Performance of an innovative treatment device for runoff from roads with high traffic densities

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ABSTRACT
Source control by the decentralised treatment of polluted runoff from motorways and highways as a sustainable alternative to classical end of pipe concepts becomes more relevant and important. Like centralised systems, small facilities can reduce the impact on receiving waters and groundwaters, so improving water quality, a requirement of the European Water Framework Directive. Small scale treatment units have the advantage that polluted and clean runoff are not mixed and treated together end of pipe. Areas with high loads of harmful substances can be equipped with filters while runoff from clean surfaces may not need to be treated at all.
The objective of this study was the further development of a pollution control unit to treat highly polluted runoff. Units must trap both solid and dissolved substances from runoff. Stormwater runoff from a distributor road in Hamburg with an average of 18,000 vehicles per day (2005) is discharged into a sensitive water body. A new treatment device consisting of two units of hydrodynamic separators and filter cartridges were retrofitted to the drainage system. The quality of water was monitored in the inflow and the outflow of the system. After one year of operation TSS were reduced by 94 % and the efficiency for the removal of heavy metals varied between 82 % for lead and 86% for zinc. Ortho-phosphate was removed by 81 %, ammonia by 91 % and more than 90 % of mineral oil type hydrocarbons were retained.

KEYWORDS
Highway drainage; heavy metals, hydrocarbons, deicing salts

INTRODUCTION
Stormwater runoff from the B75 in Hamburg-Harburg, a distributor road with an average of 18,000 vehicles per day (2005) is discharged into a biotope (water body) besides the road (Siepmann & von der Kammer 2005). The road experiences a particularly high percentage of heavy trucks, heading for the container port of Hamburg. In 2002 a catchment area of 2,300 m^2, comprising the road itself, including a traffic light stop, together with a bus stop turning area was connected to a stormwater treatment facility. This consisted of several concrete pits. The measure was initiated by the Office for Environmental Protection in Harburg and was financed by compensation allowance of a new power plant, money from the Office of Environmental Protection and the State Ministry of Urban Development and Environment. The aim of the project was to reduce total suspended solids and harmful substances such as heavy metals, hydrocarbons and nutrients from stormwater runoff to a passable level, so that

the biotope is not endangered in the long run. Maintenance intervals were required to be longer than every one or two years.
The initially installed treatment unit comprised a central DN 2500 silt trap, followed by two filter pits filled with gravel and sand and ending in a vegetation strip (swale) leading to the first pool of the biotope. However, the downward charged filters in the initial project system clogged too fast, so an alternative to the original device was retrofitted in 2006.

STORMWATER TREATMENT CONCEPT

Stormwater runoff from 6 road gullies enters the treatment unit at the central silt trap, which is equipped with a stainless steel screen to remove coarse rubbish and leaves (Figure 1). It has a security overflow for catastrophic rain events. From this first shaft the water flows via a DN 250 pipe into a control or balancing pit, from where it is distributed into two filter units consisting of two concrete shafts at DN 2,000. Only one of these shafts was retrofitted in December 2006 with two of the new treatment units. The remaining single shaft is retained in case of further developments. From the single shaft containing the filter unit the water is transported by a pipe DN 150 into a final control and sampling shaft before discharge into the vegetation strip and so to the receiving water body.
The new device was easily retrofitted into one of the existing two filter shafts, as can be seen at Figure 2. The cover of the shaft was removed and the units were installed, with the filter cartridges then fixed in each of the 2 units' housings (Figure3).
The central treatment unit itself consists of a hydrodynamic separator with an up flow filter (Figure 2). It is a further development of a filter shaft presented previously (Göbel et al. 2005) to protect groundwater by effects of infiltration (Zimmermann et al. 2004). In the system the water is cleaned by sedimentation, filtration, ion-exchange and chemical precipitation (Dierkes et al. 2005). Incoming stormwater is led down to the basal section of the filter shaft. A hydrodynamic separator promotes the sedimentation of particles. A tangential inlet forces a radial flow pattern. A silt trap is situated below the separation chamber, so particles cannot be remobilized by intense rain events. Above the separator four filter elements are situated, occupying the full shaft width, so that the water must flow through the filter by hydraulic pressure. The filter elements are situated permanently below the water level. They can be easily exchanged when they are exhausted. The cleaned water finally passes an oil trap and is directed into the final control and monitoring shaft. The units have a fixed central pipe. This central access functions both as a security/bypass overflow and secondly as an access for de-silting the silt trap chamber.

