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Evaluation of a Modular Filter Concept to Reduce Microplastics and Other Solids from Urban Stormwater Runoff

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Abstract: This paper describes an innovative Decentralized Technical Sustainable Drainage System (SuDS) concept, which is based on technical devices, such as sieves, sedimentation barriers, floating barriers and a magnetic module, which addresses, mainly, the fine matter. The SuDS is designed as a retrofit system so that no costly and time-consuming conversion measures are necessary. Due to the possibility of free configurability of individual modules in the three levels, road, gully and drain, a novel solution approach is presented, which is not available on the market, for a reduction in solids in general and microplastics in particular. The retention performance of selected modules and their combinations is demonstrated by means of bench tests according to the test procedure of the German Institute for Construction Engineering (DIBt) for the evaluation of decentralized treatment systems. Four different rain intensities, from light to medium up to heavy rain, are charged to the filter modules. Collected and fractionated road-deposited sediment (RDS) was selected as the test substance (10 kg). Additional tests with tyre powder, PE pellets, cigarette butts and candy wrappers helped to make clear the filter process of the particulate matter. The retention performance was determined by the mass balance between the defined dosage and at the outlet. For this purpose, the total volume flow of the effluent was passed over a stainless-steel sieve with a diameter of 600 mm and a mesh size of 20 µm. For the test substance, RDS retention rates up to 97% were measured. Very fine matter, particularly, was technically challenging to obtain; <63 µm up to 66% could be retained by the filter modules. Modules in the road space, such as porous asphalt or additional retention spaces, in the area of the curb as well as direct infiltration in the road drainage shaft are theoretically described and discussed. The outlook also addresses the potential of an intelligent network to reduce the input of pollution from urban stormwater runoff.

Keywords: sustainable drainage system; microplastic; road runoff; hot spot; modular; lab-scale testing procedures

Citation: Venghaus, D.; Neupert, J.W.; Barjenbruch, M. Evaluation of a Modular Filter Concept to Reduce Microplastics and Other Solids from Urban Stormwater Runoff. *Water* **2023**, *15*, 506. https://doi.org/10.3390/w15030506

Academic Editors: Jens Tränckner and Jin Zhang

Received: 13 December 2022
Revised: 20 January 2023
Accepted: 21 January 2023
Published: 27 January 2023

1. Introduction

Regarding street runoff water, the different sewage systems first have to be taken into account. If domestic wastewater and stormwater are routed together to the treatment plant, this is referred to as a combined sewer system. In a combined system, the stormwater runoff is sufficiently treated in the treatment plant. At the effluent of the treatment plant, total suspended solid (TSS) values of less than or equal to 6 mg/L [1] are achieved. Microplastics can be understood as part of the TSS. In Scheer et al. [2], a mean microplastic quantity of 8 µg/L was detected in the wastewater treatment plant effluent, resulting in a microplastic retention performance of >99%. So far, investigations show, for combined sewage, the highest concentrations of microplastics for polyethylene (PE), but also polystyrene (PS), polypropylene (PP) and styrene–butadiene rubber (SBR), representing that tyre abrasion could be identified [1,2]. High microplastic inputs are also suspected from combined sewer overflows, but the data availability is very poor here. First investigations showed microplastic concentrations of 33,010 µg/L [2]. In the case of separate sewer systems, domestic wastewater is discharged to the wastewater treatment plant and treated accordingly, and stormwater is discharged separately, mostly without any treatment, with maximum TSS concentrations of 657 mg/L [3] to 952 mg/L [4] into nearby surface waters. The quality is strongly dependent on the type and use of the corresponding catchment. In Scheid et al. [2], PE concentrations averaging 44–249 µg/L and SBR concentrations averaging 9–89 µg/L were detected in the storm sewer. Initial approaches to characterization have already been made in DWA Worksheet A 102 as a recommendation, which is not legally binding [5]. Microplastics are not considered separately here. For different inner-city driving situations, curves show up to 7-times and intersections with traffic lights show up to 3-times higher concentrations of SBR compared to straight road sections. These tyre-wear-related hot spots could be addressed with suitable filter solutions and optimized street cleaning [6].

According to the DWA M 378, 1 to 1.4 million tons of road sweepings are generated in Germany every year [7]. It is a complex mixture of materials entering the aquatic environment and some of them are toxic. The composition of road sweepings varies significantly by traffic volume, geographic location, land use of the surrounding seasonal characteristics and length of dry periods. In addition to mineral components (40–80%), organic particles (0–35%) and amorphous material (10–40%), microplastics play a growing role in the composition of road dirt [7].

