REPORT

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ACTION: A3 Valorising Activated Carbon from Cellulose (WOW-AC) for Micropollutant elimination in Constructed Wetlands

SUBJECT: D 3.3 Finding most suitable locations for AC-production (larger STP) and possible application in Constructed Wetlands -Case Study

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1 Introduction

Micropollutant have been detected ubiquitously in the aquatic environment. In addition to pesticides and industrial chemicals, pharmaceutical agents used in human and veterinary medicine have become the focus of discussion.

Since a large number of micropollutant cannot be retained in a targeted manner or only inadequately in conventional mechanical-biological sewage water treatment plants, their targeted elimination by means of micropollutant elimination stages (ozonation, adsorption on activated carbon, etc.) is currently being intensively investigated. However, micropollutant elimination stages are mainly used in larger sewage water treatment plants. Simple and robust solutions for smaller sewage water treatment plants are hardly available. However, small sewage water treatment plants sometimes have a major impact on water quality because they discharge into small receiving water bodies. A simple and effective option are constructed wetlands with activated carbon. High elimination efficiencies of 80 % have been demonstrated by (Brunsch et. al, 2018)). Biochar can also be used as an alternative to activated carbon. Biochar is a carbon material that can be produced by carbonisation (pyrolysis: combustion in the low-oxygen environment) of various bio-based materials. Activation of the biochar further increases its surface area, which improves its adsorption capacity. Within the framework of WOW! Project, the production of biochar from cellulose from wastewater (toilettpaper) as feedstock has been proved (WOW, 2020). However, the activation of the biochar showed only low efficiency. Therefore, the pyrolis of Cellulose at low temperature in combination with biological activation was tested. (Vendetti et al., 2023) showed high removal efficiency for a biological activated biochar with 50% biochar and 50% straw. In the following, biologically activated charcoal from a cellulose-straw mixture is referred to as $WOW_{Biochar}$.

In the report, solutions for biochar production (on larger sewage treatment plants (STPs)) and subsequently their use in Constracted Wetlands with $WOW_{Biochar}$ (on smaller STPs) are developed for three different areas in NWE.

2 Description of process technology

2.1 Production of $WOW_{Biochar}$

Sewage water contains a lot of cellulose, which is well suited for biochar production. The share of cellulose in the total COD in the influent of the wastewater treatment plant is about 30% (Ruiken, 2013). Fine sieves can be used to remove the cellulose from the wastewater. It can then be dewatered, dried and pressed into pellets. For the case study, a mixture of cellulose pellets and straw (50% cellulose and 50% straw by volume) was considered to produce biochar, which is carbonised under lack of oxygen at high temperatures and subsequently biologically activated. Studies by (Vendetti et al, 2023) showed the highest micropollutant elimination rates for this biochar.

Cellulose is mainly found in fibrous form in municipal sewage water and can be removed with high efficiency using fine sieves. For cellulose separation, "rotating belt fine sieves" can be used. This involves two processes: Separation of solid particles and their subsequent thickening in a space-saving form.

The sewage water passes through the continuously moving filter belt. The speed of rotation changes depending on the amount of inflowing water. The mesh size can be selected between 90 and 2000 microns, depending on the wastewater quality and purification objective. Suspended solids and solids larger than the pore diameters are retained and help to remove finer materials from the sewage water. The sieveings are washed in a cellulose scrubber and dewatered in a screw press. Figure 1 shows the fine sieve (right) and the cellulose washer (left).

Figure 1: Finesieves in Ede (WOW, 2022)

With the removal of cellulose from the sewage water, the COD-load to biological treatment stage is reduced. The required oxygen demand in the biological stage for oxidation of the carbon compounds and thus the required energy demand is reduced. However, with the use of cellulose for $WOW_{Biochar}$ production, no energy-rich primary sludge is available on the STP that can be used in the digestion stage for biogas production. In the case study, therefore, only STPs on which no primary sedimentation and no digester are installed were considered for the integration of fine sieves.

2.2 Elimination of micropollution with $WOW_{biochar}$ in constructed wetlands

Constructed wetlands are used as a nature-based sewage water treatment technology in rural areas (DWA-A 216, 2006) and for the treatment of discharge water from combined sewer systems (Grotehusmann, 2015). Studies by (Brunsch et al., 2018), showed that with constructed wetlands micropollutants such as heavy metals and pharmaceutical residues can be eliminated in the effluent of a STP by the addition of activated carbon. (Vendetti et al. 2022a, 2022b) demonstrate on a pilot scale level that also high elimination rates for micropollutants can be achieved with the use of biochar in constructed wetlands. (Venditti et al. 2023) showed on a pilot scale that a comparably high elimination performance of 80% on average can be achieved with the biologically activated $WOW_{biochar}$ from recovered cellulose from sewage water. The results show that this nature based technology can achieve comparable elimination rates to technical processes for micro-pollutant removal such as ozonation and GAK filters. Due to the simple design and low operational effort, the use of constructed wetlands with char is particularly suitable for small STPs.

The structure of a conventional constructed wetland for the purification of discharge water from combined sewer systems is shown in Figure 2. The filter body of sand (diameter 0.063-2 mm) has a layer thickness of 0.75 to 1 m. It is dewatered by a drainage system situated below the filter layer (filter gravel 2-8 mm diameter). It is dewatered by a drainage system situated below the filter layer (filter gravel 2-8 mm diameter). Beneath the drainage layer the constructed wetland is sealed against the ground with an impervious membrane. The water can be supplied either from above (vertical fow) or from the side (horizontal flow). Distribution channels ensure an even distribution of the sewage water. As the water percolates through the filter layer, both physical (adsorption) and biochemical (microbiological cleaning) processes take place, purifying the wastewater. In general, constructed wetlands are planted with reeds to ensure a permeable filter surface. (E. Christoffels, 2014).

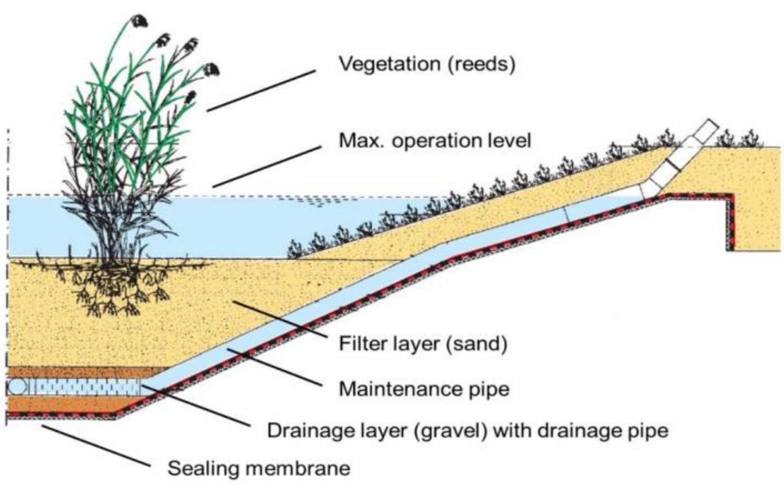


Figure 2: Filter construction of a conventional Retention Soil Filter ((E. Christoffels, 2014))

For the case study, $WOW_{biochar}$ is used for the elimination of micro-pollutants in constructed wetlands. Following (Venditti et al. 2023), a 65 cm high layer with a mixture of 85 vol.% sand with grain size 0-3 mm and 15 vol.% WOWbiochar was chosen for the filter design (see Figure 3). The elimination efficiency of the biologically activated $WOW_{biochar}$ was set at an average of 80 % for micropollutants.

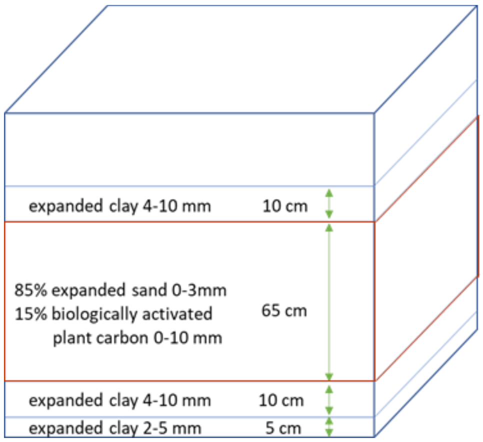


Figure 3: Filter structure of retention soil filter (RSF) with addition of biologically activated plant carbon ($WOW_{Biochar}$)

2.3 Design of constructed wetlands and fine sieves

2.3.1 Constructed wetlands

For the determination of the required filter area of the constructed wetlands with $WOW_{biochar}$, the following two approaches were considered according to (Venditti et al., 2023):

- specific area of 0.4 m²/p.e.
- Average hydraulic surface loading of 200 L/m²/d or maximum hydraulic surface loading of 400 L/m²/d

The largest area was used in the following calculation. Length and width were chosen according to the space available. For the sand and $WOW_{biochar}$ proportions, the ratios according to chapter 2.2 were taken into account. For the calculation of the $WOW_{biochar}$ mass, a char density of 1.500 kg/m³ was used. Figure 4 shows an example of the design of a soil filter for a STP with a connection size of 3.033 p.e..

WWTP	Unit	Haupersweiler
Input Data		
Connected PE	PE	3,033
Annual flow	m^3/a	794,346
Waste water flow to constructed wetland	m^3/a	525,600
Treating process	-	BB/DN/AS
Receiving water	-	OSTER
Wetlands Data		
Area	m^2	3630
Length	m	66
Width	m	55
Filterbody	m^3	2360
Volume: Sand	m^3	2006
Volume: WOW_{Char}	m^3	354
Amount of $WOW_{Biochar}$ (50% straw/cellulose)	kg	530,888
Investment costs without $WOW_{Biochar}$ production costs	€	2,050,801
Transport costs $WOW_{Biochar}$	€	4,202
Transport costs Cellulose	€	-
Total investment costs of constructed wetland	€	2,585,890
Average filter velocity	m/h	0.013
Average Hydraulic Volume Rate	$L/(m^2 \cdot d)$	323.967

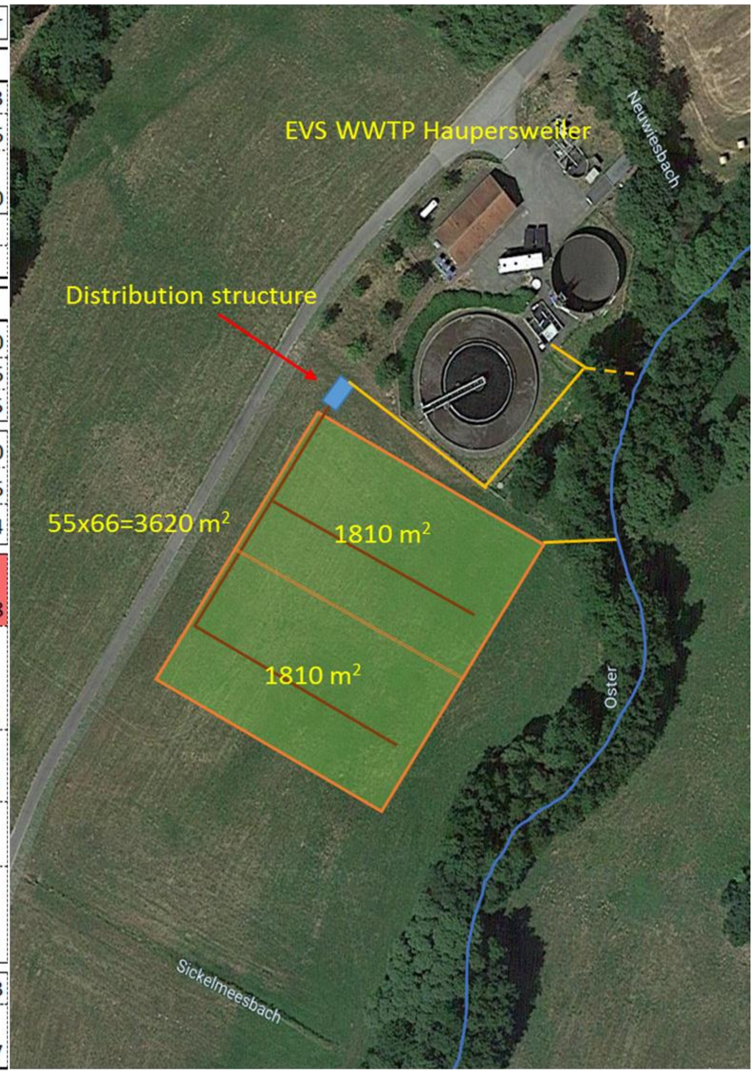


Figure 4: Example for RSF design for small STP Haupersweiler in Catchment area Blies in Saarland (Germany)

2.3.2 Fine sieves

The fine sieves were designed for the maximum sewage water flow. For the maximum hydraulic capacity of a fine sieve module, 484 m³/h was taken from a manufacturer's offer. When determining the number of fine sieve, a reserve module was always included. The purification performance of the fine sieve was determined analogously to a separation performance of a primary treatment with a hydraulic retention time of 1.5-2 h according to (DWA A 131, 2016).

2.4 Investment cost

2.4.1 Constructed wetlands

To determine the investment costs, specific investment costs in €/m² were applied depending on the filter surface area according to (Grotehusmann2015). The investment costs refer to the year 2014 and were extrapolated to the year 2021 with an inflation rate of 6% (conversion factor: 1.689). The cost curve calculated with this data is shown in Figure 5.

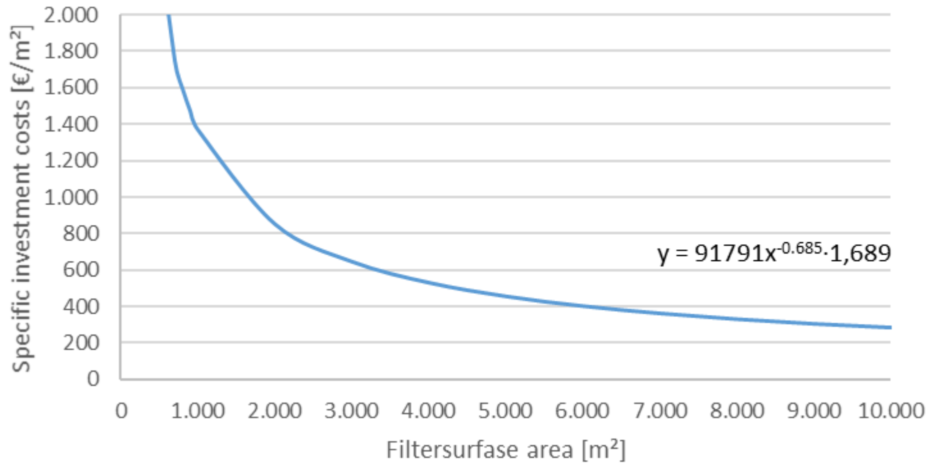


Figure 5: Specific investment costs for constructed wetlands of combined sewer overflows depending on the filter surface area for the year 2021 (modified data from (Grotehusmann, 2015) reference year 2014)

In Table 1 shows the cost shares for the constructed wetlands. In addition, the costs for pyrolysis and biological activation of the $WOW_{Biochar}$ must be taken into account. Based on manufacturer's data, a price of 1,000 €/t was estimated.