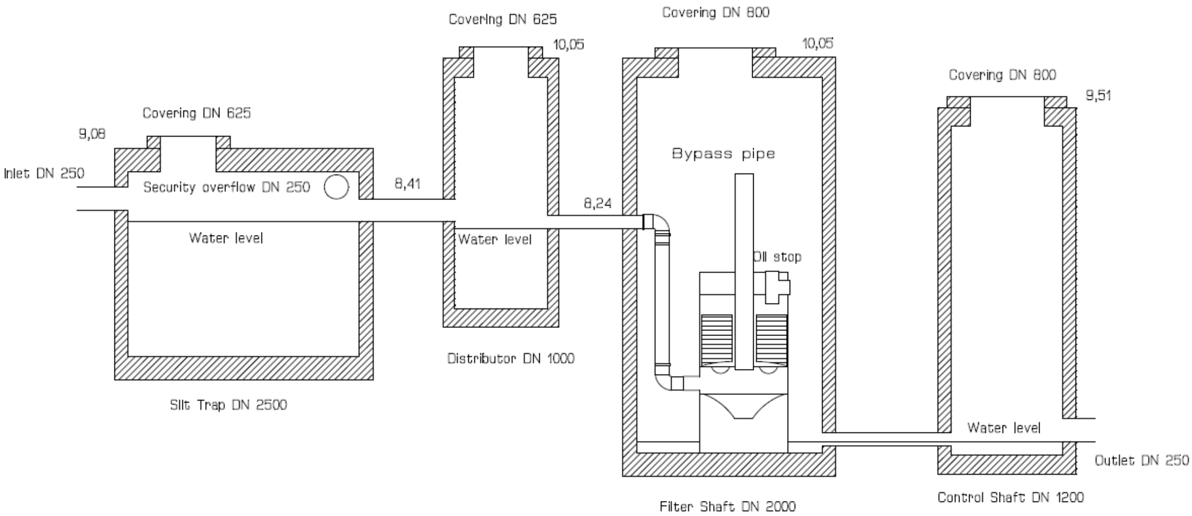

Figure 1. Sketch of the stormwater treatment facility.

Four filter elements are installed in each unit. These can be exchanged within the standard shaft. The filter elements consist of a polyethylene container with stainless steel screens. They are filled with a specific substrate that provides several processes. It has a large inner surface for the sorption of substances. The surface itself is negatively charged to provide ion exchange to trap heavy metals and other cations. By additional carbonates a buffering of the pH and chemical precipitation is generated. The size of the pores was designed for the particle size distribution found typically in stormwater runoff.

Figure 2. The installation of the system.

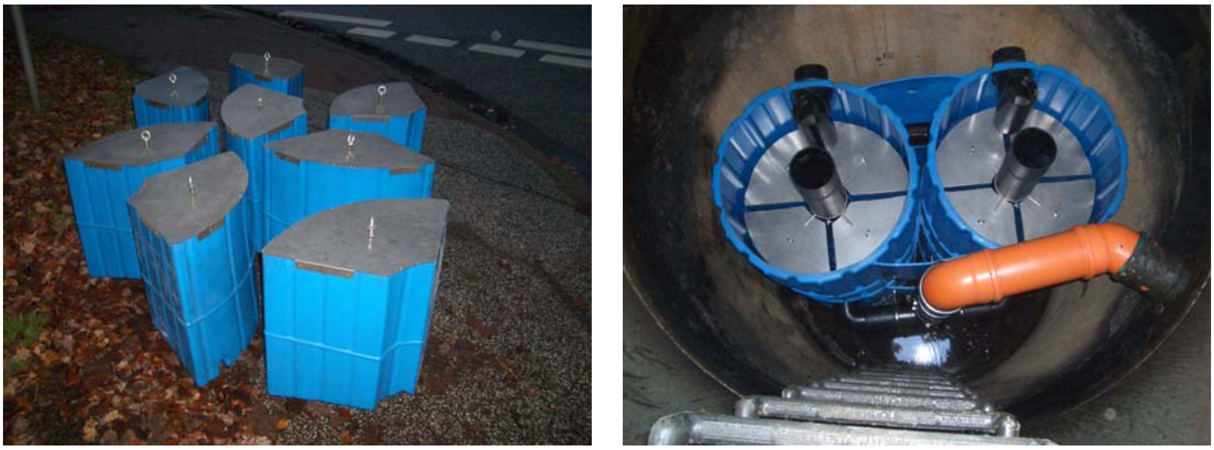

Figure 3. Filter cartridges and the system ready for operation.