Baensch-Baltruschat et al. [8] showed that, in Germany in 2021, about 98,370 t of tyre material ended up in the environment. From urban roads, potentially 16,820 t are flooded into nearby surface water bodies, such as lakes and rivers. Not to be neglected is the share of littering, such as cigarette butts and packaging waste, in road dirt. These small particles and their contents are suspected to harm aquatic organisms [9]. The aim is to minimize water pollution by treating road runoff depending on the catchment area and, thus, to contribute to an improvement in the aquatic environment, such as rivers, lakes and seas.

In order to reduce the input of these pollutants into the aquatic environment, there are measures for manual and mechanical street cleaning and SuDS for decentralized or semi-centralized treatment of stormwater runoff [10].

Street cleaning is currently the only comprehensively applied method to reduce the potential input of pollutants to surface waters, but it is non-specific.

Green and technical (semi)-centralized systems, such as grassed swale and soil filters, are connected to lager catchment areas [11]. Another option offers decentralized systems for small catchment areas, which are related to a single gully. Here, compact systems for new construction and remodeling or so-called retrofit systems, which can be retrofitted in the existing gully without major construction measures, are available. The systems developed up to now cannot be adapted to the different catchment areas.

This motivated the development of modular solutions that can be selected and combined depending on the catchment area.

A test procedure is presented that was originally developed for the approval of decentralized SuDS for infiltration of road runoff. An official testing protocol for direct discharge of road runoff into surface waters is currently not available [11].

For the evaluation of the retention rate of selected modules, defined tests were carried out on special test stands at TU Berlin.

2. Materials and Methods

2.1. Conceptual Design of the Modules

The modules were developed according to the basic separation process filtration, sieving, sedimentation and adsorption (magnet), and have the goal to retain solid-related pollutants. The modules address both pollutants that are generated directly on the road surface and those that are introduced into the road area from outside. In this case, it is assumed that the pollutants mainly accumulate in the peripheral area of the roadway [12,13]. The technical requirements are defined by the physical properties of density, size and adhesion as well as low maintenance requirements. The total mass of pollutants that can be retained is limited by the available retention volume. This results in the additional requirement to realize as much retention volume as possible. The corresponding catchments can be described by characterizing them by season, type of use and vegetation [5].

The focus lies in particulate pollutants. Possibilities for the retention of dissolved substances (e.g., activated charcoal) from wastewater and the influence of different pH values were not considered [14,15].

Important criteria in the conception phase were the definition of different types of hot spots for different pollutants and their loads as well as the time horizon for which a module should be installed. The most relevant criteria are shown in Table 1.

Table 1. Criteria of use case scenarios.

Criteria	Parameter
Permanent	Till the next necessary maintenance
Temporary	Defined time period
Event area	Littering of larger fragments and single use products
Residential area	Leaves, pollen, sand, wood, animal excrement and other organic matter
Commercial and industrial area	Tyre abrasion, sand, break abrasion, plastic pellets
Parking area	Tyre abrasion, sand, break abrasion
Much vegetation	Leaves, pollen, sand, wood
Traffic hot spot	Tyre abrasion, break abrasion
Recreation area	Leaves, pollen, sand, wood, infiltration-capable runoff

In addition to the actual pollutants emitted, external factors also play an important role in the evaluation of the pollutant load recorded in the stormwater runoff. These include weather forecast, street-cleaning performance and intervals, and seasonal differences in vegetation or intensity of use. These include, for example, temporarily increased traffic volumes or events in the catchment area, such as public festivals, Christmas markets and similar major events, as well as construction-site operations and traffic accidents. Particularly for temporarily limited pollution peaks, it seems sensible to integrate a suitable, easily retrofitted filter element into existing work processes, if possible.

During the conceptual design of the filter modules, the three areas of street, gully and drain were defined first. This structure allows for the selection of individual or combined retention devices for each gully and the associated catchment area. Table 2 shows the module concepts in the development phase, for the three levels: road, gully and drain.

Table 2. Overview and evaluation of the tested filter modules.

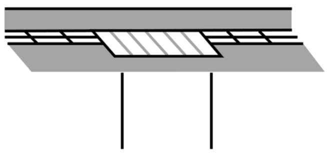
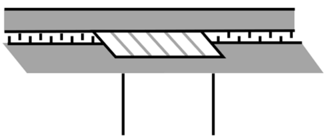
#	Filter Module	Position	Concept	Use Case	Lab Test
1	Side grid	Road/curb		Permanent Event area Much vegetation Residential area	No
2	Retention space	Road/curb		Permanent Traffic hot spot Parking area Commercial and industrial areas	No