Table 1: Constructed wetlands with $WOW_{Biochar}$ cost breakdown (modified, Dieter Grotehusmann, M. U. (2015))

Constructed wetlands cost breakdown	Capital expenditures breakdown in %	Depreciation period in years
Earthwork and filters installation	45 %	25a
Inlet and outlet structures	25 %	40a
Sealing	10 %	25a
Instrumentation and control engineering (ICE)	10 %	10a
Plants	5 %	25a
Rest	5 %	10a
WOW_{Char}	$\frac{WOW_{Char}\ Costs}{Costs\ without\ WOW_{Char}}$	**25a**
Sum	100%+WOW_{Char}Costs [%]	

2.4.2 Fine sieves

Table 2 shows the cost for the fine sieves for cellulose recovery. The number of fine sieves depends on the maximum inflow volume flow. The costs of instrumentation and control engineering are estimated at 15% of the costs for the machine technology. The integration of the cellulose recovery plant into an existing STP is estimated at 50% of the total investment costs.

Table 2: Investment Cellulose fine sieve

Cellulose finesieve cost breakdown			
Pos.	Name	Depreciation period (year)	Preis (€)
1	Cellulose Screen	15	100,000
2	Cellulose scrubber	15	35,000
3	Screw press	15	40,000
4	Instrumentation and control engineering (ICE): 15% Machine technology	15	15%
5	Integration: 50% total costs		50% total costs

2.5 Case Study

Considering the design approaches and costs described above, concepts for recovery of cellulose and subsequent production of WOWBiochar on larger STPs and the construction of constructed wetlands on smaller STPs were investigated for the following three regions.

- River catchment in Saarland / Germany
- Region in the south-west of Ireland
- Scottland

3 Saarland: River Blies

3.1 Description of the catchment area

The Blies is the largest tributary of the Saar and lies almost entirely in the Saarland. The total area of the Blies catchment is 1,960 km². The upper part of the Blies catchment selected for further consideration lies entirely in the Saarland and covers an area of 445 km². The catchment area contains 33 STPs with a capacity of between 30 and 75,000 p.e.. The total number of connected inhabitants is 206,000 p.e.. Drainage takes place in a combined system.

On the most important tributary, the Oster, with a flow length of almost 30 km, there are 15 STPs (including the small tributaries) with a capacity of between 30 and 4,000 p.e. and with the following process technology:

- 7 wastewater treatment plants with activated sludge processes: with nitrification, denitrification and aerobic sludge stabilisation,
- 2 aerated pond plants with sliding immersion tanks,
- 5 SBR plants
- 1 constructed wetland.

The total connected population is 17,777 p.e.. The catchment area with the STPs is shown in Figure 6.

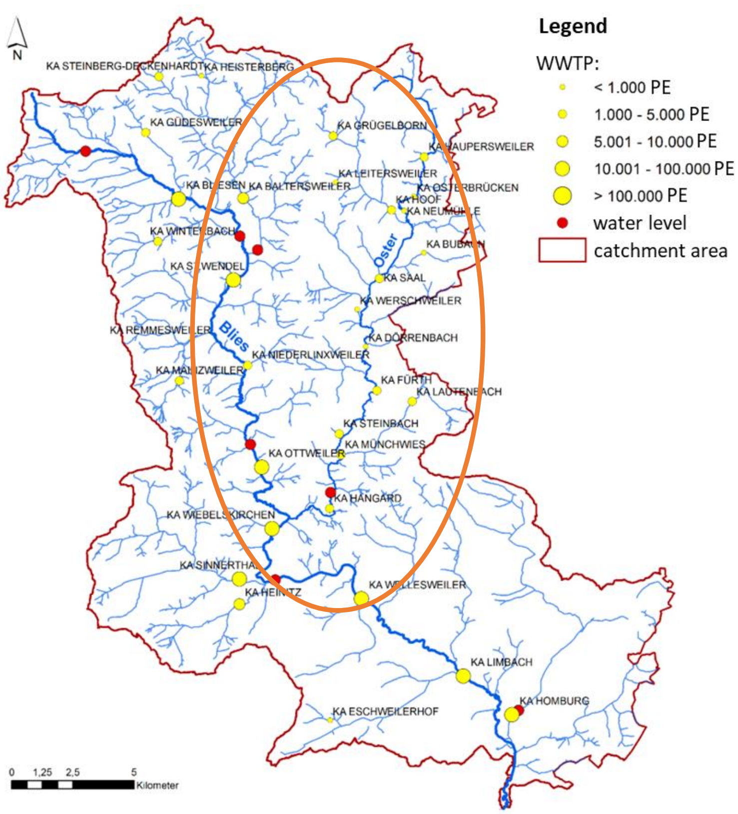


Figure 6: Selected part of catchment area Blies, Saarland (Germany) with considered STP for RSFs installation (modified) (Schmitt et al., 2019)

For the sub-catchment of the Blies described above a study was carried out in 2015 to assess the impact of STPs on the water body (Schmitt et al., 2019). The receiving water bodies of the STPs are relatively small, but some STPs discharge their effluent near the spring area, therefore they have a high influence on the micro pollution concentration in the water body. Figure 7 shows the balanced diclofenac concentration along the flow path of the river Oster. With the discharge of the Haupersweiler STP, the concentration already rises above the quality criteria of the Environmental Quality Standards Directive (EQSD). With the discharge of other STPs, the concentration rises to over 80 ng/l.

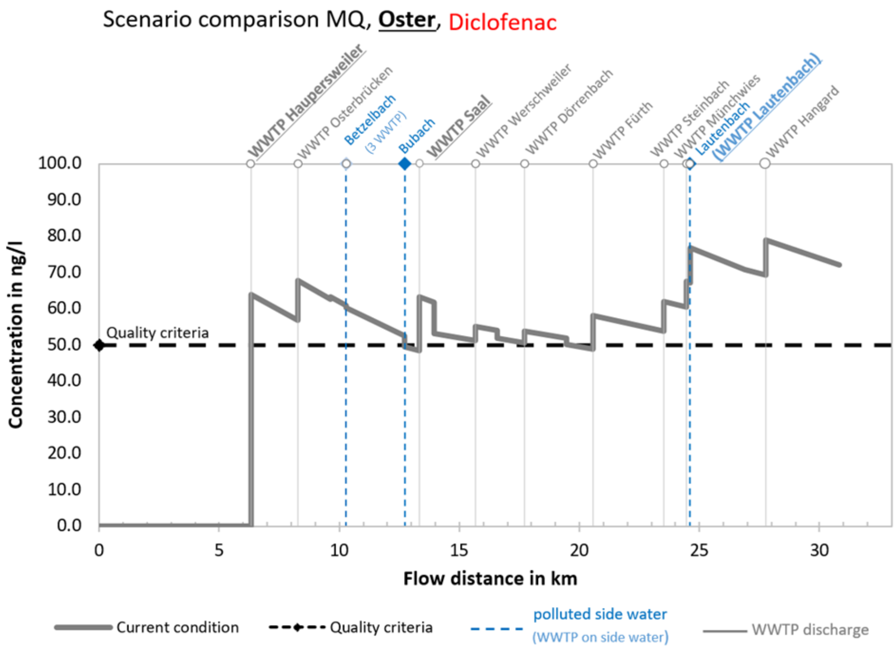


Figure 7: Concentration profile of River Oster for Diclofenac (modified) (Schmitt et al., 2019)

For this sub-catchment, it was investigated whether the quality criteria for the parameter diclofinac in the Oster river can be met by implementation of constructed wetlandes with $WOW_{biochar}$. Furthermore, it should be examined whether sufficient cellulose for the production of $WOW_{biochar}$ can be recovered in the catchment. Here, only the integration of cellulose recovery with fine sieves at the STP was considered in detail. For the production of biochar, it was assumed that a pyrolysis plant near the Ottweiler STP could be used. This location is relatively centrally located, thus minimising the transport costs for the cellulose and the $WOW_{biochar}$. Two variants were investigated for the Blies catchment:

- **Variant 1** describes the case where STP Haupersweiler, STP Saal and Lautenbach are extended by constructed wetlands with $WOW_{biochar}$, with cellulose recovery taking place at the STP Haupersweiler, STP Sinnerthal and STP Ottweiler. STP Haupersweiler has a high influence on the micro-pollutant concentration (see Figure 7) and it is planned to connect additional 800 p.e. to the treatment plant. By installing fine sieves, the cost-intensive expansion of the plant can be avoided. STP Saal is an aerated pond system with disc baffles, which should be converted to an activated sludge system in about 10 years, resulting in enough space for a constructed wetlands with

WOW$_{biochar}$. The STP Lautenbach has a small tributary as a receiving water body, so that the installation of an RSF makes sense here as well.

- **Variant 2** combines all treatment plants where it would be possible to install a constructed wetlands with WOW$_{biochar}$. Since in this case a much higher quantity of WOW$_{Biochar}$ would be required, the number of treatment plants where cellulose recovery is installed increases. The variant is intended to demonstrate the maximum possible reduction of micropollutants in water bodies through the use of constructed wetlands with WOW$_{biochar}$ at smaller STPs.

Table 3 provides an overview of the two variants.

Table 3: Variants for the implementation of constructed wetlands and fine sieves for the river catchemnt Blies (Saarland, Germany)

	Variant 1		Variant 2	
WWTP	Constructed Wetland + WOW$_{Biochar}$	Finesieve	Constructed Wetland + WOW$_{Biochar}$	Finesieve
Haupersweiler	X	X	X	X
Saal	X		X	
Lautenbach	X		X	
Osterbrücken				
Werschweiler			X	
Dörrenbach				
Fürth			X	
Steinbach				
Münchwies				
Hangard			X	
Leitersweiler			X	
Hoof			X	
Grügelborn			X	
Bubach/Ostertal				
Sinnerthal		X		X
St.Wendel				X
Bliesen				X
Ottweiler		X		X
Wiebelskirchen				X

3.2 Variant 1

3.2.1 Implementation of constructed wetlands with WOW$_{biochar}$ at small STPs

For the design of the micro pollution elimination stage of a STP, it is sufficient if a partial sewage water amount is treated. According to (KOM-M.NRW, 2016), the following criteria are recommended for determining the design sewage water amount:

- The design sewage water amount should be greater than or equal to the maximum dry weather runoff in the annual average.
- sewage water amount treated with the soil filter must be greater than or equal to 70% of the annual water volume.

The procedure is explained using the STP Haupersweiler as an example. The dry weather days were determined using the polygon of the moving 21-day minima of the daily discharges (ATV-DVWK-A 198.

(2003)). This method considers a time interval of 10 days before and 10 days after the observed day. All daily flows between the minimum daily flow and 1.2 times the minimum daily flow are classified as dry weather flows (see Figure 8). The maximum dry weather flow was determined for these days. This results in a mean dry water flow of 54 m³/h and a maximum dry water flow of 73 m³/h (annual mean value) for the STP Haupersweiler.

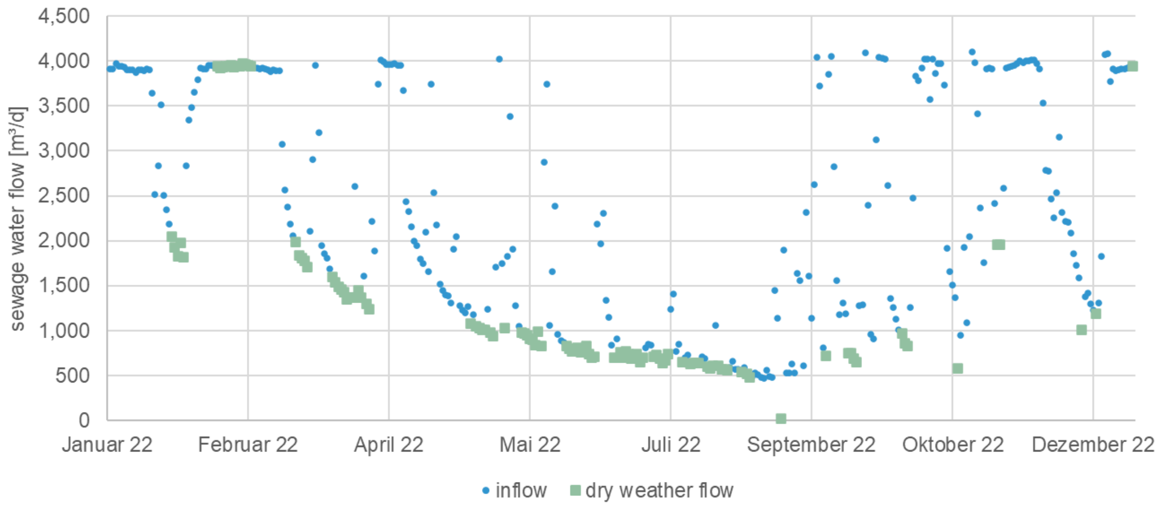


Figure 8: Dry weather days in 2022: STP Haupersweiler

The determination of 70 % of the annual wastewater volume is shown in Figure 9. Due to the high influence of infiltration water, the value is 90 m³/h. Table 4 summarises the results for the three STPs considered. All STPs have a very high amount of infiltration water, which leads to large surfaces for the constructed wetlands and associated high costs. For an economic implementation, a reduction of the infiltration water content is therefore necessary. A reduction of the infiltration water content to 30% was taken into account for the case study. This results in a design water volume of 60 m³/h for the Haupersweiler STP, 17 m³/h for the Saal STP and 45 m³/h for the Lauterbach STP.