METHODS AND SAMPLING EQUIPMENT

Sampling and monitoring equipment was installed to observe the performance of the system.
Flow rates through the system were measured by an ISCO 6700 automatic sampler with bubbler flow meter and a V-notch weir with an angle of 60°. It was installed in the second control pit. Hydraulic pressure in the system was measured in the overflow pipe of the system by a BOIE pressure probe for 0.4 bar with data logger. All data was stored at 5 minute intervals.
Water samples were taken by the ISCO 6700 sampler and also manually by a sampling pump.
Water samples were analysed for TSS (DIN EN 872), heavy metals (DIN 38406-8:), hydrocarbons (ISO 9377-4 H 53), ammonia (DIN 38406-5-1) and phosphorous (DIN EN

1189 (D11)). Samples were pre-treated by a strong acid and high pressure to crack the different metal species.

RESULTS AND DISCUSSION

All results refer to the sampling period from December 7th 2006 to December 6th 2007, representing one year of operation.

Hydraulics

Rainfall data from a gauge in Hamburg Fuhlsbüttel was used. The total amount of rainfall monitored was recorded at 1,083 mm for the sampling period. As the average annual rainfall for Hamburg is 780 mm per year, the amount of rainfall was unusually high. The highest monthly rainfall was in June 2007 with 215.6 mm, the lowest monthly rainfall monitored was April, with only 1.8 mm and a dry period of more than 5 weeks.

Daily rainfall amounts are presented in Figure 4. It is apparent there are several days with more than 25 mm of rainfall.

The runoff coefficient of the catchment was calculated from flow meter data and the rainfall at 0.9. Altogether 2,240 m^3 of stormwater runoff reached the treatment unit during the first year of the project.

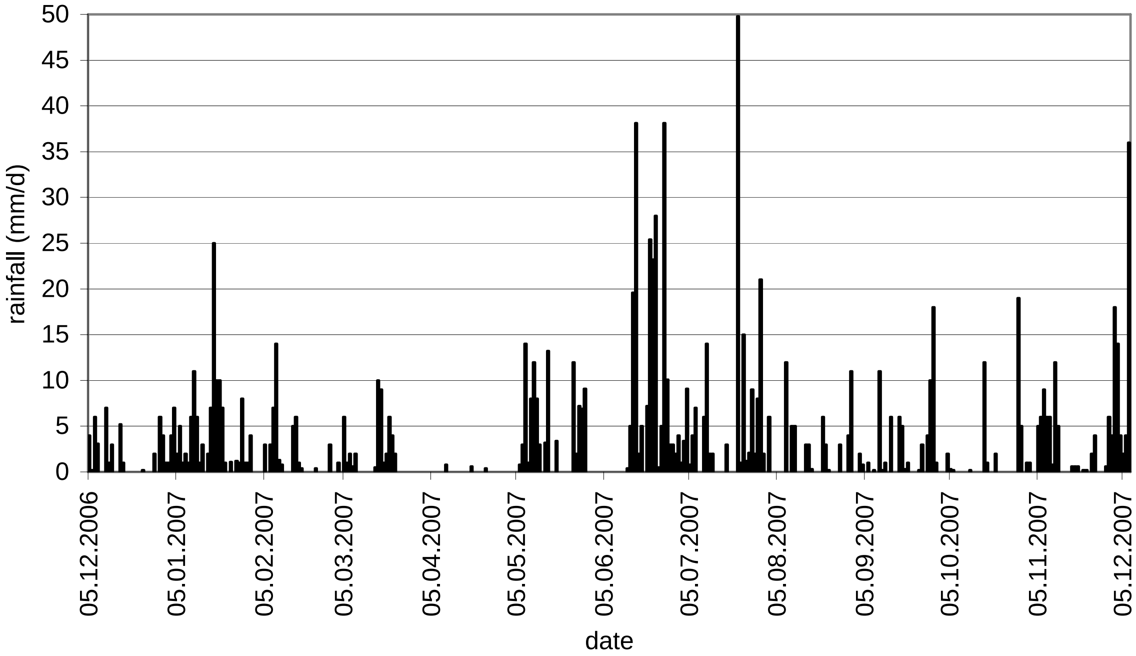

Figure 4. Daily rainfall over the sampling period.

The hydraulic pressure in the system indicates, if the internal overflow of the systems has operated or not. All filters need a certain pressure for operation. But the back-pressure level should not be so high that there is significant back-up of water and the water can not drain freely into the system. Therefore an internal bypass is installed. Reaching a certain water height, a part of the water flow will bypass the filter and this portion of the flow will only be treated in the hydrodynamic separator. The system is designed to treat more than 98 % of the total annual amount of water. Figure 5 shows the water pressure over three months of operation from September to December 2007. The rainfall events can be seen very clearly. During two storm events the bypass pipe operated, but for both events the by-pass flow duration was less than five minutes. During the total period of operation 6 overflow events were recorded, and less than 2 % of the runoff bypassed the filters.