Table 2. *Cont.*

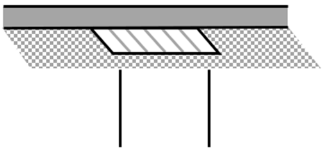
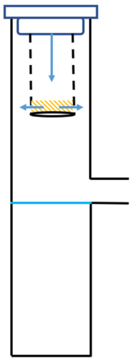
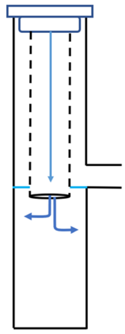
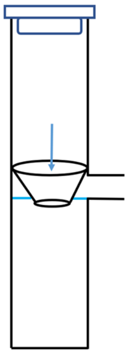
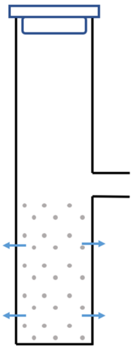
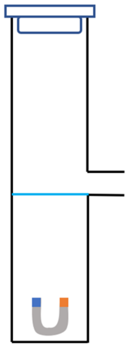
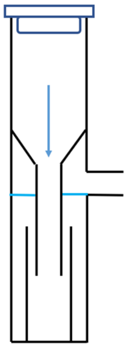
#	Filter Module	Position	Concept	Use Case	Lab Test
3	Sedimentation in road	Road/pavement		Permanent Traffic hot spots Parking area Commercial and industrial areas	No
4	Optimized foliage basket incl. granulate	Gully/top		Temporary or permanent Traffic hot spots Parking area Commercial and industrial areas	Yes
5	Mesh skirt	Gully/top		Temporary or permanent Event area Much vegetation Residential area Parking area Commercial and industrial area	Yes
6	Funnel	Gully/insert		Temporary or permanent Event area Much vegetation Residential area Parking area Commercial and industrial area	Yes
7	Infiltration	Drain/construction		Permanent No traffic Residential area Much vegetation Recreation area	No

Table 2. *Cont.*

#	Filter Module	Position	Concept	Use Case	Lab Test
8	Magnet module	Drain/insert		Temporary or permanent Traffic hot spots Industry area Parking area	Yes
9	Sedimentation walls	Drain/insert		Permanent Traffic hot spots Industry area Parking area	Yes

For the street area, Module 1 provides a lateral inlet grating with a rear drainage channel, which leads to the gully, in the curb area. The main aim is to keep as much coarse dirt as possible in the gutter area and, at the same time, to drain off the street runoff water. The retained materials can be removed by street cleaning.

Module 2 is designed to provide additional retention space below the curb and to retain floating and sedimentable materials by alternating flow barriers at the top and bottom. Again, water will be directed to the storm drain and cleaning of the retention areas will be accomplished through suction by the street-sweeping vehicle.

Module 3 porous asphalt can be used at the edge of the roadway to provide additional retention space for fine and sedimentable materials through an open-pore structure. The runoff water continues to be directed towards the gully and maintenance is carried out by the mechanical street-cleaning system, with a combination of rotating cleaning brushes and automatic suction.

All modules in the street space essentially aim to provide additional retention space for solids outside the gully.

For the level of the gully, Module 4 is based on the approach of the existing leaf basket in order to separate solids from the incoming runoff water by means of a screen structure.

The mesh skirt (module 5) is essentially intended to guide the flow of the incoming road runoff water through the wet sludge trap area of the gully and, at the same time, to allow for lateral runoff at any time via a defined pore size.

Module 6 follows the principle of a funnel and is designed to reduce the turbulence of the entering water to allow for better sedimentation of particles.

All gully modules have to be cleaned by the street-cleaning service during a regular maintenance interval and the retained pollutants have to be extracted from the gully.

For the level of the drain, Module 7 (infiltration) focuses on maintaining the local water balance. Infiltration in the gully at the site would, thus, discharge less water. However, this is only worth considering if the combination with other modules can guarantee sufficient cleaning performance in advance.

The magnetic module (module 8) is particularly intended to “hold” the fine fraction < 63 μm without clogging.

The sedimentation walls module is intended to reduce the flow velocity in the gully, retaining floating and sedimentable materials, similar to module 2.

All modules in the drain have to be cleaned via street cleaning at a regular maintenance appointment and the retained pollutants have to be extracted from the gully.

Not considered here is the potential of the networking of freely available user data—on the one hand, a reduction in emissions by optimized or anticipatory traffic routing and, on the other hand, a reduction in emissions by networking weather forecast data and street-cleaning operations. This offers the possibility of removing pollutants as close as possible to a rain event, thus, reducing the load on the filter and extending maintenance intervals. The performance of intelligent networking is not part of the investigations. The corresponding potential is discussed below with regard to filter service intervals.

2.2. Evaluation Method and Test Procedure

An important premise for the test stand investigations and comparability of the retention efficiencies of different filter modules is the representativeness of the test design. In the following section, the rainfall intensities and durations are defined and the quality and quantity of the test substances are described.

