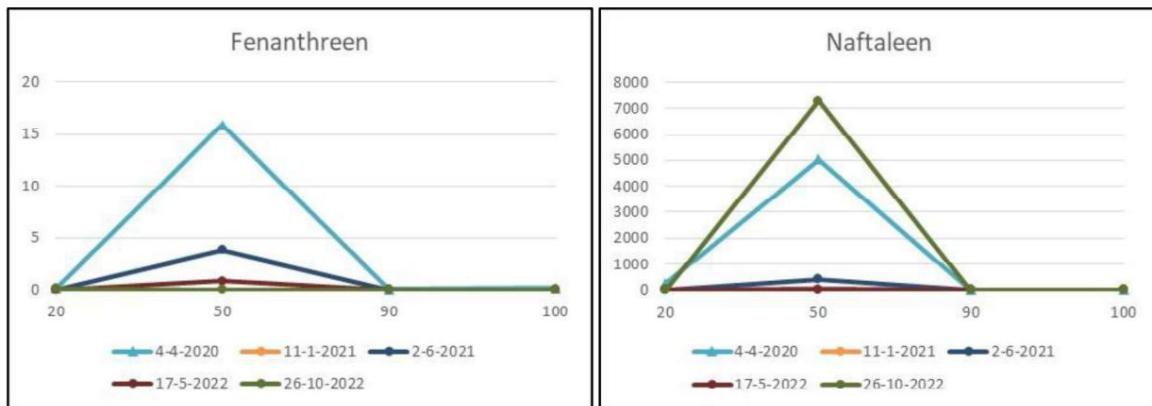
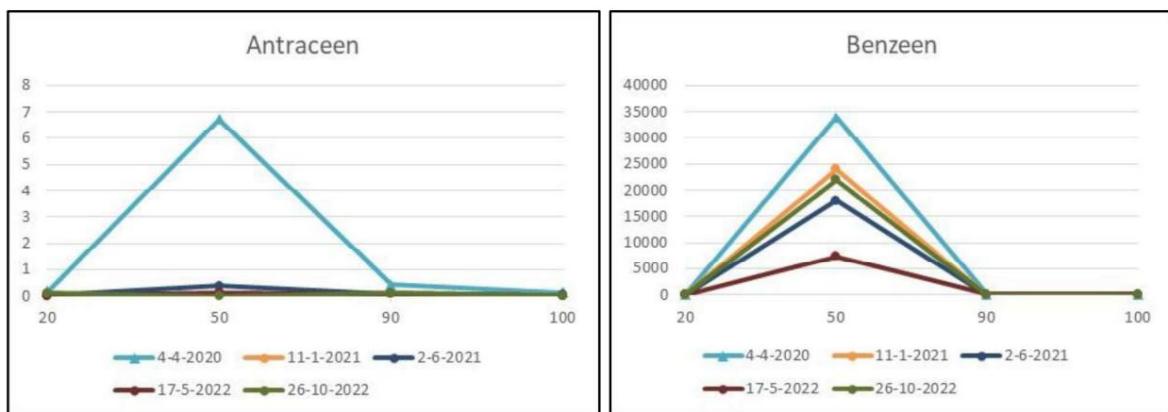
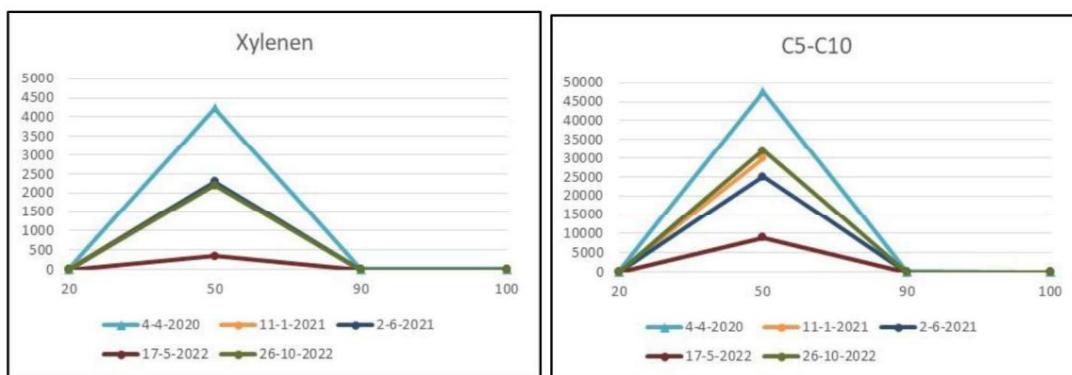