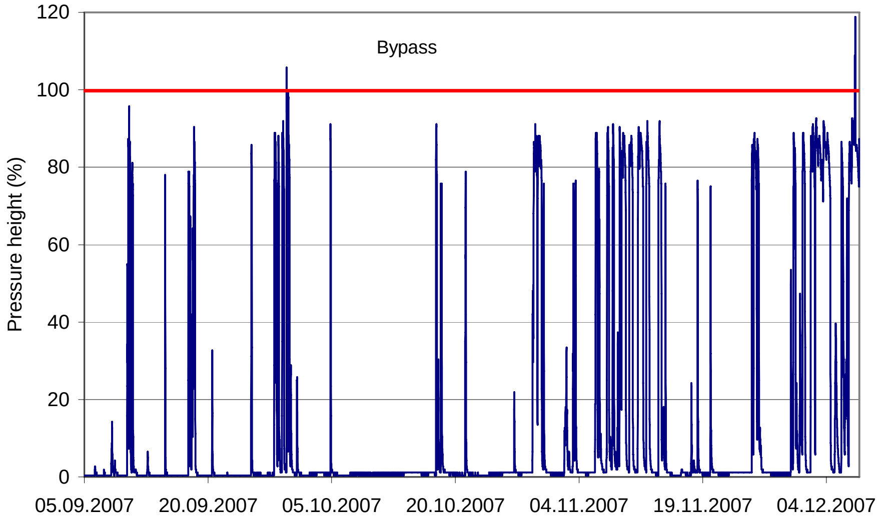

Figure 5. Hydraulic pressure in the system.

Concentrations in runoff

Stormwater from roads with high traffic density contains a number of pollutants like heavy metals and organic substances (Dannecker et al. 1989, Sansalone & Bucherger 1996, Stachel et al. 2007).

Water quality of the road runoff at Hamburg was compared to data from a large literature study that combined more than 100 different investigations of road runoff (Göbel et al. 2006). The results can be seen in Table 1. pH in the stormwater is unusually low at 6.4 units. The reason for this is not clear. Usually the pH in road runoff in Germany is between 7 and 8 units. The concentration of total suspended solids (TSS) is notably high. This may be the result of an unpaved road which feeds into the catchment. Dirt particles on tyres of vehicles from this road are deposited within the catchment itself. As a result the TSS values are double those expected. Zinc concentrations are a little bit higher than the average in literature; lead is lower as an effect of unleaded fuel. Notably, the copper concentrations are also very high, perhaps an effect of the traffic light (causing slowing down of the vehicles and therefore abrasion of the brakes) and the high amount of heavy trucks and buses on the road.

Phosphorous concentrations are a little bit higher than in the literature, whilst ammonia is as anticipated from the literature study. Mineral oil type hydrocarbons are lower than the studies published, but the general trend in runoff during the last 20 years in Germany is for decreasing concentrations of hydrocarbons in road runoff. Leakage from cars has been decreased significantly, which can be seen on many results (Kasting 2002).

Table 1. Concentrations in road runoff.

	pH	TSS	Zn	Cu	Pb	Cd	PO_4-P	NH_4	HC
	-	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Literature	7.4	163	0.41	0.097	0.170	0.0019	0.29	0.90	4.2
Runoff B 75	6.5	425	0.68	0.279	0.113	< 0.0025	0.52	0.83	2.2

In summary, TSS and Copper concentrations are higher than expected; all other parameters seem to be within the range of literature data (TSS = total suspended solids, HC = hydrocarbons)

Performance of the system
Observations of the outflow of the system showed that most parameters were reduced significantly. pH is buffered from 6.5 to 7.4. The suspended solids are reduced by 94 %, a result apparent even from simple visual observation of the water samples.
Total zinc is reduced by 86 % from 0.680 mg/L to 0.090 mg/L. For comparison the permissible limit for seepage in Germany is 0.5 mg/L. Copper and lead were removed with efficiencies between 82 % and 84 %.
For the receiving water body, the biotope, it is the nutrients, especially nitrate and phosphates that are also of special interest. Nitrate can not be removed in this unit facility, because the contact times of the water with the filters are too short for biological processes. To prevent eutrophication only the phosphates can be reduced. Here the reduction rate for phosphorus is about 81 %. Ammonia is removed by 91 %.