The test stand of the Department of Urban Water Management is located in Peter-Behrens-Halle on the premises of the TIB building complex at the Technical University of Berlin. The setup complies with the requirements according to the “Approval principles for stormwater treatment plants Part 1: Systems for decentralized treatment of wastewater from motor vehicle traffic areas for subsequent infiltration into soil and groundwater” of DIBt. The test implementation is based on a study by the Bavarian State Office for the Environment (LfU). In this study, a proposal is made for rain intensities to investigate decentralized precipitation water-treatment systems with the accruing rainwater from metal roof runoff [16]. The LfU proposes 4 different rainfall intensities ranging from 2.5 to 100 l*(s*ha)-1 for the investigations. The test duration decreases with increasing rainfall intensity and ranges from 480 to 15 min. These proposed test rainfall intensities are used, among other things, in the DIBt approval principle for decentralized stormwater systems and the test specification for decentralized treatment systems for traffic area runoff with subsequent discharge into the receiving water [17,18].

The test stand (Figure 1) was used to determine the retention performance of the SuDS modules investigated. The test stand consists of a storage tank (10 m^3), a centrifugal pump, two measuring sections, each with a magnetic-inductive flow meter (MFM) and electric control valve, a dosing station (rotary valve), a transparent gully (decentralized purification system) and an intermediate tank for the discharge. The measuring sections consist of a main line in DN 100 for the conveyance of flows from 3 L/s to 16 L/s and a secondary line in DN 25 for the conveyance of flows < 3 L/s and can, thus, simulate any precipitation dynamics of connecting areas from 250 m^2 to 1000 m^2. The flow is regulated by a magnetic-inductive flow meter and Siemens SIMATIC SP3 software (Karlsruhe, Germany). In order to sample the run-off water, a 20 μm stainless-steel sieve with a diameter of 600 mm was used to separate the rinsed test materials from the complete flow at the effluent, followed by fractionation by wet sieving, drying and weighing. For fractionating the sample, a sieve cascade of six sieves with mesh sizes of 1000 μm, 500 μm, 250 μm, 125 μm, 63 μm and 20 μm was installed on a shaking tower for 5 min. After washing down, the solids were dried for 10 days at 60 degrees. Due to the lower separation limit of 20 μm when sampling, in this work, the fine section of the TSS is defined as TSS_{fine} within a size range of 20–63 μm sieves.

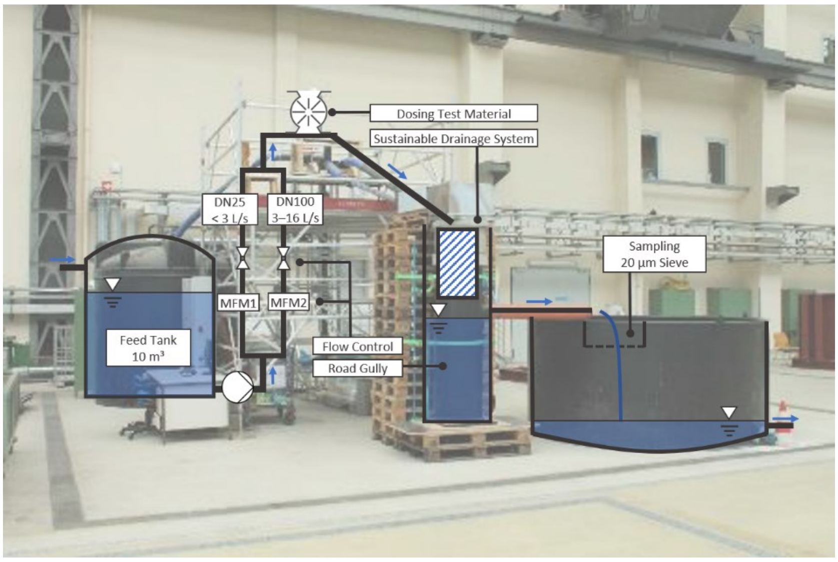


Figure 1. Test stand in the Department of Urban Water Management at the TU of Berlin according to DIBt requirements.

For the tests of the filter modules in the standard shaft, a connection area of 400 m^2 was assumed. The total test is divided into 4 partial tests. Table 3 shows the characteristics of the partial tests.

Table 3. Total test for standard shaft [17].

Partial Test	Test Duration [min]	Volume Flow [$\frac{L}{s}$]	Volume [L]	Total Freight Share [%]
1	240 *	0.10	1440	50
2	100 *	0.24	1440	33
3	48	1.00	2880	17
4	15	4.00	3600	-
Total	403	/	9360	100

Note: * For reasons of practicability, the test duration was halved according to the TU's specifications.

Preliminary testing of the prototype filter modules was carried out in a transparent miniature gully with 16.7% of the volume of the standard gully. The inflow was controlled by a float-flow meter and then directed onto a PVC chute. A shaker chute was used to continuously dose the test material to the inflow of the miniature gully into which the various prototypes were inserted. At the outlet of the gully, a sieve cascade (1000 µm–20 µm) was used to collect the test material that was not retained.