Figure 50. Acenaphthene and pyrene ($\mu\text{g/l}$) in groundwater at pb 20, 50, 90 and 100

Figure 51. Phenanthrene and naphthalene ($\mu\text{g/l}$) in groundwater at pb 20, 50, 90 and 100Figure 52. Anthracene and benzene ($\mu\text{g/l}$) in groundwater at pb 20, 50, 90 and 100Figure 53. Anthracene and benzene ($\mu\text{g/l}$) in groundwater at pb 20, 50, 90 and 100

It is striking that in the baseline situation (4-4-2020), prior to the installation of the reactive mat, the highest concentrations were found in the groundwater for most substances. It is also striking that by far the lowest concentrations were found in the groundwater in the monitoring wells in May 2022. While the highest concentrations were detected in surface water in May 2022. This corresponds to the assumption that at that time, as a result of the drought, the surface water is mainly fed by the deep groundwater directly under the Lieve (seepage) and not by the groundwater from the direction of the bank in which the monitoring wells are located (see paragraaf 3.3.1.3.1, 'Pollution').

After the low groundwater concentration level in May 2022, it will recover to a medium to high level, although it should be noted that only the groundwater in monitoring well 50 contains a strong contamination (e.g. 200 µg/l acenaphthene, 7,000 µg/l naphthalene, 20,000 µg/l benzene and 30,000 µg/l C5-C10 in October 2022) and the groundwater in the other monitoring wells contain little or no contamination.

Head difference

The difference in head height between the groundwater in the monitoring wells in the bank (3-5 m - mv) and the surface water of the Lieve, to determine whether there is groundwater flow towards the Lieve. The results are included in Table 11.

Datum	Waterstand Lieve tov m TAW	Grondwaterniveau OIP 5 (m TAW)	Verhang (m) Grondwater - Lieve
3-2-2020	-	4,521	-
30-3-2020	-	4,531	-
4-6-2020	-	4,331	-
5/11-1-2021	4,66	4,961	0,301
26-3-2021	4,68	5,011	0,331
2-6-2021	4,70	4,961	0,261
27-9-2021	4,63	4,831	0,201
6-1-2022	4,72	4,681	-0,04
17-5-2022	4,81	4,791	-0,02
12-7-2022	4,70	5,031	0,331
26-10-2022	4,63	4,781	0,151

Table 11. Water levels of groundwater and surface water and head difference (slope)

It can be seen from the table that during 6 of the 8 measurements there was a gradient of the groundwater on the bank towards the Lieve, varying from 15 to 33 cm. At 2 moments there is no to a slightly negative gradient (no flow of this groundwater towards the Lieve), varying from -2 to -4 cm on January 6, 2022 and May 17, 2022, respectively. This would also be expected to be the case on July 12, 2022, but apparently the groundwater level has (just?) been restored at that time.

3.3.1.4 Summary It has

been shown that a reactive mat construction with green adsorbent (Natural CatchTAUW) can function well and achieve the expected purification efficiencies. For PAH these yields are generally higher than for benzene, xylenes and C5-C10. This is also in line with expectations based on the distribution coefficients of the substances in question. After an operational period of 2 years, biochar does not yet appear to be saturated and/or to reach high concentrations based on the flux measurements carried out.



Figure 54. Impression of the Lieve section with reactive mat construction in January 2022

It has been noted that the efficiency of the current construction depends on the combination

by:

- The mutual connection of mat elements;
- Gas formation in the waterbed and (temporary) accumulation thereof in the mat
- construction; The presence of pure product in the water bottom directly under the
- mat construction; Strong flow of surface water or rainwater from an overflow onto the slab.

As a result, short-circuit flow of groundwater with high concentrations or even pure product can occur, resulting in a rapid decline in purification efficiency and a decline in surface water quality.