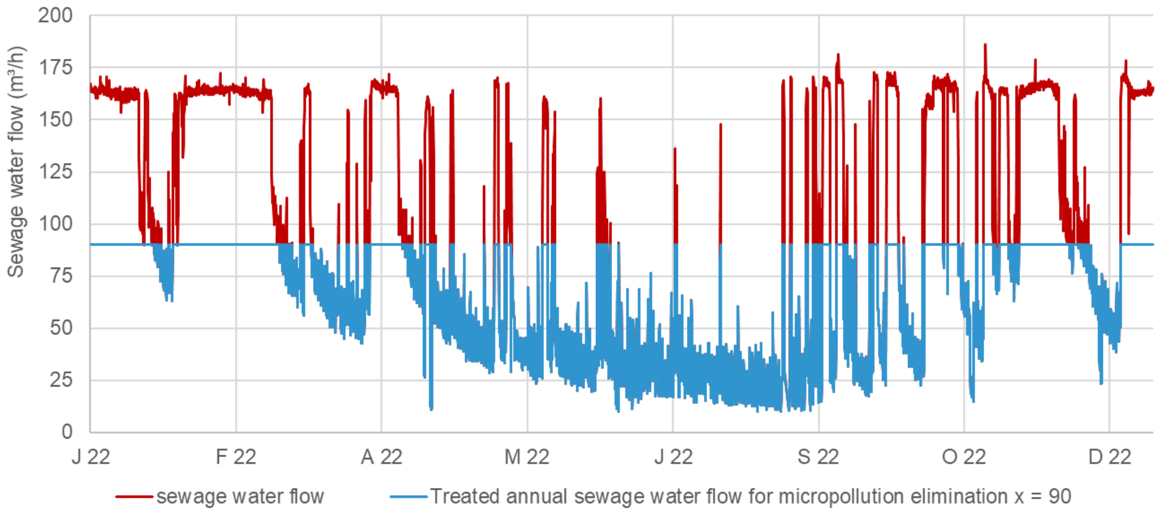


Figure 9: Treated annual sewage water flow of 70% with a design sewage water of 90 m³/h

Table 4: Design sewage water flow for constructed wetlands with $WOW_{biochar}$ considering the infiltration water

		Haupersweiler		Lautenbach		Saal	
		current state	reduce infiltration	current state	reduce infiltration	current state	reduce infiltration
EW	PE	3,033	3,033	3,118	3,118	1,632	1,632
annual water flow	m³/a	794,346	509,870	454,448	410,025	204,633	196,194
sewage water	m³/a	112,438	112,438	154,000	154,000	55,085	55,085
rain water	m³/a	369,322	369,322	217,525	217,525	127,338	127,338
infiltration water	m³/a	312,586	28,110	82,923	38,500	22,210	13,771
infiltration water: share Fremdwasseranteil	%	74	20	35	20	29	20
micropollutant elimination: share	%	70	(54)	70	(62)	70	(52)
micropollutant elimination: Max flow	m³/d	2,160	1,440	1,440	1,080	720	408
micropollutant elimination: Max flow	l/PE/d	712	475	462	346	441	250
Filter surface	**m²**	**5400**	**3600**	**3600**	**2700**	**1800**	**1020**
Filter surface	**m²/EW**	**1.78**	**1.19**	**1.15**	**0.87**	**1.10**	**0.63**
max hydraulic surface load	l/m²/d	400					

Table 5 summarises the input data and results for variant 1. The required surface area sums up to 7,400 m² for the three STPs and a required $WOW_{biochar}$-quantity of 1,082 tonnes.

Table 5: Design constructed wetlands with $WOW_{Biochar}$ for variant 1

WWTP	Unit	Haupersweiler	Saal	Lautenbach	Sum
Input Data					
Connected PE	PE	3,033	1,632	3,118	7,783
Annual flow	m^3/a	794,346	196,194	410,025	
Waste water flow to constructed wetland	m^3/a	525,600	148,920	394,200	
Treating process	-	BB/DN/AS	BT/STK	BB/DN/AS	
Receiving water	-	OSTER	OSTER	LAUTENBACH	
Wetlands Data					
Area	m^2	3630	1050	2720	7,400
Length	m	66	30	68	
Width	m	55	35	40	
Filterbody	m^3	2360	683	1768	4,810
Volume: Sand	m^3	2006	580	1503	4,089
Volume: WOW_{Char}	m^3	354	102	265	722
Amount of $WOW_{Biochar}$ (50% straw/cellulose)	kg	530,888	153,563	397,800	1,082,250
Investment costs without $WOW_{Biochar}$ production costs	€	2,050,801	1,387,483	1,872,587	5,310,871 €
Transport costs $WOW_{Biochar}$	€	4,202	760	2,618	7,579 €
Transport costs Cellulose	€	-	-	-	13,519 €
Total investment costs of constructed wetland	€	2,585,890	1,541,805	2,273,005	**6,414,219 €**
Average filter velocity	m/h	0.013	0.011	0.012	
Average Hydraulic Volume Rate	$L/(m^2 \cdot d)$	323.967	274.286	282.353	

3.2.2 Implementation of fine sieves on larger STPs

To determine the amount of cellulose, a specific cellulose content in the wastewater of 0.0317 kg/p.e./d was used according to (WOW, 2019). Since the $WOW_{Biochar}$ is produced from a cellulose-straw mixture, the amount added to the pyrolysis is twice as large. The pyrolysis and biological activation processes result in high feedstock losses, and the total yield of activated $WOW_{Biochar}$ is 20%. Only larger STPs without pre-treatment and sludge digestion were considered as locations for cellulose recovery. In the catchment area, 6 STPs could be equipped with cellulose recovery under these boundary conditions (see Table 6). For variant 1, three STPs were selected for cellulose recovery. This results in an annual cellulose amount of 371 t/a respective 148 t/a $WOW_{Biochar}$ (see Table 7). With this amount of $WOW_{Biochar}$, the selected STPs can be equipped with constructed wetlands for micro pollution elimination within 8 years (see Table 8).

Table 6: Selected STP for finesieve installation in the catchment area

Name	Connected PE	Annual flow	Primary clarifier	Digester	Finesieve	Cellulose Amount	$WOW_{Biochar}$ Amount
		m³/a	yes / no	yes / no	Anzahl	kg/d	kg/d
Haupersweiler	3033	714102	no	no	2	96	38
Ottweiler	9,628	1,712,649	no	no	2	305	122
Sinnerthal	19,381	3,080,558	no	no	3	614	246
St.Wendel	13,316	2,400,343	no	no	3	422	169
Bliesen	7,082	1,433,392	no	no	2	224	90
Wiebelskirchen	8,996	971,596	no	no	2	285	114

Table 7: Total production per year for Variant 1

$WOW_{Biochar}$	kg/a	**148,297**
Straw-Amount	t/a	370.742
Cellulose-Amount	t/a	370.742
The ammount to be pyrolyzed (Straw + Cellulose)	t/a	741.484

Table 8: Time schedule for variant 1 for the implementation of constructed wetlands with $WOW_{biochar}$

Year	kg $WOW_{Biochar}$ (Cell.+Straw)	
1	148,297	**Haupersweiler**
2	148,297	
3	148,297	
4	148,297	530,888
5	210,596	**Saal** 153,563
6	205,331	**Lautenbach**
7	148,297	
8	148,297	397,800

3.2.3 Impact of the fine sieve on the treatment capacity

With the integration of the fine sieves on the STPs, the COD load to the biological stage is reduced. This has an influence on the required activated sludge tank volume as well as on the required oxygen demand. In order to quantify the influence, the biological stage for the Haupersweiler and Ottweiler STPs was designed according to German design rules (DWA-A 131, 2016). The results are shown in Figure 10. Compared to the current state (szenario 0), the integration of a fine sieve (scenario 1) reduces the required activated sludge tank volume for both STPs by about 40 % and the required oxygen demand at the average annual temperature by about 20 %. At the Haupersweiler STP, additional 800 p.e. could be connected without exceeding the existing basin volume. At the Ottweiler STP, wastewater from nearby plants in Mainzweiler and Niederlinxweiler can be transferred, resulting in an additional load of 3,600 p.e.. With the increase in connection capacity, the required air volume for the biological stage also increases. However, it is in the same order of magnitude for both plants compared to the current state. Furthermore, the required basin volume is shown in order to achieve the planned increase in the expansion capacity of the two treatment plants without the integration of a fine sieve. The tank volume and the aeration system would have to be expanded by about 20 %.

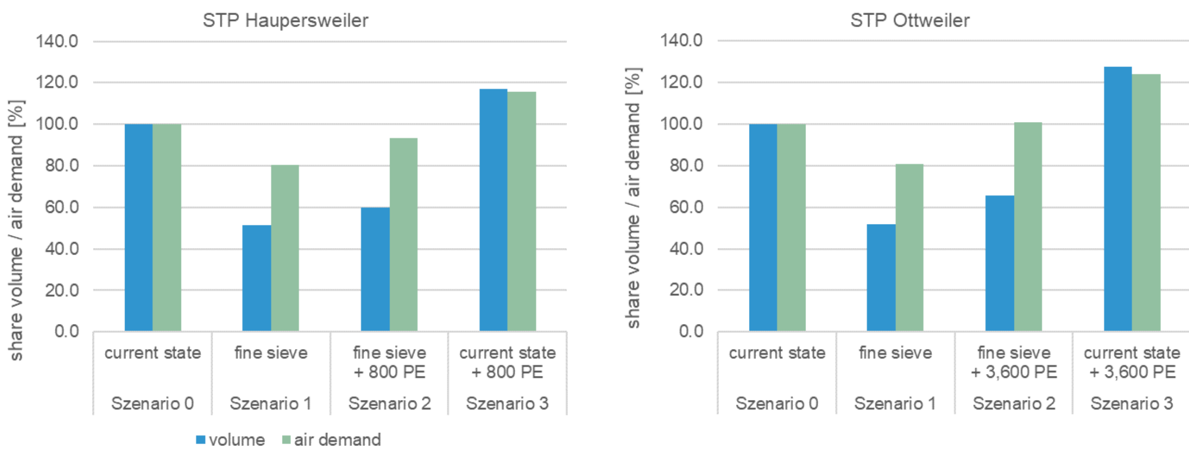


Figure 10: Influence of the fine sieve on the treatment capacity and air volume for aeration of STP Haupersweiler and STP Ottweiler for different scenarios

3.2.4 Logistic WOW$_{biochar}$

The following logistic must be taken into account for the production and installation of the WOW$_{biochar}$:

- Transport of the cellulose from the STPs with cellulose recovery to the pyrolysis plant.
- Transport of the WOW$_{biochar}$ to the small STPs for the construction of the constructed wetlands

For the location of the pyrolysis plant, the industrial area near STP Ottweiler was chosen. This site is centrally located in selected sub-catchment area, which allows short transport distances and times. In the calculation, the specific transport costs for the cellulose as well as for the WOW$_{biochar}$ of 10 €/(truck·km) and a loading quantity of a motor vehicle of 25 t/truck were assumed. This results in transport costs of 13,519 € for the cellulose and 6,874 € for the WOW$_{Biochar}$ (see Table 9 and Table 10).

Table 9: Transport cost of cellulose and WOW$_{biochar}$ for variant 1

Variant **1**				
Transport of cellulose from large KA towards the pyrolysis plant (location: Industrial area near WWTP Ottweiler)				
from	km	t/a	€/a	to
Haupersweiler	19	35	382	Ottweiler
Sinnerthal	8	111	416	Ottweiler
St.Wendel	10	224	892	Ottweiler
Sum			1,690	
Total transport costs for recovered cellulose on large WWTPs with corresponding construction times: 8 years				
			13,519 €	

Table 10: Transport cost of $WOW_{biochar}$ for variant 1

Variant 1				
Transport of $WOW_{biochar}$ from pyrolysis plant to constructed wetlands				
from	km	t/a	€/a	to
Haupersweiler	19	531	4,202	Ottweiler
Saal	13	154	936	Ottweiler
Lautenbach	11	398	1,736	Ottweiler
Sum			6,874	

3.2.5 Investment cost

Table 11 shows the investment costs and the cost break down for the installation of the three constructed wetlands with $WOW_{biochar}$ for variant 1. The investment costs without consideration of the $WOW_{biochar}$ production were calculated with the specific area-related investments costs from section 2.4.1. The $WOW_{Biochar}$-production costs were assumed to be 1000 €/t. This results in overall investment costs of 6.4 million €. Compared to a conventional constructed wetland, additional costs of 21% are incurred for the production and transport of the $WOW_{biochar}$.

Table 12 shows the cost composition for cellulose recovery for variant 1. In total 8 fine sieves modules are required on the three STPs. For each STP with cellulose recovery system, a screw press and a switch cabinet have to be considered.

The total investment costs for both the constructed wetlands with $WOW_{biochar}$ and the fine sieves for variant 1 sums up to € 8.86 million.

Table 11: Cost breakdown of constructed wetlands for Variant 1

Constructed wetlands cost breakdown Variant 1	Capital expenditures breakdown in %	Depreciation period	Capital expenditures breakdown in €
Earthwork and filters installation	45 %	25a	2,389,892 €
Inlet and outlet structures	25 %	40a	1,327,718 €
Sealing	10 %	25a	531,087 €
Instrumentation and	10 %	10a	531,087 €
Plants	5 %	25a	265,544 €
Rest	5 %	10a	265,544 €
WOW_{Char} including transport costs	**21%**	**25a**	**1,103,348 €**
Sum	121%		6,414,219 €
spezif. cost CWetl.			682 €/m²
spezif. cost inkl. WOW_{Char}			824 €/m²

Table 12: Cost breakdown of cellulose fine sieves for Variant 1

Cellulose finesieve cost breakdown					
Pos.	**Name**	**Depreciation period (year)**	**Preis (€)**	**Amount**	**Total (€)**
1	Cellulose screen	15	100,000	7	700,000
2	Cellulose scrubber	15	35,000	7	245,000
3	Screw press	15	40,000	3	120,000
4	Instrumentation and control engineering (ICE): 15% Machine technology	10	159,750		159,750
5	Installation: 50% total cost				1,224,750
	Total				**2,449,500**

3.3 Variant 2

3.3.1 Implementation of constructed wetlands with $WOW_{biochar}$ at small STPs

In variant 2, 9 STPs are extended with constructed wetlands with $WOW_{biochar}$ in the Oster catchment area. 13,863 p.e. are connected to the 9 STPs. The integration of constructed wetlands is not technically possible at the remaining STPs. The filter area was determined for the additionally considered STPs in comparison to variant 1 using a specific area of 0.4 m²/p.e., as no data on the sewage water volume was available.Table 13 summarises the input data and results for variant 2. The required surface area sums up to 13,545 m² for the three STPs and a required $WOW_{biochar}$-quantity of 3,107 tonnes.