The amount of test material, as well as the volume of the flow, was adjusted by a factor of 0.167 according to the size of the standard gully. The resulting discharge volumes are shown in Table 4.

Table 4. Partial tests 1–3 for miniature shaft.

Partial Test	Test Duration [min]	Volume Flow [$\frac{L}{s}$]	Volume [L]	Total Freight Share [%]
1	240 *	60	240	50
2	100 *	144	240	33
3	48	600	480	17
total	388	/	960	100

Note: * For reasons of practicability, the test duration was halved according to the TU's specifications.

2.3. Test Substances

The DIBt test protocol specifies Millisil W4 quartz flour as the test substance. The advantage of this material is, primarily, its availability in certified quality. However, the properties of the material are controversial in the representation of real road runoff conditions. An alternative test substance was, therefore, presented in Neupert et al. [13]. Road-deposited sediments (RDSs) are collected by sweeping various road sections and then processed. In the process, the RDSs are divided into size fractions by sieving. Finally, the fractions can be compiled into defined particle-size distributions. This ensures a consistent quality (particle-size distribution) in every test and, at the same time, the best possible real representation of the particulate load of the road runoff in order to determine the retention of TSS and TSS_{fine} in the filter modules.

Since RDS is a multi-substance mixture, the morphology of the individual particles cannot be precisely defined.

In the DIBt test, a total test substance mass of 20 kg is provided; for reasons of feasibility, 50% of this mass was used for the standard test and 16.7% for the miniature shaft. Table 5 shows the defined RSD composition divided into 6 fractions according to Neupert et al. [13].

Table 5. Test substance composition/road-deposited sediments (RDSs).

Fraction	Mass Share
[µm]	[%]
0–63	2.3
63–125	10.9
125–250	29.4
250–500	31.7
500–1000	16.9
>1000	8.9

The addition of 3340 g of total material is carried out continuously on the miniature test stand for partial tests 1 to 3 with the partial quantities shown in Table 6.

Table 6. Test substance composition (RSD) standard test.

Fraction	PT 1	PT 2	PT 3	Total
[µm]	[g]	[g]	[g]	[g]
<63	114.7	75.7	39.0	229.4
63–125	545.1	359.7	185.3	1090.1
125–250	1468.1	969.0	499.2	2936.2
250–500	1584.6	1045.9	538.8	3169.3
500–1000	843.0	556.4	286.6	1685.9
1000–2000	444.6	293.4	151.1	889.1
Total	5000.0	3300.0	1700.0	10,000.0

At the large test stand, a total of 10,000 g of test substance is added continuously throughout partial tests 1 to 3 over a period of 5000 to 1700 g per partial test, as indicated in Table 4.

In addition, the impact of littering was considered. In a separate test, the retention performance of typical littering materials was investigated, which affects the filter module due to different material properties, such as density and size. Due to a lack of data on the littering composition, our own littering test substances were defined for the tests.

Table 7 shows the defined test material mixture of cigarette filters, coffee-cup lids and candy wrappers, which were selected as test materials to represent carelessly discarded plastic soiling (Figure 2). Number and weight were selected as the units here in order to reduce the testing effort. The mass of 5000 g for the mixture of the defined test substances had to be arbitrarily determined because there were no scientific data on possible inputs per street drain at the time of testing. For cigarette filters, coffee-cup lids and candy wrappers, it was defined to take from 50 to 100 pieces each. The retention was evaluated by counting the pieces that passed the filter. The retention rate for the plastic pellets was evaluated by measuring the total mass of flushed-out pellets. The plastic granulate is representative for pellet losses in the road area, which plays an important role as a basic material in the industrial production of plastic products [19].

Table 7. Defined test substance/littering.

Component	Mass	Material	Density [g/cm^3]
Cigarette filter	100 Pcs/19 g	Celluloseacetat	1.3
Coffee cup lids	50 Pcs/116.5 g	Polypropylene (PP)	0.9
Candy wrappers	50 Pcs/8 g	Polybutylenterephthalat (PBT)	1.4
Plastic pellets	4890 g	High-density polyethylene (HDPE)	0.95
Total	5000 g		
Tyre powder	1000 g	Heavy-duty vehicle tyre powder	1.17

Figure 2. Test substances from left to right: real street dust, defined substances and tyre powder.

The retention of tyre powder was determined in a separate test, since it could not be ruled out that adhesion of the fine test material to the other defined test materials would not lead to misinterpretation of the results. The total mass of 1000 g tyre powder was also chosen arbitrarily.

3. Results

After the conceptual design phase, the modules funnel (#6) and sedimentation wall (#9) were selected to be initially tested under defined conditions on the small test stand also with the addition of road sweepings as the test substance, as shown in Table 8.

Table 8. Results for the retention rate for tests at the small test stand.