3.3.2 Evaluation results

3.3.2.1 Evaluation with regard to achieving the remediation objective

- It has been shown that the use of a reactive mat filled with green adsorption materials (Natural CatchTAUW) such as biochar and peat (sod peat) can significantly improve the quality of a surface water that receives contaminated groundwater with PAH, BTEX and mineral oil. An efficiency of 80-99% has been achieved with optimal operation, with the exception of benzene with an efficiency of 73-80%.
- For eight substances that exceed the environmental quality standard for surface water (EQS value) in the zero situation, the concentration is reduced to below the EQN value when the reactive mat functions optimally: mineral oil (C5-C10), anthracene, phenanthrene, benzo(a)anthracene, benzo(k)fluoranthene, benzo(ghi)perylene, benzo(b)fluoranthene and fluorene. But even with the high efficiency of the reactive mat at optimal operation, this EQS value is not achieved for all substances. The 4 substances to which this applies are acenaphthene, pyrene and fluoranthene (PAH) and benzene. For the PAH in question, this has to do with the relatively low EQS values (0.06, 0.04 and 0.12 µg/l respectively) compared to the relatively high initial concentrations in the surface water (10, 2.2 respectively). and 3.4 µg/l) and therefore the high influx. For benzene, this largely has to do with the mobility of the substance (adsorbs the least) in combination with the relatively high influx; the EQS value in this case is 10 µg/l compared to an initial concentration in the surface water of 112 µg/l (an efficiency of approximately 91% would be required).

3.3.2.2 Criteria for success

The following factors regarding mat construction and environment can negatively influence the successful use of a permeable reactive mat as applied in Ghent:

- Gas formation in the water bottom under the mat construction. Biological activity in the waterbed produces methane gas and possibly also carbon dioxide and hydrogen sulphide under anaerobic conditions. This gas is then (temporarily) captured by upward pressure by the reactive mat:
 - Door insluiting van gas ('gascloggeling') wordt de adsorptiecapaciteit beperkt. A part of the mat, and therefore the adsorption capacity, is therefore inaccessible to the contaminated groundwater and there is a higher flux through the wet parts.
 - The gas bubbles that subsequently escape from the slab can accelerate the introduction of contaminated groundwater, resulting in a more limited contact time with the adsorbent and therefore less adsorption. However, these will be relatively small amounts.
- Removing extra sludge reduces this gas production. This must be taken into account in the feasibility study and during the preparatory clearance of the surface water.
- Mutual connection or connection of the mat elements. If there is insufficient connection or connection between mat elements, short-circuit flow of contaminated groundwater via the seam towards the surface water can occur, without contact with adsorbent and therefore without adsorption. If pure product is present in the waterbed, as is locally the case in the Lieve, short-circuit currents can be disastrous for the surface water quality.
- A liquid-tight foil flap over the seam, both at the bottom (on the water bottom) and at the top, reduces this risk (NB In the design for the Lieve, only a foil flap was present at the top). By weighing down the foil flap at the top with, for example, a ship's chain, the risk of shifting due to surface water currents is prevented. An alternative to weighting is the use of Velcro.
- Presence of pure product in the water bottom directly under the mat. In addition to the aforementioned combination with short-circuit current, the technical life of the reactive mat in the presence of pure product will be more limited than currently calculated (10 years based on dissolved product) due to a faster saturation with contamination. Removing a few extra decimeters of waterbed where pure product occurs and filling it with the same amount of clean sand limits this risk. This must be taken into account in the feasibility study and during the preparatory clearance of the surface water. In fact, the reactive mat is intended for capturing dissolved contamination and not pure product
 - Changes in geohydrology (current paths) as a result of developments in the environment or as a result of climate change. This could include:
 - Installing or removing paving at ground level, resulting in less or more infiltration of precipitation;
 - Installing or constructing vertical sheet pile walls, resulting in disruption of horizontal groundwater transport;
 - Establishing or terminating groundwater extraction; ○ Prolonged droughts.

If these changes are foreseeable, they must be taken into account in the feasibility study and during the design. In the worst case, the use of a reactive mat in the intended location should be avoided.