Table 13: Design constructed wetlands with $WOW_{Biochar}$ for variant 2

WWTP	Unit	Haupers weiler	Saal	Wersch weiler	Fürth	Lauten bach	Hangard	Leiters weiler	Hoof	Grügel born	Sum
Input Data											
Connected PE	PE	3,033	1,632	525	1,482	3,118	1,806	517	935	815	13,863
Annual flow	m^3/a	794,346	196,194		193,971	410,025	207,288	73,471			
Waste whater flow to be treated in RSF	m^3/a	525,600	148,920		155,177	394,200	165,830	58,777			
Treating process	-	BB/DN/AS	BT/STK	BT/STK	SBR	BB/DN/AS	SBR	BB/DN/AS	BB/DN/AS	BB/DN/AS	
Receiving water	-	OSTER	OSTER	ZUR OSTER	OSTER	LAUTENBA(	OSTER	HOTTENBA	BETZELBAC	BLEISCHBA	
Constructed Wetlands Data											
Area	m^2	3630	1050	210	2135	2720	2275	820	375	330	13,545
Length	m	66	30	21	61	68	65	41	25	22	
Width	m	55	35	10	35	40	35	20	15	15	
Filterbody	m^3	2360	683	137	1388	1768	1479	533	244	215	8,804
Volume: Sand	m^3	2006	580	116	1180	1503	1257	453	207	182	7,484
Volume: WOW_{Char}	m^3	354	102	20	208	265	222	80	37	32	1,321
Amount of WOW_{Char}	kg	530,888	153,563	30,713	312,244	397,800	332,719	119,925	54,844	48,263	1,980,956
Investment costs without WOW_{Char} production costs	€	2,050,801	1,387,483	835,703	1,735,055	1,872,587	1,770,117	1,283,525	1,003,166	963,573	12,902,010 €
Transport costs WOW_{Char}	€	4,202	936	215	1,385	1,736	728	827	491	441	10,960 €
Transport costs Cellulose	€	-	-	-	-	-	-	-	-	-	20,953 €
Total investment costs of constructed wetland	€	2,585,890	1,541,981	866,631	2,048,683	2,272,123	2,103,564	1,404,277	1,058,500	1,012,276	**14,914,879 €**
Average filter velocity	m/h	0.013	0.011		0.008	0.012	0.008	0.008			
Average Hydraulic Volume Rate	$L/(m^2 \cdot d)$	323.967	274.286		199.130	282.353	199.705	196.381			

3.3.2 Implementation of fine sieves on larger STPs

Due to the higher demand for $WOW_{biochar}$ compared to variant 1, 6 STPs are equipped with a cellulose recovery system. This results in an annual cellulose amount of 711 t/a respective 284 t/a $WOW_{Biochar}$ (see Table 6 and Table 14). With this amount of $WOW_{Biochar}$, the selected STPs can be equipped with constructed wetlands for micro pollution elimination within 7 years (see Table 15).

Table 14: Total production per year for Variant 2

$WOW_{Biochar}$	kg/a	**284.338**
Straw-Amount	t/a	710,845
Cellulose-Amount	t/a	710,845
The ammount to be pyrolyzed (Straw + Cellulose)	t/a	1.422

Table 15: Time schedule for variant 2 for the implementation of constructed wetlands with $WOW_{biochar}$

<table>
<tr><th>Year</th><th colspan="4">kg WOW_{Char} (Cell.+Straw)</th></tr>
<tr><td>1</td><td>284,338</td><td rowspan="2">Haupersweiler 530,888</td><td></td><td></td></tr>
<tr><td>2</td><td>284,338</td><td></td><td></td></tr>
<tr><td>3</td><td>322,127</td><td>Leitersweiler 119,925</td><td>Saal 153,563</td><td></td></tr>
<tr><td>4</td><td>332,977</td><td>Fürth 312,244</td><td></td><td></td></tr>
<tr><td>5</td><td>305,072</td><td>Grügelborn 48,263</td><td>Hoof 54,844</td><td>Werschweiler 30,713</td></tr>
<tr><td>6</td><td>455,591</td><td>Lautenbach 397,800</td><td></td><td></td></tr>
<tr><td>7</td><td>342,129</td><td>Hangard 332,719</td><td></td><td></td></tr>
</table>

3.3.3 Logistic $WOW_{biochar}$

The following logistic must be taken into account for the production and installation of the $WOW_{biochar}$:

- Transport of the cellulose from the STPs with cellulose recovery to the pyrolysis plant.
- Transport of the $WOW_{biochar}$ to the small STPs for the construction of the constructed wetlands

For the location of the pyrolysis plant, the industrial area near STP Ottweiler was chosen. This site is centrally located in selected sub-catchment area, which allows short transport distances and times. In the calculation, the specific transport costs for the cellulose as well as for the $WOW_{biochar}$ of 10 €/(truck·km) and a loading quantity of a motor vehicle of 25 t/truck were assumed. This results in transport costs of 20,953 € for the cellulose and 10,960 € for the $WOW_{Biochar}$ (see Table 16 and Table 17).

Table 16: Transport cost of cellulose and WOW$_{biochar}$ for variant 2

Variant **2**				
Transport of cellulose from large KA towards the pyrolysis plant (location: Industrial area near WWTP Ottweiler)				
from			€/a	to
Haupersweiler	19	35	382	Ottweiler
Sinnerthal	8	111	416	Ottweiler
St.Wendel	10	224	892	Ottweiler
Bliesen	16	0	1,132	Ottweiler
Ottweiler	0	82	0	Ottweiler
Wiebelskirchen	3	104	172	Ottweiler
Sum			2,993	
Total transport costs for recovered cellulose on large WWTPs with corresponding construction times: 7 years				
			20,953 €	

Table 17: Transport cost of WOW$_{biochar}$ for variant 2

Variant **2**				
Transport of cellulose from large KA towards the pyrolysis plant (location: Industrial area near WWTP Ottweiler)				
from			€/a	to
Ottweiler	19	531	4,202	Haupersweiler
Ottweiler	13	154	936	Saal
Ottweiler	11	398	1,736	Lautenbach
Ottweiler	11	31	215	Werschweiler
Ottweiler	11	312	1,385	Fürth
Ottweiler	5	333	728	Hangard
Ottweiler	17	120	827	Leitersweiler
Ottweiler	16	55	491	Hoof
Ottweiler	22	48	441	Grügelborn
Sum			10,960	

3.3.4 Investment cost

Table 18 shows the investment costs and the cost break down for the installation of the nine constructed wetlands with WOW$_{biochar}$ for variant 2. The investment costs without consideration of the WOW$_{biochar}$ production were calculated with the specific area-related investments costs from section 2.4.1. The WOW$_{Biochar}$-production costs were assumed to be 1000 €/t. This results in overall investment costs of 14.9 million €. Compared to a conventional constructed wetland, additional costs of 16% are incurred for the production and transport of the WOW$_{biochar}$.

Table 19 shows the cost composition for cellulose recovery for variant 2. In total 14 fine sieves modules are required on the six STPs. For each STP with cellulose recovery system, a screw press and a switch cabinet have to be considered.

The total investment costs for both the constructed wetlands with WOW$_{biochar}$ and the fine sieves for variant 2 sums up to 19.81 million €.

Table 18: Cost breakdown of constructed wetlands for variant 2

Constructed wetlands cost breakdown Variant 2	Capital expenditures breakdown in %	Depreciation period	Capital expenditures breakdown in €
Earthwork and filters installation	45 %	25a	5,805,904 €
Inlet and outlet structures	25 %	40a	3,225,502 €
Sealing	10 %	25a	1,290,201 €
Instrumentation and control engineering (ICE)	10 %	10a	1,290,201 €
Plants	5 %	25a	645,100 €
Rest	5 %	10a	645,100 €
WOW$_{Char}$ including transport costs	**16%**	**25a**	**2,012,870 €**
Sum	116%		14,914,879 €
spezif. cost CWetl.			931 €/m²
spezif. cost inkl. WOW$_{Char}$			1,076 €/m²

Table 19: Cost breakdown of cellulose fine sieves for variant 2

Cellulose finesieve cost breakdown					
Pos.	**Name**	**Depreciation period (year)**	**Preis (€)**	**Amount**	**Total (€)**
1	Cellulose Screen	15	100,000	14	1,400,000
2	Cellulose scrubber	15	35,000	14	490,000
3	Screw press	15	40,000	6	240,000
4	Instrumentation and control engineering (ICE): 15% Machine technology	15	319,500		319,500
5	Integration: 50% total costs				2,449,500
	Total				**4,899,000**

3.4 Summary of the case study: Saarland

3.4.1 Impact on water quality

Figure 11 shows the balanced diclofenac concentration along the flow path of the river Oster for the current status and for the two variants. For the two variants, an elimination rate of 80 % for the parameter diclofenac was assumed for the STPs with constructed wetlands with WOW$_{biochar}$ (see chapter 2.2). With the integration of a micropollutant elimination stage at only three STPs, the quality criteria of the EQS can be met almost over the entire flow path. In variant 2, the diclofinac concentration can be reduced to below 35 ng/l and is well below the quality criteria of the EQS.

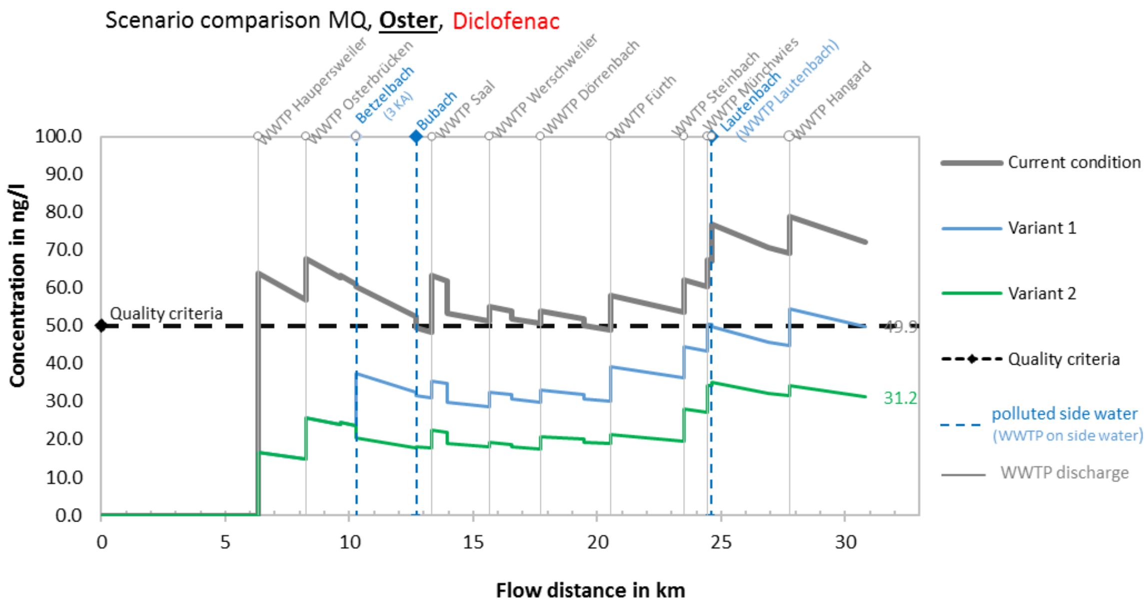


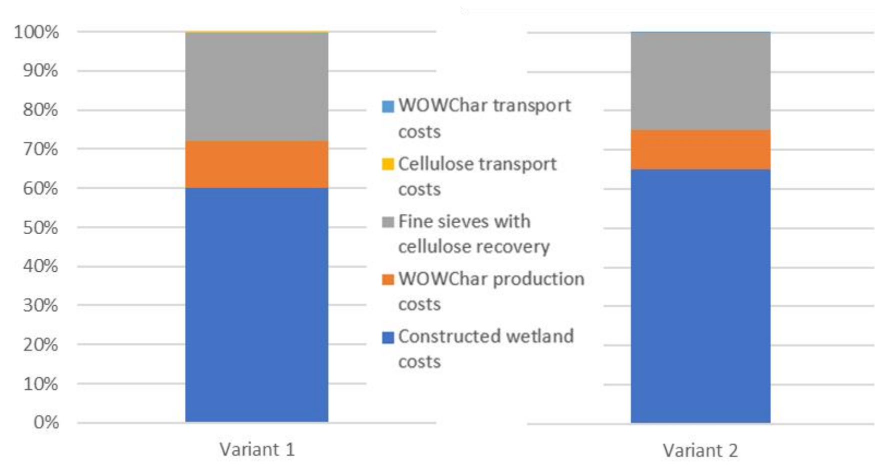
Figure 11: Concentration profile of River Oster for Diclofenac (modified) (Schmitt et al., 2019) for the current condition, for variant 1 and variant 2

3.4.2 Cost comparison

The total investment costs for variant 1 and variant 2 are shown in Table 20. The costs for variant 2 with 9 constructed wetlands are twice as high as for variant 1. A comprehensive integration of constructed wetlands is therefore not recommended.. The integration of micropollutant removal stages should take place at STPs with the greatest impact on the water body. The integration of fine sieves should be implemented at STPs that are overloaded or where additional p.e. are to be connected. This results in cost advantages, as an enlargement of the STP plant can be dispensed by integrating fine sieves. The costs for constructed wetlands account for 60% of the total costs. The transport costs have only a minor share of the total investment costs if the pyrolysis plant is located close to the catchment area.

Table 20: Total investment costs for variant 1 and variant 2

Investment costs	Variant 1		Variant 2	
Constructed wetland costs	5.310.871 €	59,9%	12.902.010 €	65,1%
WOW_{Char} production costs	1.082.250 €	12,2%	1.980.956 €	10,0%
Fine sieves with cellulose recovery	2.449.500 €	27,6%	4.899.000 €	24,7%
Cellulose transport costs	13.519 €	0,2%	20.953 €	0,1%
WOW_{Char} transport costs	6.874 €	0,1%	10.960 €	0,1%
Total	8.863.014 €	100%	19.813.879 €	100%



4 Ireland

4.1 Description of the catchment area

To assess the impact of constructed wetlands with WOW$_{biochar}$ on water quality in a catchment in Ireland, a typical region in the south-east of Ireland was selected with one large STP (Kilkenny STP) and many small STPs. Only STPs located within approximately 20 kilometres of the town of Kilkenny and with more than 500 connected residents were considered. On the Kilkenny STP with 35,643 connected residents, the cellulose recovery system was installed. On the other STPs, constructed wetlands with WOW$_{biochar}$ for micro-pollutant elimination were installed.