Retention Overall Test Small Gully with RSD				
Fraction [µm]	**Magnet**	**Funnel Below**	**Funnel Top**	**Sedimentation Walls**
TSS_{fine}	45%	28%	52%	-
TSS	94%	94%	98%	-

The results already show that the magnet and the funnel can be used in operation without any problems. Regarding the positioning of the funnel module, especially for fine particles, the retention is significantly better if the module is positioned above the gully outlet.

The test of the sedimentation walls, on the other hand, showed a rapid clogging of the module already in partial test 1, so that the test had to be stopped and the concept was postponed.

With the findings of the small test stand, six modules and module combinations were subsequently tested on the large test stand with the addition of road sweepings. With the prototype construction, the modules were partially changed constructively, as shown in Table 9, compared to the first approach shown in Table 2 within the concept phase. The corresponding principal sketches of the tested modules are described in the following Table 9.

Table 9. Overview and evaluation of the tested filter modules.

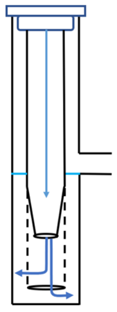
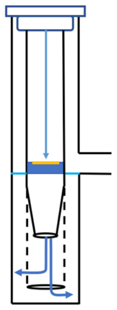
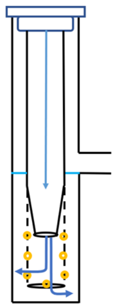
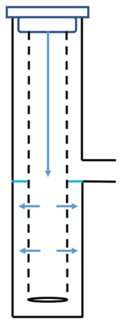
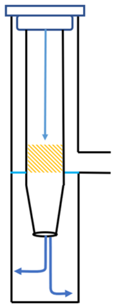
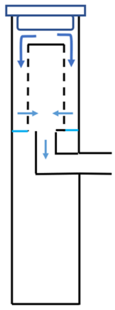
Filter Modul	Efficiency	Recommendation	Concept	Pro/Con
Funnel + Mesh skirt	TSS = 97% TSS_{fine} = 66%	In situ-tests		Maintenance (+) Installation (+) Clogging (+)
Funnel + Mesh skirt + baffle plate	TSS = 96% TSS_{fine} = 63%	Optimization of the baffle plate		Maintenance (+) Installation (+) Clogging (+)
Funnel + Mesh skirt + Magnets	TSS = 96% TSS_{fine} = 60%	Optimize positioning of the magnets		Maintenance (0) Installation (+) Clogging (+)
Mesh skirt	TSS = 92% TSS_{fine} = 22%			Maintenance (+) Installation (+)

Table 9. *Cont.*

Filter Modul	Efficiency	Recommendation	Concept	Pro/Con
Funnel + Granulat	TSS = 92% TSS_{fine} = 66%	For short term use		Maintenance (-) Installation (+) Retention of disolved pullutatns (+) Extra waste (-)
Optimized leaf basket	TSS = 60% TSS_{fine} = 9%	Optimization of the baffle plate		Maintenance (+) Max. sludge volume (+)

The evaluation of the results shows that for the mesh skirt alone and in combination with other modules for the TSS, a retention rate of >92% could be achieved. The same applies to the funnel module to which a granular packing of clay balls with a diameter of 2–4 mm was added. The module of the optimized leaf basket could only achieve a retention of 60% for the TSS as a whole, which is probably due to a short-circuit flow in the area of the baffle plate.

Significant differences can be seen in the comparative retention performance with TSS_{fine}. Here, the retention for the optimized leaf basket is <10% due to the short-circuit flow. For the filter skirt as a single module, only 22% can be achieved, which is probably due to the turbulent flow in the gully.

The combination of mesh skirt and funnel as well as funnel with granules could achieve the highest retention with 66% for the TSS_{fine}. Additional modules, such as the magnetic module or an additional baffle plate to reduce turbulence, on the other hand, do not bring any further improvement. The combination of funnel and granules could only be operated by means of emergency overflow after addition of the test substance.

For the module combination mesh skirt and funnel, very good retention efficiencies > 92% were also achieved for PE pellets, candy wrappers and cigarette filters, as shown in Table 10. For coffee-cup lids, on the other hand, 31 out of 50 pieces were flushed out. The retention of tyre powder at 21% also represents a comparatively low value.

Table 10. Results for defined test substance.

Modul	Mesh Skirt + Funnel
Cigarette filter	92%
Coffee-cup lids	38%
Candy wrappers	94%
Plastic pellets	99%
Tyre powder	21%

4. Discussion

The described test stand investigations are very suitable to determine the performance capability for retrofit filter modules in the gully. The same test conditions for different modules allow for good comparability and guarantee repeatable weather-independent conditions. The transparent gully allows for a clear detection of emergency overflows. The behavior of the particles in the gully and in the filter can be easily observed during a test. Optimization potentials can be systematically identified and improvements can be evaluated. The test substance dosing by rotary valve and the subsequent full flow sampling at the outlet of the gully allows for a precise description of the retention performance.