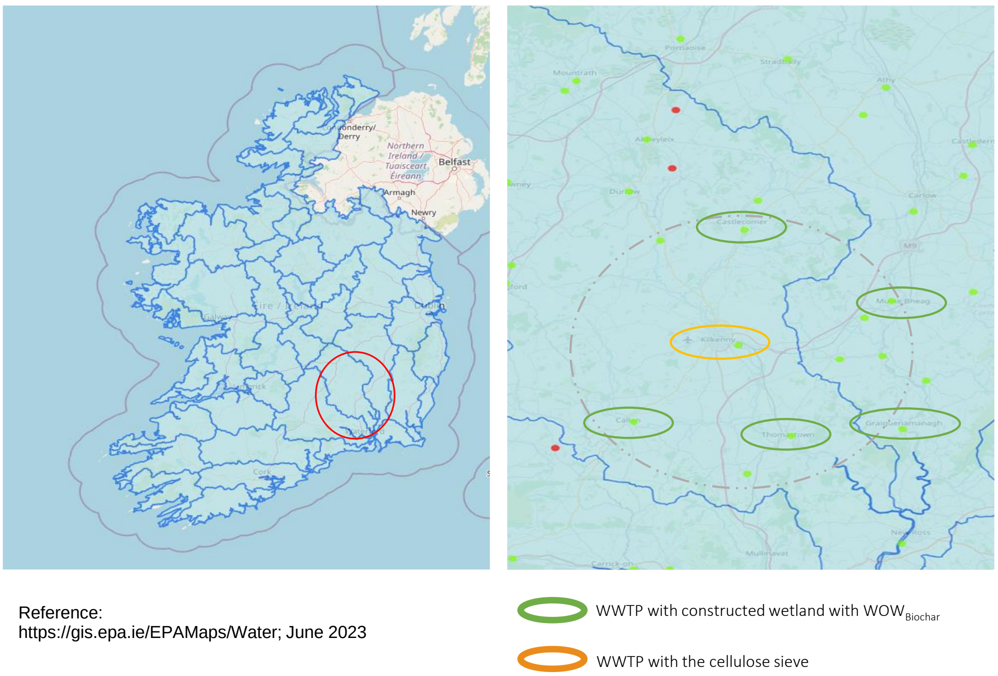


Figure 12: Catchment area in the south-east of Ireland

4.2 Implementation of fine sieves on larger STPs

9 STPs are extended with constructed wetlands with WOW$_{biochar}$. 26,707 p.e. are connected to the 9 STPs. The filter area was determined using a specific area of 0.4 m²/p.e., as no data on the sewage water volume was available. Table 21 summarises the input data and results. The required surface area sums up to 11,000 m² for the 9 STPs and a required WOW$_{biochar}$-quantity of 1,107 tonnes. Detailed information on implementation is summarised in the fact sheets for each STP in the Annex.

Table 21: Design constructed wetlands with WOWBiochar for a catchment area in Irland

WWTP	unit	Graignuenama	Callan	Thomastown	Castlecomer	Muinebheag	Ballyragget	Paulstown	Gowran	Goresbridge	Sum
Input Data											
Connected PE	PE	2,267	2,247	3,522	2,077	12,248	1,920	1,000	826	600	26,707
Annual flow	m^3/a	0	0	0	0	466,470	0	0	0	0	
Waste water flow to constructed wetland	m^3/a	0	0	0	0	373,176	0	0	0	0	
Wetlands Data											
Area	m^2	920	900	1,420	840	5,160	780	400	340	240	11,000
Length	m	46	45	71	42	86	39	16	17	12	374
Width	m	20	20	20	20	60	20	25	20	20	225
Filterbody	m^3	598	585	923	546	3,354	507	260	221	156	7,150
Volume: Sand	m^3	508	497	785	464	2,851	431	221	188	133	6,078
Volume: WOW_{Char}	m^3	90	88	138	82	503	76	39	33	23	1,073
Amount of WOW-Biochar (50% straw/cellulose)	kg	134,550	131,625	207,675	122,850	754,650	114,075	58,500	49,725	35,100	1,351,350
→ Amount of straw	kg	336,375	329,063	519,188	307,125	1,886,625	285,188	146,250	124,313	87,750	
Investment costs without WOW_{Char} production costs	€	1,330,902	1,321,719	1,525,892	1,293,305	2,291,066	1,263,463	1,023,769	972,677	871,604	11,894,397
Transport costs WOW_{Char}	€	1,511	1,270	1,539	1,059	7,129	1,080	521	313	413	12,509
Transport costs Cellulose	€	-	-	-	-	-	-	-	-	-	50,569
Total investment costs of constructed wetland	€	1,330,902	1,321,719	1,525,892	1,293,305	2,291,066	1,263,463	1,023,769	972,677	871,604	11,944,966
Average filter velocity	m/h	0.000	0.000	0.000	0.000	0.008	0.000	0.000	0.000	0.000	
Maximum Hydraulic Volume Rate	$L/(m^2 \cdot d)$	0.000	0.000	0.000	0.000	198.140	0.000	0.000	0.000	0.000	

4.3 Implementation of fine sieves on larger STPs

To determine the amount of cellulose, a specific cellulose content in the wastewater of 0.0317 kg/p.e./d was used according to (WOW, 2019). Since the $WOW_{Biochar}$ is produced from a cellulose-straw mixture, the amount added to the pyrolysis is twice as large. The pyrolysis and biological activation processes result in high feedstock losses, and the total yield of activated $WOW_{Biochar}$ is 20%. For cellulose recovery STP Kilkenny was chosen (see Table 22). This results in an annual cellulose amount of 412 t/a respective 165 t/a $WOW_{Biochar}$ (see Table 23). With this amount of $WOW_{Biochar}$, the selected STPs can be equipped with constructed wetlands for micro pollution elimination within 9 years (see Table 24).

Table 22: Selected STP for fine sieve installation for a catchment area in Irland

Name	Connected PE	Annual flow	Primary clarifier	Digester	Finesieve	Cellulose Amount	$WOW_{Biochar}$ Amount
		m³/a	yes / no	yes / no	Anzahl	kg/d	kg/d
Kilkenny City Waste Water Treatment plant	35,643	3,523,345	no	-	4	1130	452

Table 23: Total production per year for a catchment area in Irland

$WOW_{Biochar}$	kg/a	**164,963**
Straw-Amount	kg/a	412,407
Cellulose-Amount	kg/a	412,407

Table 24: Time schedule for the implementation of constructed wetlands with $WOW_{biochar}$ for a catchment area in Irland

Year	kg WOWBiochar (Cell.+Straw)				
1	164,963	**Muinebheag**			
2	164,963				
3	164,963				
4	164,963				
5	164,963	754,650			
6	235,128	**Thomastown** 207,675			
7	192,416	**Callan** 131,625			
8	225,753	**Castlecomer** 122,850			
9	267,866	**Ballyragget** 114,075	**Paulstown** 58,500	**Gowran** 49,725	**Goresbridge** 35,100

4.4 Logistic $WOW_{biochar}$

The following logistic must be taken into account for the production and installation of the $WOW_{biochar}$:

- Transport of the cellulose from the STPs with cellulose recovery to the pyrolysis plant.
- Transport of the $WOW_{biochar}$ to the small STPs for the construction of the constructed wetlands

It was assumed that the site for the pyrolysis plant would be an industrial area near the Kilkenny STP. This avoids the costs of transporting the cellulose. In the calculation, the specific transport costs for the cellulose as well as for the $WOW_{biochar}$ of 10 €/(truck·km) and a loading quantity of a motor vehicle of 25 t/truck were assumed. This results in transport costs of 50,569 € for the cellulose (see Table 25).

Table 25: Transport cost of cellulose for a catchment area in Irland

Variant 1		
Transport of cellulose from large KA towards the pyrolysis plant (location KA Ottweiler)		
from	€/a	to
Muinebheag	1,378	Kilkenny City
Thomastown	341	Kilkenny City
Callan	428	Kilkenny City
Castlecomer	210	Kilkenny City
Graignuenamanagh Tinnahinch	504	Kilkenny City
Ballyragget	215	Kilkenny City
Paulstown	174	Kilkenny City
Gowran	156	Kilkenny City
Goresbridge	206	Kilkenny City
Sum	3,612	
Total transport costs for recovered cellulose on large WWTPs with corresponding construction times		
	50,569 €	

4.5 Investment cost

Table 26 shows the investment costs and the cost break down for the installation of nine constructed wetlands with $WOW_{biochar}$. The investment costs without consideration of the $WOW_{biochar}$ production were calculated with the specific area-related investments costs from section 2.4.1. The $WOW_{Biochar}$-production costs were assumed to be 1000 €/t. This results in overall investment costs of 13.5 million €. Compared to a conventional constructed wetland, additional costs of 14% are incurred for the production and transport of the $WOW_{biochar}$.

Table 27 shows the cost composition for cellulose recovery on the STP Kilkenny. In total 4 fine sieves modules, a screw press and a switch cabinet have to be considered.

The total investment costs for both the constructed wetlands with $WOW_{biochar}$ and the fine sieves sums up to 14.8 million €.

Table 26: Cost breakdown of constructed wetlands for a catchment area in Irland

Constructed wetlands cost breakdown	Capital expenditures breakdown in %	Depreciation period	Capital expenditures breakdown in €
Earthwork and filters installation	45 %	25a	5,352,479 €
Inlet and outlet structures	25 %	40a	2,973,599 €
Sealing	10 %	25a	1,189,440 €
Instrumentation and control engineering (ICE)	10 %	10a	1,189,440 €
Plants	5 %	25a	594,720 €
Rest	5 %	10a	594,720 €
WOW_{Char} including transport costs	**14%**	**25a**	**1,608,750 €**
Sum	114%		13,503,147 €
spezif. cost CWetl.			445 €/m²
spezif. cost inkl. WOW_{Char}			506 €/m²

Table 27: Cost breakdown of cellulose fine sieves for a catchment area in Irland

Cellulose finesieve cost breakdown					
Pos.	**Name**	**Depreciation period (year)**	**Preis (€)**	**Amount**	**Total (€)**
1	Cellulose screen	15	100,000	4	400,000
2	Cellulose scrubber	15	35,000	4	140,000
3	Screw press	15	40,000	1	40,000
4	Instrumentation and control engineering (ICE): 15% Machine technology	10	87,000	1	87,000
5	Installation: 50% total cost				667,000
	Total				**1,334,000**

5 Scotland

5.1 Description of the catchment area

For this case study, the whole of Scotland was considered rather than a single catchment area.. To simplify the analysis, Scotland was divided into 4 regions:

- Region 1 (blue): north
- Region 2 (purple): central on the eastern coast
- Region 3 (orange): densely populated area between Glasgow and Edinburgh
- Region 4 (green): south and on the western coast.

Figure 13 shows the STPs and how they are allocated to the regions. For each region, the diclofenac reduction is calculated if all plants with less than 5,000 p.e. are extended with a constructed wetland with $WOW_{biochar}$.

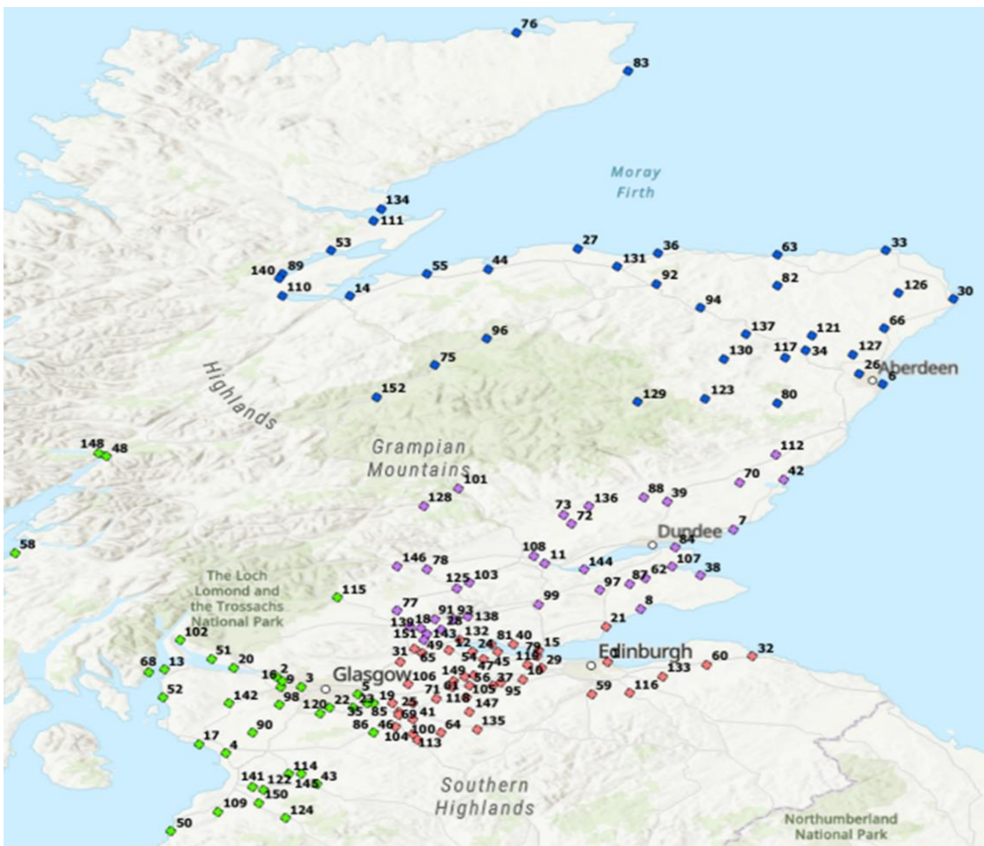


Figure 13: Distribution of the STP in Scotland in Scotland, divided into 4 regions. Region 1- blue, Region 2- purple, Region 3- orange, Region 4- green

5.2 Implementation of constructed wetlands with $WOW_{biochar}$ at small STPs

The installation of a constructed wetland with WOWbiochar was only considered for WWTPs with a connected population of 5000 p.e. or less. Since there was only information about the number of connected inhabitants and no water quantities were available, a specific area of 0.4 m²/p.e. was used for the calculation of the filter area (see also chapter 2.3). All other characteristic values, such as filter layer depth, $WOW_{biochar}$-density etc. were taken from chapter 2.3

For the calculation of the diclofenac load, the specific diclofenac load of 0.78 mg/p.e.*d from (Schmitt, 2019) was used. For the determination of the reduction amounts, the treatment efficiency of 26.45% and 80% was assumed for a conventional STP and STP with constructed wetlands with $WOW_{biochar}$, respectively.

5.3 Implementation of fine sieves on larger STPs

For a preliminary assessment, the following locations were chosen for the installation of a cellulose recovery plant (see also Figure 14):

- Region 1: STP Allanfearn and Persley
- Region 2: STP Perth city
- Region 3: STP East Calder
- Region 4: STP Meadowhead

Detailed data on the individual sites would be required for an accurate site selection. For the pyrolysis plant, a site close to the STP with a cellulose recovery plant was chosen. This avoided the cost of transporting cellulose to a pyrolysis plant.

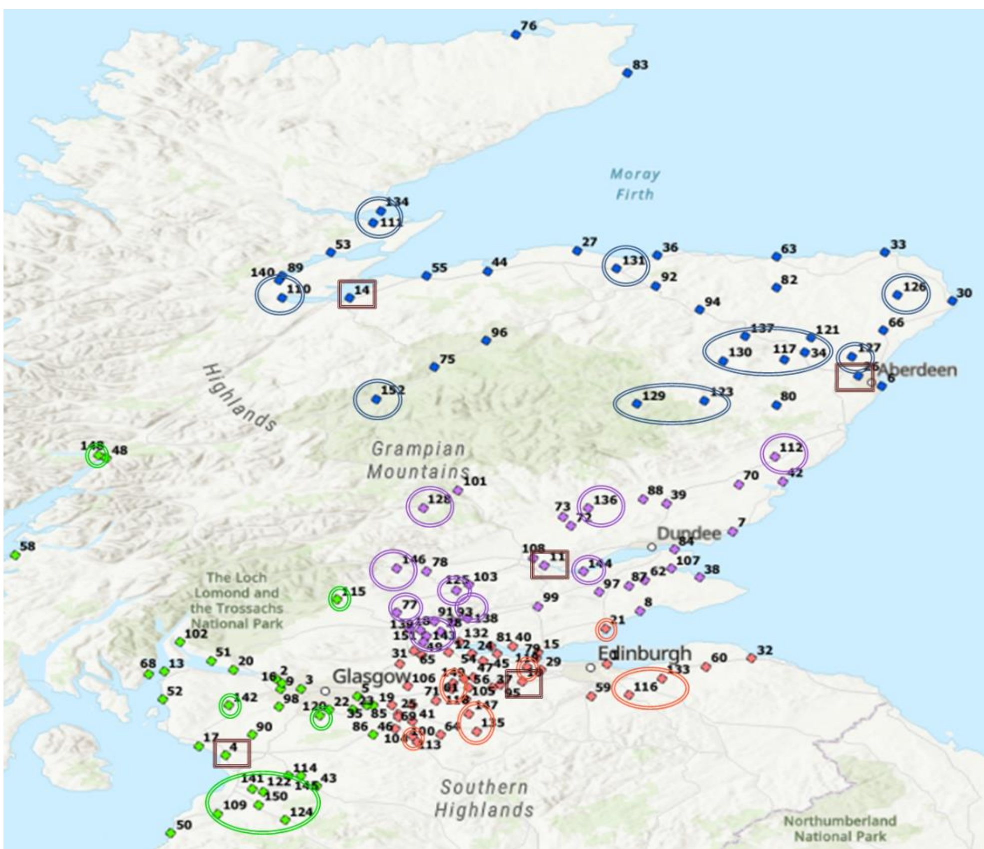


Figure 14: Selected locations of STP for different regions in Scotland where the constructed wetlands with $WOW_{biochar}$ could be installed (circles) and selected STP for cellulose recovery (squares)

5.4 Investment costs

Table 28 shows the proportion of wastewater treatment plants that are equipped with a constructed wetland with $WOW_{biochar}$, broken down by region. It also shows the duration of expansion and the investment costs for these plants. The constructed wetland accounts for the largest share of the costs. The transport costs, on the other hand, account for only a very small share of the total costs, less than 1%.

Table 28: Investment cost of constructed wetlands with $WOW_{biochar}$ in Scotland

	Share of WWTP (load entering < 5000 PE) that could be expanded by RSF [%]	Expansion time [a]	Total cost (Filter+$WOW_{Biochar}$+Transport) [€]	$WOW_{Char.}$ Costs [€]	$WOW_{Char.}$ Costs [%]	Filter costs [€]	Filter costs [%]	Transport costs [€]	Transport costs [%]
REGION 1	39%	11	23,917,875 €	2,819,261 €	11.79%	21,050,123 €	88.01%	48,491 €	0.20%
REGION 2	29%	4	16,063,112 €	1,719,315 €	10.70%	14,306,066 €	89.06%	37,731 €	0.23%
REGION 3	21%	4	15,175,986 €	1,756,170 €	11.57%	13,395,278 €	88.27%	24,538 €	0.16%
REGION 4	31%	2	18,530,290 €	2,148,413 €	11.59%	16,336,015 €	88.16%	45,863 €	0.25%

5.5 Impact on water quality

Figure 15 shows the potential diclofenac reduction for each regions and for Scotland as a whole that can be achieved with the integration of constructed wetlands with $WOW_{biochar}$. In Region 1, which is characterised by smaller STPs, the theoretically possible reduction is 5 %. The total reduction for Scottland is only 2 %. The low impact on the total pollutant reduction is due to the fact that the small STPs (< 5,000 p.e.) only have a low share of 2.5 % compared to other size classes in Scotland (see Figure 16). Although the overall impact is very low, the improvement which could be achieved at small river catchment areas could be of relevance.

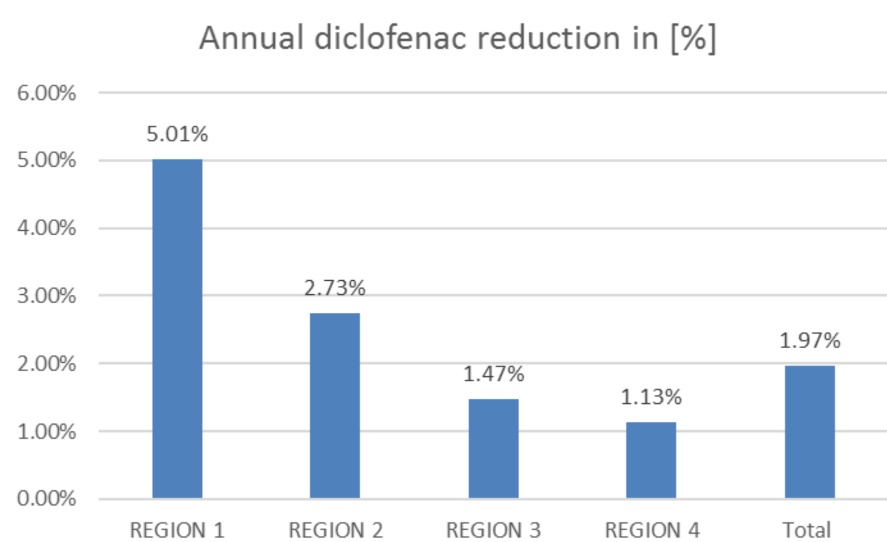


Figure 15: Annual diclofenac reduction in % for Scottland

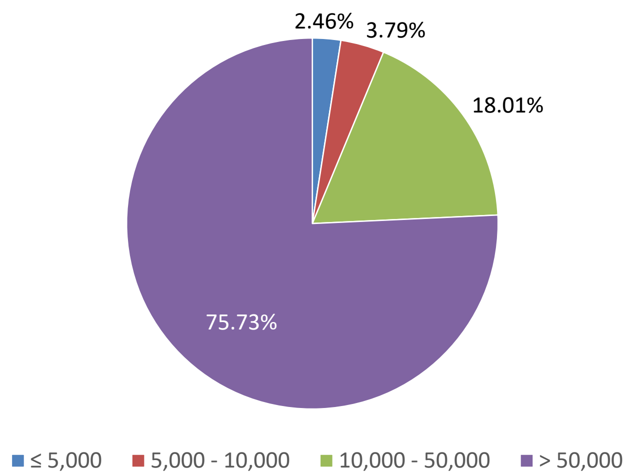


Figure 16: Share of the Diclofenac load in the effluent for Scotland depending on the size of STP in [%]

6 Conclusions

The case studies show that the combination of cellulose recovery with fine sieves in order to provide $WOW_{Biochar}$ for constructed wetlands for micro pollutant removal in a river catchment is possible. Although the load reduction from small STP in comparison to the whole load from all STP in the catchment is small, the impact on the river quality for small receiving water bodies is high. For implementation further investigation into hydraulic load and invest costs is necessary.

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8 Abbreviations

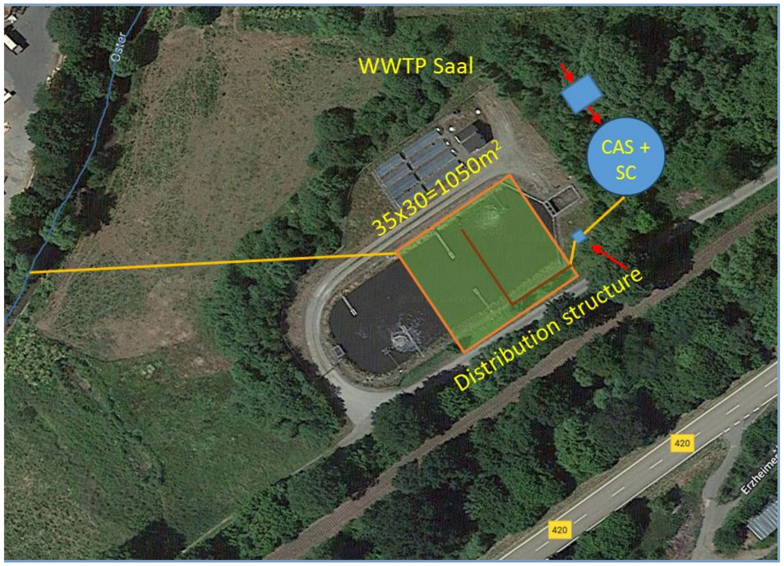
p.e.	People equivalent
STP	Wate water treatment plant
COD	Chemical oxygen demand
$WOW_{Biochar}$	Biochar produced from 50% straw and 50% cellulose
BB	Activated sludge srocess
DN	Denitrification/ Nitrification
AS	Aerobic sludge stabilisation
BT	Wastewater treatment pond
STK	Submerged rotary body
EVS	Entsorgungsverband Saar
MQ	Mean flow rate

9 Appendix

9.1 Steckbriefe Saarland

WWTP Saal
constructed wetland with activated carbon additive

Site plan

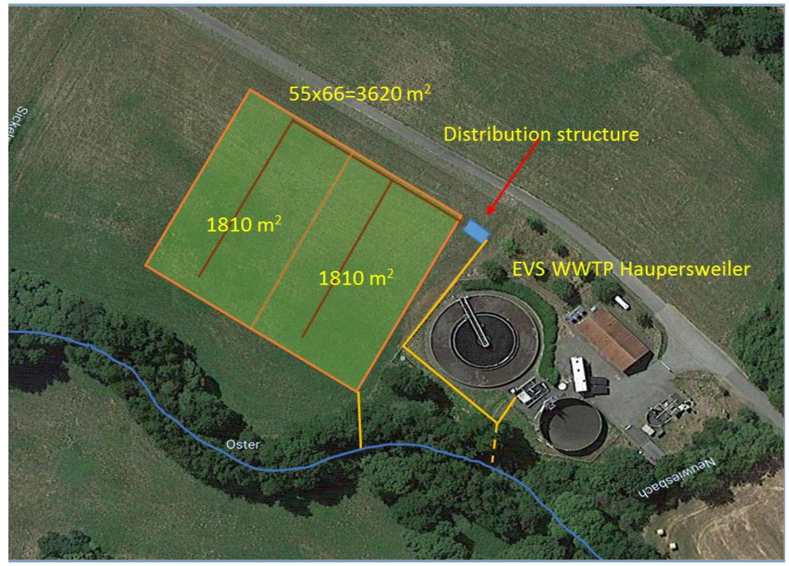


Technical details

Plant details		Fine sieve / Volume	
		Volume: Sand [m³]	580
Capacity in People Equivalent [PE]	1,900	Volume: WOW_{Char} [m³]	102
Connected PE [PE]	1,632	WOW_{Char} amount [t]	153,563
Annual flow [m³/a]	204,633	Mean hydraulic surface rate [L/m²·d]	274
Infiltration water percentage [%]	N.A.	Maximum hydraulic surface rate [L/m²·d]	518
• Wastewater Treatment Pond		Mean filter velocity [m/h]	0.011
		Maximum filter velocity [m/h]	0.022
Constructed wetlands details		**Fine sieve**	
Filter surface area [m²]	1,050	Fine sieve number [-]	-
Filter volume [m³]	683	Maximum hydraulic capacity [m³/h]	-
Width [m]	35	**Costs**	
Length [m]	30	Investment costs [Mio. €]	1.54 €
Depth [m]	0.65	• Constructed wetland [Mio. €]	1.54 €
		• Fine sieve [Mio. €]	-

WWTP Haupersweiler
constructed wetland with activated carbon additive

Site plan



Technical details

Plant details			
		Volume: Sand [m³]	2,006
Capacity in People Equivalent [PE]	4,000	Volume: WOW_{Char} [m³]	354
Connected PE [PE]	3,033	WOW_{Char} amount [t]	531
Annual flow [m³/a]	714,102	Mean hydraulic surface rate [L/m²·d]	324
Infiltration water percentage [%]	75	Maximum hydraulic surface rate [L/m²·d]	529
• Aerobic sludge stabilisation		Mean filter velocity [m/h]	0.013
• Activated sludge process with deni- and nitrifikation		Maximum filter velocity [m/h]	0.022
Constructed wetlands details		**Fine sieve**	
Filter surface area [m²]	3,630	Fine sieve number [-]	2
Filter volume [m³]	2,360	Maximum hydraulic capacity [m³/h]	484
Width [m]	55	**Costs**	
Length [m]	66	Investment costs [Mio. €]	3.29 €
Depth [m]	0.65	• Constructed wetland [Mio. €]	2.59 €
		• Fine sieve [Mio. €]	0.71 €

WWTP Fürth
constructed wetland with activated carbon additive

Site plan

Technical details

Plant details			
Capacity in People Equivalent [PE]	1,750	Volume: Sand [m³]	1,180
Connected PE [PE]	1,482	Volume: WOW_{Char} [m³]	208
Annual flow [m³/a]	193,971	WOW_{Char} amount [t]	312,244
Infiltration water percentage [%]	60	Mean hydraulic surface rate [L/m²·d]	199
• Sequencing Batch Reactor (SBR)		Maximum hydraulic surface rate [L/m²·d]	266
		Mean filter velocity [m/h]	0.008
		Maximum filter velocity [m/h]	0.011
Constructed wetlands details		**Fine sieve**	
Filter surface area [m²]	2,135	Fine sieve number [-]	-
Filter volume [m³]	1,388	Maximum hydraulic capacity [m³/h]	-
Width [m]	35	**Costs**	
Length [m]	61	Investment costs [Mio. €]	2.05 €
Depth [m]	0.65	• Constructed wetland [Mio. €]	2.05 €
		• Fine sieve [Mio. €]	-