A disadvantage compared to in situ operation is the exclusion of environmental influences, such as temperature, pH changes, storms and snow. Due to the separation limit of the 20 μm stainless-steel sieve for sampling the effluent, the retention of the fraction < 20 μm cannot be reliably evaluated. Since the test stand trials can only partially represent reality, investigations over 12 months under real conditions should also be carried out for promising modules.

If the existing infrastructure offers enough space or if solutions can be taken into account in new planning, green or (semi)-centralized cleaning systems are a good alternative to decentralized solutions. Some of these alternative solutions can address additional challenges such as floods, as well as decentralized systems, as they are already available on the market and can be an alternative [11,20]. However, these systems cannot be adapted to the conditions of a hot spot by configuring several modules.

Alternatively, the source of the respective pollutants should always be targeted in order to minimize the generation and release into the environment. Here, urban planning can contribute in advance by excluding certain pollutant emitters within city planning. In addition, road traffic can be influenced in such a way that vehicle kilometers traveled are reduced and emissions are reduced by keeping traffic flowing as smoothly as possible [21].

In the future, material innovations can contribute to reductions in emitted pollutants. Through an ever-broader knowledge of the mechanism of emissions, corresponding technical retention facilities can be continuously improved. By raising the awareness of citizens, emissions from traffic could be reduced by defensive driving as well as carelessly discarding waste [21–23].

With the European Water Resources Act, the basis for surface water protection and improvement is in place, since road runoff is considered as wastewater. With worksheet DWA 102, an instrument for the selection of catchment areas requiring treatment has been defined for Germany. For microplastics from stormwater runoff, solutions are currently being discussed throughout Europe.

The modular filter concept describes the possibility to relieve the water bodies connected to the direct inlet of stormwater runoff, especially for pollutant hotspots. The generally simple design of the filter modules in the level of gully and drain shows a robust operation and can be easily retrofitted into the existing infrastructure system for the gully area.

Depending on the type of pollution and the corresponding exposure time, a time-defined deployment should also be considered. For example, the modules can be used for the period of a construction phase, accidental damage or even festival activities in the catchment area to help retain partly large loads with low maintenance. The maintenance would have to be realized within or at the end of a certain event.

The modules in the road area should be considered during new planning or renovation. Here, a long-term period of use must be assumed due to the structural measure.

The tests show that most of the modules can be reliably operated with half of the load applied according to DIBt 50 g/m^2 at 400 m^2. In order to be able to optimally select the developed modules, for now, it would help to obtain specific sweeping samples for the catchment areas to be cleaned and to individually test promising modules of the described variants. A more detailed description of the potential load of specific pollutants entering the gully can help to optimize filter modules and operational maintenance, even though the workload is enormous. In the future, a steadily growing data pool can be used to describe catchment areas better and to specifically retain defined pollutants with suitable filters. The modular approach can then contribute significantly to simplifying the selection of filter inserts. In this way, maintenance intervals can be extended and investment costs minimized.

The maximum possible load that can be retained results, for almost all modules, from the available retention space in the road and gully areas. This means that different potentials can be realized depending on the design of the road modules, which actually do not take the retention of solids into account, or the dimensioning of the gully. The retention space in the funnel and granular module offers the least scope here. However, by choosing absorbent granular materials, the retention of oils or dissolved substances can be considered for low solid loads.

The retention rates for TSS of up to 97% and TSS_{fine} of up to 66% already show that it is possible to retain a large part of the contaminants with structurally simple inserts in the gully. For increasingly defined pollutant loads, such as PE pellets, candy wrappers or even cigarette filters, the retention rates of up to 99% are also worth mentioning. This clearly shows that filter modules, such as the combination of mesh skirt and funnel, could already be very effective today, especially in gullies where no further inputs are expected in addition to the known pollutants.

For the application of the plastic coffee lids, a concept in the street space, such as with module 1 (side grid in curb), is a good option proposed to dispose of the pollution with street cleaning before it enters the gully.

After the bench tests with tyre powder, which showed a rather poor retention rate of 21% for the module combination funnel and mesh skirt, it must be questioned whether tyre powder is suitable as a test substance for tyre abrasion. Compared to the tyre and road-wear particle (TRWP), as is present on the road surface, the cryogenically ground tyre rubber material lacks up to 50% material, which is incorporated into the agglomerate from the road surface. This increases the density from 1.17 g/cm^3 for tyre powder to 1.8 g/cm^3 [24] for TRWP, which favors the sedimentation process in practice. Here, in situ measurements could provide better insight into the effectiveness of modules in the gully in the future. Outside the gully, a large retention potential for the parameter TRWP can be expected for the concept of porous asphalt structure (module 3) because these particles tend to settle at the side of the roadway where large areas between gullies could be used. Here, future studies on the wash-off behavior of TRWP and other pollutants under different rainfall intensities and for different asphalt structures would be useful as well as the development of an adapted street-cleaning concept. These investigations could not be implemented. For this purpose, a representative road surface on a laboratory scale would have to be available and the test substance dosage and contamination for the relevant surfaces in the roadside area have to be defined. A first promising investigation has already been conducted in the Netherlands [25].