WWTP Werschweiler
constructed wetland with activated carbon additive

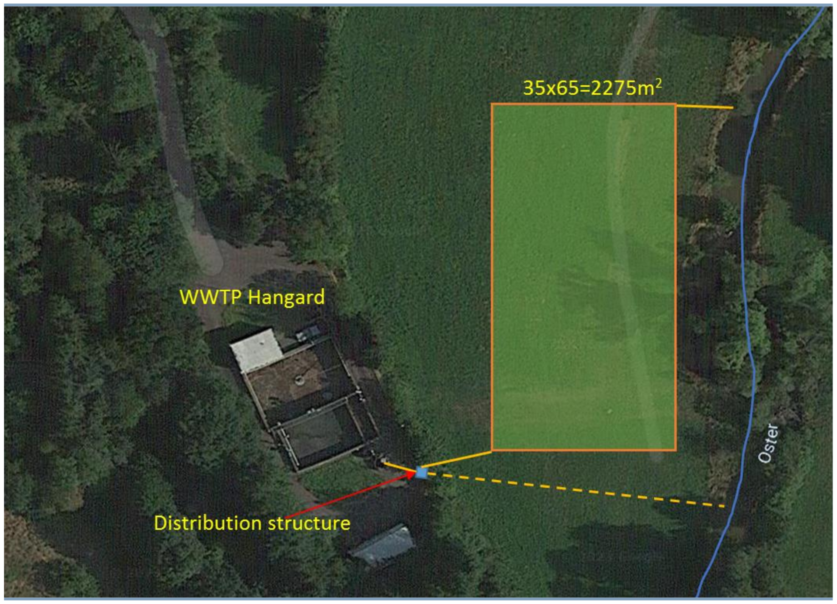
Site plan

Technical details

Plant details			
Capacity in People Equivalent [PE]	600	Volume: Sand [m³]	116
Connected PE [PE]	525	Volume: WOW_{Char} [m³]	20
Annual flow [m³/a]	N.A.	WOW_{Char} amount [t]	30,713
Infiltration water percentage [%]	N.A.	Mean hydraulic surface rate [L/m²·d]	N.A.
• Wastewater Treatment Pond		Maximum hydraulic surface rate [L/m²·d]	N.A.
		Mean filter velocity [m/h]	N.A.
		Maximum filter velocity [m/h]	N.A.
Constructed wetlands details		**Fine sieve**	
Filter surface area [m²]	210	Fine sieve number [-]	-
Filter volume [m³]	137	Maximum hydraulic capacity [m³/h]	-
Width [m]	10	**Costs**	
Length [m]	21	Investment costs [Mio. €]	0.87 €
Depth [m]	0.65	• Constructed wetland [Mio. €]	0.87 €
		• Fine sieve [Mio. €]	-

WWTP Hangard
constructed wetland with activated carbon additive

Site plan

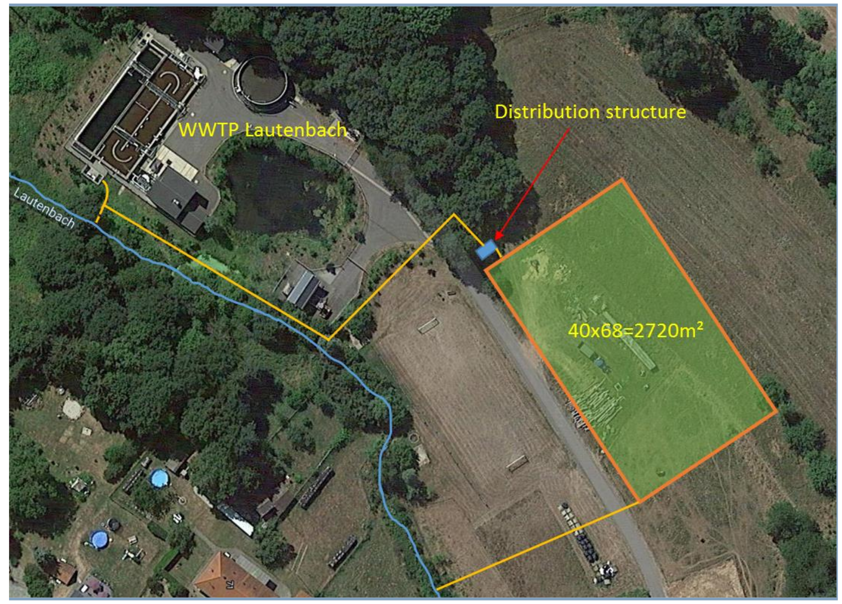


Technical details

Plant details		Volume: Sand [m³]	1,257
Capacity in People Equivalent [PE]	2,400	Volume: WOW_{Char} [m³]	222
Connected PE [PE]	1,806	WOW_{Char} amount [t]	332,719
Annual flow [m³/a]	207,288	Mean hydraulic surface rate [L/m²·d]	200
Infiltration water percentage [%]	62	Maximum hydraulic surface rate [L/m²·d]	266
• Aerobic sludge stabilisation		Mean filter velocity [m/h]	0.008
• Activated sludge process with deni- and nitrifikation		Maximum filter velocity [m/h]	0.011
Constructed wetlands details		**Fine sieve**	
Filter surface area [m²]	2,275	Fine sieve number [-]	-
Filter volume [m³]	1,479	Maximum hydraulic capacity [m³/h]	-
Width [m]	35	**Costs**	
Length [m]	65	Investment costs [Mio. €]	2.10 €
Depth [m]	0.65	• Constructed wetland [Mio. €]	2.10 €
		• Fine sieve [Mio. €]	-

WWTP Lautenbach
constructed wetland with activated carbon additive

Site plan

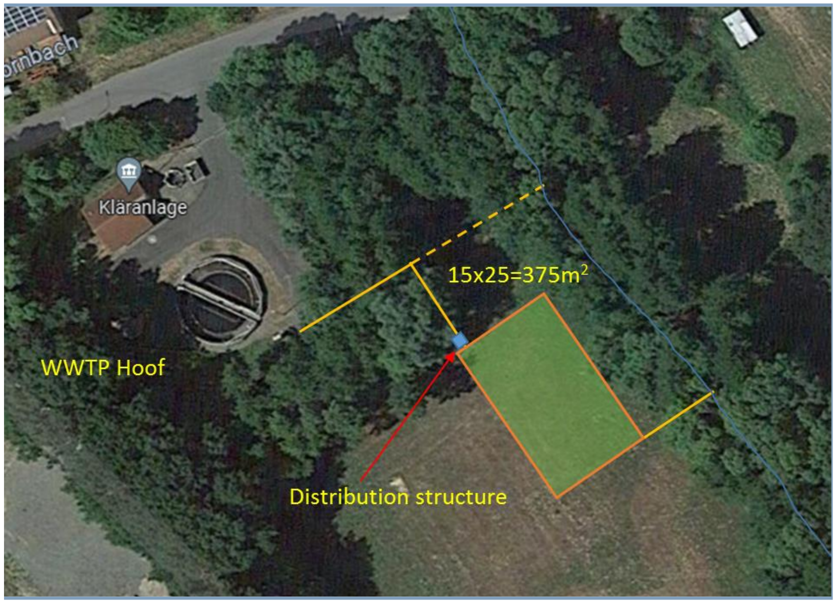


Technical details

Plant details		Volume: Sand [m³]	1,503
Capacity in People Equivalent [PE]	3,500	Volume: WOW_{Char} [m³]	265
Connected PE [PE]	3,118	WOW_{Char} amount [t]	397,800
Annual flow [m³/a]	235,991	Mean hydraulic surface rate [L/m²·d]	282
Infiltration water percentage [%]	35	Maximum hydraulic surface rate [L/m²·d]	529
• Aerobic sludge stabilisation		Mean filter velocity [m/h]	0.012
• Activated sludge process with deni- and nitrifikation		Maximum filter velocity [m/h]	0.022
Constructed wetlands details		**Fine sieve**	
Filter surface area [m²]	2,720	Fine sieve number [-]	-
Filter volume [m³]	1,768	Maximum hydraulic capacity [m³/h]	-
Width [m]	40	**Costs**	
Length [m]	68	Investment costs [Mio. €]	2.27 €
Depth [m]	0.65	• Constructed wetland [Mio. €]	2.27 €
		• Fine sieve [Mio. €]	-

WWTP Hoof
constructed wetland with activated carbon additive

Site plan

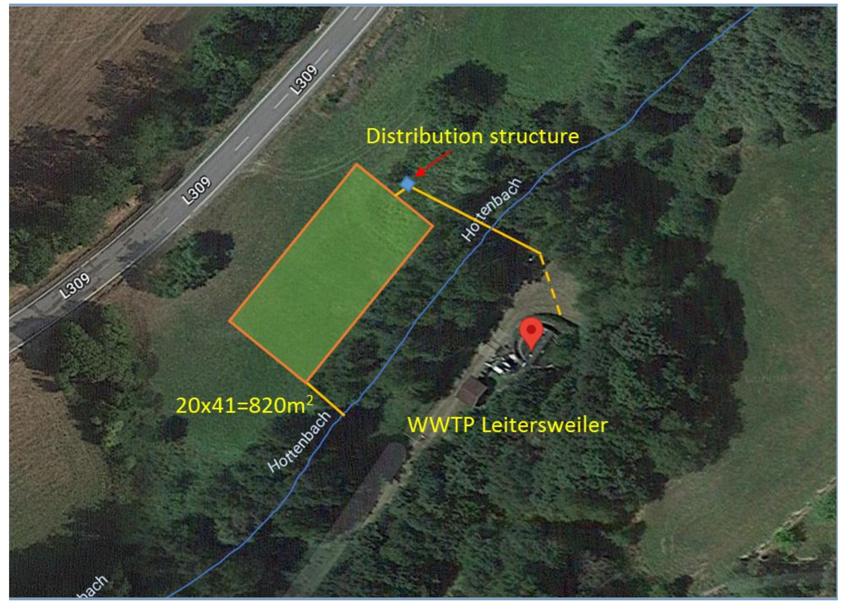


Technical details

Plant details			
		Volume: Sand [m³]	207
Capacity in People Equivalent [PE]	1,250	Volume: WOW_{Char} [m³]	37
Connected PE [PE]	935	WOW_{Char} amount [t]	54,844
Annual flow [m³/a]	N.A.	Mean hydraulic surface rate [L/m²·d]	N.A.
Infiltration water percentage [%]	N.A.	Maximum hydraulic surface rate [L/m²·d]	N.A.
• Aerobic sludge stabilisation		Mean filter velocity [m/h]	N.A.
• Activated sludge process with deni- and nitrifikation		Maximum filter velocity [m/h]	N.A.
Constructed wetlands details		**Fine sieve**	
Filter surface area [m²]	375	Fine sieve number [-]	-
Filter volume [m³]	244	Maximum hydraulic capacity [m³/h]	-
Width [m]	15	**Costs**	
Length [m]	25	Investment costs [Mio. €]	1.06 €
Depth [m]	0.65	• Constructed wetland [Mio. €]	1.06 €
		• Fine sieve [Mio. €]	-

WWTP Leitersweiler
constructed wetland with activated carbon additive

Site plan

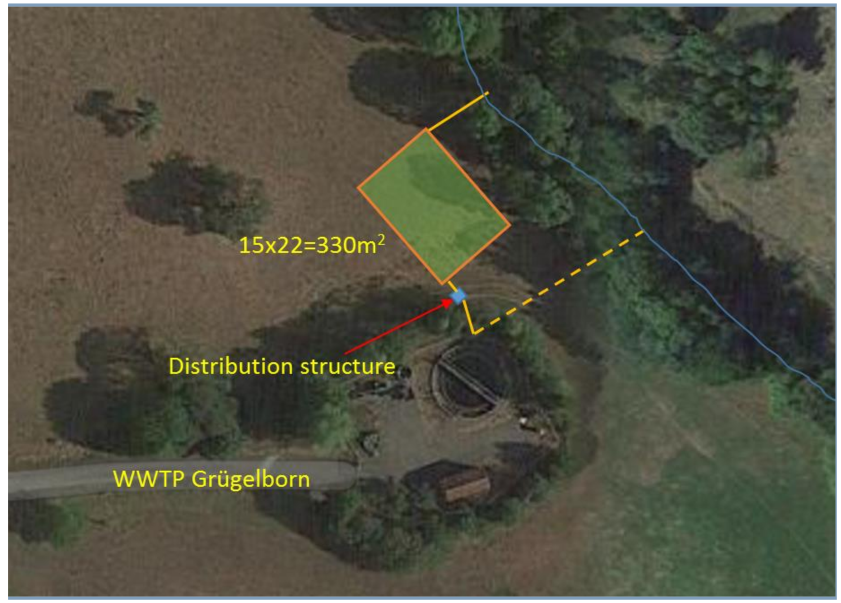


Technical details

Plant details			
		Volume: Sand [m³]	453
Capacity in People Equivalent [PE]	600	Volume: WOW_{Char} [m³]	80
Connected PE [PE]	517	WOW_{Char} amount [t]	119,925
Annual flow [m³/a]	73,471	Mean hydraulic surface rate [L/m²·d]	196
Infiltration water percentage [%]	64	Maximum hydraulic surface rate [L/m²·d]	262
• Aerobic sludge stabilisation		Mean filter velocity [m/h]	0.008
• Activated sludge process with deni- and nitrifikation		Maximum filter velocity [m/h]	0.011
Constructed wetlands details		**Fine sieve**	
Filter surface area [m²]	820	Fine sieve number [-]	-
Filter volume [m³]	533	Maximum hydraulic capacity [m³/h]	-
Width [m]	20	**Costs**	
Length [m]	41	Investment costs [Mio. €]	1.40 €
Depth [m]	0.65	• Constructed wetland [Mio. €]	1.40 €
		• Fine sieve [Mio. €]	-

WWTP Grügelborn
constructed wetland with activated carbon additive

Site plan



Technical details

Plant details		Volume: Sand [m³]	182
Capacity in People Equivalent [PE]	1,100	Volume: WOW_{Char} [m³]	32
Connected PE [PE]	815	WOW_{Char} amount [t]	48,263
Annual flow [m³/a]	N.A.	Mean hydraulic surface rate [L/m²·d]	N.A.
Infiltration water percentage [%]	N.A.	Maximum hydraulic surface rate [L/m²·d]	N.A.
• Aerobic sludge stabilisation		Mean filter velocity [m/h]	N.A.
• Activated sludge process with deni- and nitrifikation		Maximum filter velocity [m/h]	N.A.
Constructed wetlands details		**Fine sieve**	
Filter surface area [m²]	330	Fine sieve number [-]	-
Filter volume [m³]	215	Maximum hydraulic capacity [m³/h]	-
Width [m]	15	**Costs**	
Length [m]	22	Investment costs [Mio. €]	1.01 €
Depth [m]	0.65	• Constructed wetland [Mio. €]	1.01 €
		• Fine sieve [Mio. €]	-

9.2 Steckbriefe Irland

WWTP Graignuenamanagh Tinnahinch constructed wetland with activated carbon additive

Site plan

Technical details

Plant details		Volume: Sand [m³]	508
Capacity in People Equivalent [PE]	3,000	Volume: WOW_{Char} [m³]	90
Connected PE [PE]	2,267	WOW_{Char} amount [t]	134.550
Annual flow [m³/a]	N.A.	Mean hydraulic surface rate [L/m²·d]	N.A.
Infiltration water percentage [%]	N.A.	Maximum hydraulic surface rate [L/m²·d]	N.A.
• Aerobic sludge stabilisation		Mean filter velocity [m/h]	N.A.
• Activated sludge prozess with deni- and nitrifikation		Maximum filter velocity [m/h]	N.A.
Constructed wetlands details		**Fine sieve**	
Filter surface area [m²]	920	Fine sieve number [-]	-
Filter volume [m³]	598	Maximum hydraulic capacity [m³/h]	-
Width [m]	20	**Costs**	
Length [m]	46	Investment costs [Mio. €]	1.47 €
Depth [m]	0.65	• Constructed wetland [Mio. €]	1.47 €
		• Fine sieve [Mio. €]	-