The magnetic module did not improve the filter performance with the described test procedures, but the observation that particularly fine particles adhered to the magnet can be used for future investigations to develop a clog-free retention element. One parameter to be optimized seems to be a large reaction area, which could be realized if the complete gully would be designed by magnetic material.

Additional potential is offered by intelligent networking in which existing data, such as weather forecasts and street-cleaning plans, as well as bathing water monitoring, are coordinated with each other. This would allow pollutants to be removed from relevant hot spots before a stormwater event, thus, relieving the burden on water bodies and extending the maintenance intervals of the filter modules in the gully, since less mass has to be retained here. As climate change and heavy stormwater events increase, the requirements for flushing out already retained pollutants will grow and further increase the potential of intelligent networking.

The concept of the modular street filter provides an open-source approach that proposes solutions that can be implemented easily and at low cost by retaining high loads of

TSS (<97%). Further, the fine matter < 63 μm could be restrained up to 66% with modules that do not tend to clog. The retention of the fine matter in the gully offers the possibility to avoid raise road dust, on the one hand, as well as the transportation of these particles over long distances within the connected surface waters, such as rivers.

The final design offers the user, in addition, the possibility to consider local particularities. For this reason, the design of the modules is deliberately kept simple.

For efficient use, it is recommended to install filter modules at pollutant hot spots where stormwater runoff is discharged directly into surface waters. The installation of filter modules is expected to increase the maintenance effort. In order to keep the effort and the associated costs as low as possible, the modules were always designed to be easy to maintain. The modules can either be removed from the shaft for maintenance or can remain there directly. The maintenance effort was not investigated at the test stand. For large-scale use, the time required for maintenance as well as professional expertise and technical tools should be described. This information can be stored in a maintenance log for the service team.

The modules are designed in such a way that, apart from the retained pollutants, there are no other substances that need to be disposed of. The construction of the filter modules is designed for long-term use, so that it can be assumed that the maintenance costs will exceed the investment costs. For this reason, the concept of intelligent networking should always be examined for the selected locations. The developed modules do not limit the existing use of the connected areas in any way.

As an end-of-pipe solution, decentralized filters always describe one additional possibility to keep pollutants away from surface waters. For certain hot spots and in combination with an intelligent network of available data to utilize avoidance potential on the emission side as well as optimizing the street cleaning and the maintenance of the filter modules, the modular filter concept offers a promising approach to reduce the load of pollutants into our surface water bodies.

5. Conclusions

With the modular approach for filter modules and the corresponding intelligent networking concept, a novel solution concept for reductions in pollutants from road runoff water was developed. It was shown that structurally simple retrofit systems for the gully can already achieve very good retention performance and that there is also potential for creating additional retention space for pollutants outside the gully. The modular approach allows optimal retention facilities to be configured according to the requirements for the pollutants to be retained at a hot spot and adapted to future changes if necessary. If additional site-specific data can be intelligently networked, the load of pollutants into the gully can be additionally reduced and, thus, maximum maintenance intervals can be achieved.

To determine the maximum retention quantity for the gully systems, the quantity of the test material should be increased successively in follow-up tests on the test stand. In this way, the optimum maintenance interval can be defined depending on the area load of the corresponding catchment area. Depending on the pollutant hot spot, it should be investigated whether leaching of pollutants occurs from the retained pollutants due to, for example, pH value changes.

For further optimization of the filter modules, it would be helpful to estimate which annual loads and which fractions are flushed into the gully at different hot spots. These findings can be used, for example, to define the optimal pore structure for the road module porous asphalt and to adapt the mechanical road cleaning accordingly. In addition to the description of the particle-size distribution, it would help to obtain more information about the morphology and density of the corresponding particles in order to optimize the geometry and the installation position of the modules in the gully.

As an end-of-pipe solution, decentralized filters always describe only one additional possibility to keep pollutants away from surface waters. In general, the reduction or avoidance potential on the emission side should also be examined and understood systemically.

Author Contributions: Conceptualization, D.V. and J.W.N.; methodology, D.V.; validation, D.V. and J.W.N.; formal analysis, D.V.; investigation, D.V. and J.W.N.; resources, M.B.; data curation, D.V. and J.W.N.; writing—original draft preparation, D.V.; writing—review and editing, D.V. and J.W.N.; visualization, D.V. and J.W.N.; supervision, M.B.; project administration, D.V.; funding acquisition, D.V. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Audi Environmental Foundation.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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