WWTP Kilkenny City constructed wetland with activated carbon additive

Site plan

Technical details

Plant details		Volume: Sand [m³]	7,901
Capacity in People Equivalent [PE]	77,000	Volume: WOW_{Char} [m³]	1,394
Connected PE [PE]	35,643	WOW_{Char} amount [t]	2,091
Annual flow [m³/a]	3,523,345	Mean hydraulic surface rate [L/m²·d]	540
Infiltration water percentage [%]	n.a	Maximum hydraulic surface rate [L/m²·d]	720
• diffused aeration/clarification		Mean filter velocity [m/h]	0.023
• activated sludge process		Maximum filter velocity [m/h]	0.030
Constructed wetlands details		**Fine sieve**	
Filter surface area [m²]	14,300	Fine sieve number [-]	4
Filter volume [m³]	9,295	Maximum hydraulic capacity [m³/h]	484
Width [m]	50	**Costs**	
Length [m]	286	Investment costs [Mio. €]	11.30 €
Depth [m]	0.65	• Constructed wetland [Mio. €]	9.97 €
		• Fine sieve [Mio. €]	1.33 €

WWTP Thomastown
constructed wetland with activated carbon additive

Site plan

Technical details

Plant details			
Capacity in People Equivalent [PE]	7,500	Volume: Sand [m³]	785
Connected PE [PE]	3,522	Volume: WOW_{Char} [m³]	138
Annual flow [m³/a]	N.A.	WOW_{Char} amount [t]	208
Infiltration water percentage [%]	N.A.	Mean hydraulic surface rate [L/m²·d]	N.A.
• diffused aeration/clarification		Maximum hydraulic surface rate [L/m²·d]	N.A.
• activated sludge process		Mean filter velocity [m/h]	N.A.
		Maximum filter velocity [m/h]	N.A.
Constructed wetlands details		**Fine sieve**	
Filter surface area [m²]	1,420	Fine sieve number [-]	-
Filter volume [m³]	923	Maximum hydraulic capacity [m³/h]	-
Width [m]	20	**Costs**	
Length [m]	71	Investment costs [Mio. €]	1.73 €
Depth [m]	0.65	• Constructed wetland [Mio. €]	1.73 €
		• Fine sieve [Mio. €]	-

WWTP Callan
constructed wetland with activated carbon additive

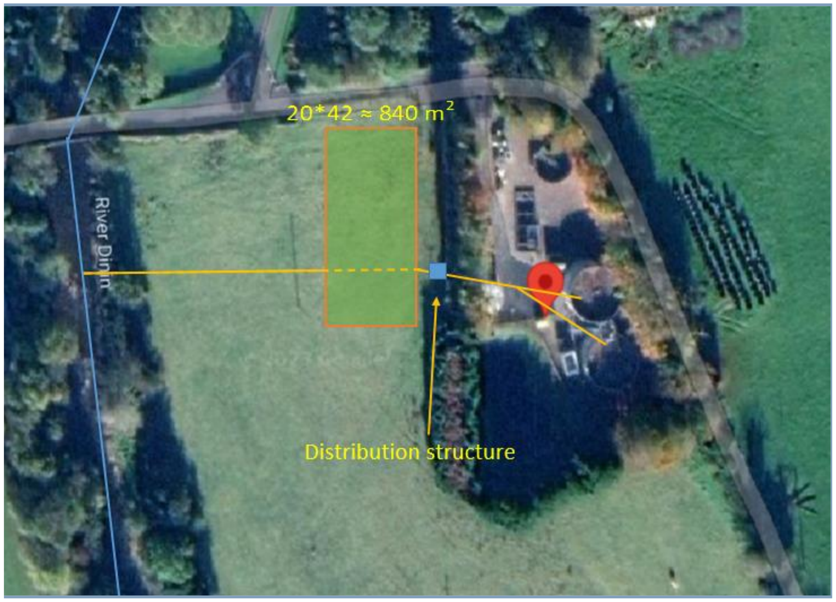
Site plan

Technical details

Plant details			
Capacity in People Equivalent [PE]	4,000	Volume: Sand [m³]	497
Connected PE [PE]	2,247	Volume: WOW_{Char} [m³]	88
Annual flow [m³/a]	N.A.	WOW_{Char} amount [t]	131.625
Infiltration water percentage [%]	N.A.	Mean hydraulic surface rate [L/m²·d]	N.A.
• diffused aeration/clarification		Maximum hydraulic surface rate [L/m²·d]	N.A.
• activated sludge process		Mean filter velocity [m/h]	N.A.
		Maximum filter velocity [m/h]	N.A.
Constructed wetlands details		**Fine sieve**	
Filter surface area [m²]	900	Fine sieve number [-]	-
Filter volume [m³]	585	Maximum hydraulic capacity [m³/h]	-
Width [m]	20	**Costs**	
Length [m]	45	Investment costs [Mio. €]	1.45 €
Depth [m]	0.65	• Constructed wetland [Mio. €]	1.45 €
		• Fine sieve [Mio. €]	-

WWTP Castlecomer
constructed wetland with activated carbon additive

Site plan

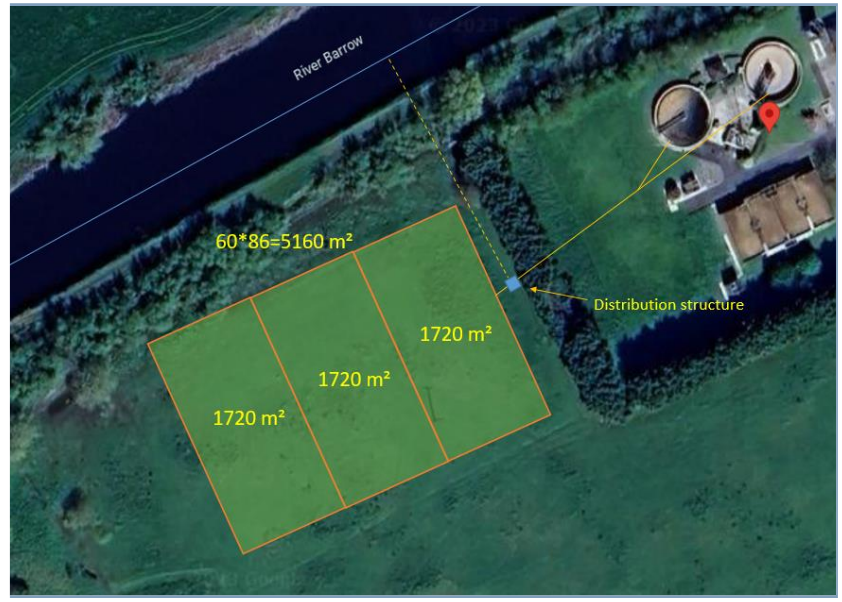


Technical details

Plant details			
		Volume: Sand [m³]	464
Capacity in People Equivalent [PE]	2,500	Volume: WOW_{Char} [m³]	82
Connected PE [PE]	2,077	WOW_{Char} amount [t]	123
Annual flow [m³/a]	N.A.	Mean hydraulic surface rate [L/m²·d]	N.A.
Infiltration water percentage [%]	N.A.	Maximum hydraulic surface rate [L/m²·d]	N.A.
• diffused aeration/clarification		Mean filter velocity [m/h]	N.A.
• activated sludge process		Maximum filter velocity [m/h]	N.A.
Constructed wetlands details		**Fine sieve**	
Filter surface area [m²]	840	Fine sieve number [-]	-
Filter volume [m³]	546	Maximum hydraulic capacity [m³/h]	-
Width [m]	20	**Costs**	
Length [m]	42	Investment costs [Mio. €]	1.42 €
Depth [m]	0.65	• Constructed wetland [Mio. €]	1.42 €
		• Fine sieve [Mio. €]	-

WWTP Muinebheag
constructed wetland with activated carbon additive

Site plan



Technical details

Plant details			
		Volume: Sand [m³]	2,851
Capacity in People Equivalent [PE]	5,500	Volume: WOW_{Char} [m³]	503
Connected PE [PE]	12,248	WOW_{Char} amount [t]	754.650
Annual flow [m³/a]	466,470	Mean hydraulic surface rate [L/m²·d]	198
Infiltration water percentage [%]	N.A.	Maximum hydraulic surface rate [L/m²·d]	264
• diffused aeration/clarification		Mean filter velocity [m/h]	0.008
• activated sludge process		Maximum filter velocity [m/h]	0.011
Constructed wetlands details		**Fine sieve**	
Filter surface area [m²]	5,160	Fine sieve number [-]	-
Filter volume [m³]	3,354	Maximum hydraulic capacity [m³/h]	-
Width [m]	60	**Costs**	
Length [m]	86	Investment costs [Mio. €]	3.05 €
Depth [m]	0.65	• Constructed wetland [Mio. €]	3.05 €
		• Fine sieve [Mio. €]	-

WWTP Paulstown
constructed wetland with activated carbon additive

Site plan

Technical details

Plant details			
Capacity in People Equivalent [PE]	1,000	Volume: Sand [m³]	221
Connected PE [PE]	1,000	Volume: WOW_{Char} [m³]	39
Annual flow [m³/a]	N.A.	WOW_{Char} amount [t]	58.500
Infiltration water percentage [%]	N.A.	Mean hydraulic surface rate [L/m²·d]	N.A.
• diffused aeration/clarification		Maximum hydraulic surface rate [L/m²·d]	N.A.
• activated sludge process		Mean filter velocity [m/h]	N.A.
		Maximum filter velocity [m/h]	N.A.
Constructed wetlands details		**Fine sieve**	
Filter surface area [m²]	400	Fine sieve number [-]	-
Filter volume [m³]	260	Maximum hydraulic capacity [m³/h]	-
Width [m]	25	**Costs**	
Length [m]	16	Investment costs [Mio. €]	1.08 €
Depth [m]	0.65	• Constructed wetland [Mio. €]	1.08 €
		• Fine sieve [Mio. €]	-

WWTP Ballyragget
constructed wetland with activated carbon additive

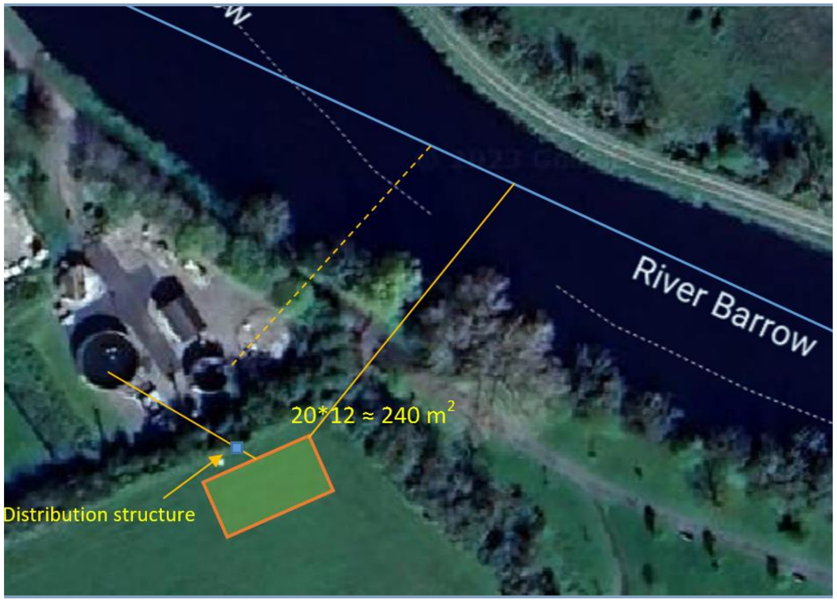
Site plan

Technical details

Plant details			
Capacity in People Equivalent [PE]	1,920	Volume: Sand [m³]	431
Connected PE [PE]	1,920	Volume: WOW_{Char} [m³]	76
Annual flow [m³/a]	N.A.	WOW_{Char} amount [t]	114.075
Infiltration water percentage [%]	N.A.	Mean hydraulic surface rate [L/m²·d]	N.A.
• diffused aeration/clarification		Maximum hydraulic surface rate [L/m²·d]	N.A.
• activated sludge process		Mean filter velocity [m/h]	N.A.
		Maximum filter velocity [m/h]	N.A.
Constructed wetlands details		**Fine sieve**	
Filter surface area [m²]	780	Fine sieve number [-]	-
Filter volume [m³]	507	Maximum hydraulic capacity [m³/h]	-
Width [m]	20	**Costs**	
Length [m]	39	Investment costs [Mio. €]	1.38 €
Depth [m]	0.65	• Constructed wetland [Mio. €]	1.38 €
		• Fine sieve [Mio. €]	-

WWTP Goresbridge constructed wetland with activated carbon additive

Site plan



Technical details

Plant details			
Capacity in People Equivalent [PE]	600	Volume: Sand [m³]	133
Connected PE [PE]	600	Volume: WOW_{Char} [m³]	23
Annual flow [m³/a]	N.A.	WOW_{Char} amount [t]	35.100
Infiltration water percentage [%]	N.A.	Mean hydraulic surface rate [L/m²·d]	N.A.
• diffused aeration/clarification		Maximum hydraulic surface rate [L/m²·d]	N.A.
• activated sludge process		Mean filter velocity [m/h]	N.A.
		Maximum filter velocity [m/h]	N.A.
Constructed wetlands details		**Fine sieve**	
Filter surface area [m²]	240	Fine sieve number [-]	-
Filter volume [m³]	156	Maximum hydraulic capacity [m³/h]	-
Width [m]	20	**Costs**	
Length [m]	12	Investment costs [Mio. €]	0.91 €
Depth [m]	0.65	• Constructed wetland [Mio. €]	0.91 €
		• Fine sieve [Mio. €]	-

WWTP Gowran constructed wetland with activated carbon additive

Site plan

Technical details

Plant details			
Capacity in People Equivalent [PE]	826	Volume: Sand [m³]	188
Connected PE [PE]	826	Volume: WOW_{Char} [m³]	33
Annual flow [m³/a]	N.A.	WOW_{Char} amount [t]	49.725
Infiltration water percentage [%]	N.A.	Mean hydraulic surface rate [L/m²·d]	N.A.
• diffused aeration/clarification		Maximum hydraulic surface rate [L/m²·d]	N.A.
• activated sludge process		Mean filter velocity [m/h]	N.A.
		Maximum filter velocity [m/h]	N.A.
Constructed wetlands details		**Fine sieve**	
Filter surface area [m²]	340	Fine sieve number [-]	n.a
Filter volume [m³]	221	Maximum hydraulic capacity [m³/h]	n.a
Width [m]	20	**Costs**	
Length [m]	17	Investment costs [Mio. €]	1.02 €
Depth [m]	0.65	• Constructed wetland [Mio. €]	1.02 €
		• Fine sieve [Mio. €]	-