Table 2. Performance of the system.

	pH	TSS	Zn	Cu	Pb	Cd	PO_4-P	NH_4	HC
	-	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Runoff	6.5	425	0.680	0.279	0.113	< 0.0025	0.52	0.83	2.2
Outflow	7.4	27	0.090	0.046	0.021	< 0.0005	0.10	0.07	0.2
Efficiency	-	94	86	84	82	-	81	91	91
Aim	-	50	0.500	0.050	0.025	0.0050	0.1	0.1	0.2

The amount of mineral type hydrocarbons in runoff decreased during the last years. The inflow concentrations were 2.2 mg/L. At the outflow 0.2 mg/L were measured. All parameters indicate that the water could also be infiltrated toward groundwater according to the German seepage limits from the German Soil Restoration law. Figure 6 shows graphically the input and output concentrations for selected key parameters.

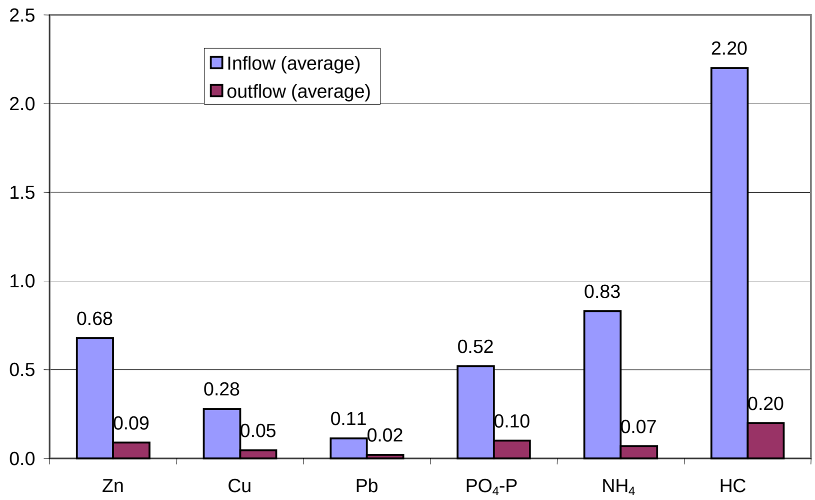

Figure 6. Performance of the system (concentration in mg/L)

Influence of de-icing salts on Filter Performance.
A fundamental research and operational consideration for filters to treat road runoff is the behavior during the winter time, when de-icing salt occurs on the street. By ion exchange processes Zn and Cu for example can be exchanged by Na out of the road salt. If this occurs, then it is possible that the trapped metals could be remobilized, and so be discharged into the

water environment. Only absorbed metals or precipitated species can not be removed easily by the salts. To see if there were effects during winter time, three rain events influenced by road salts were examined and are shown below. From Table 3 electrical conductivity is seen to be very high, directly attributable to the de-icing salts. Electrical conductivity in the outlet was also high which indicates, that the salt itself can not be removed by the filters. However, the corresponding heavy metal concentrations in the discharge show that they are not significantly influenced by the road salting. Zinc and copper concentrations are not higher than during the rest of the year. Zinc does not exceed the permissible limit in one sample, for copper one sample is above the limit, but the average concentration is below 0.05 mg/L.

Table 3. Results of three rain events during the winter time.

Date	el. cond. mS/cm	pH -	TSS mg/L	Zn mg/L	Cu mg/L	Pb mg/L	Cd mg/L
Inflow							
10.02.2007	28000	6.3	278	0.40	0.110	0.033	< 0.0025
14.03.2007	436	6.7	1892	0.25	0.250	0.021	< 0.0005
02.04.2007	19600	6.7	231	0.88	0.420	0.086	0.0013
Outflow							
10.02.2007	24100	7.0	65	0.23	0.070	0.020	< 0.0005
14.03.2007	2360	7.3	23	0.01	0.019	0.003	< 0.0005
02.04.2007	20500	7.3	37	0.07	0.028	0.003	< 0.0005
Aim	-	-	50	0.50	0.050	0.025	0.0050

Comparison with other stormwater treatment devices.

A comparison is presented below of the results of the first year of operation at Hamburg with other stormwater treatment devices by way of assessing the overall performance of the new unit at the Hamburg test site (Table 4). The current “State of the art” in the separate (surface water) systems in Germany still is a sedimentation tank with oil barrier or separators. With such devices, sedimentation takes place, but there are only limited chemical and physical processes occurring.

Retention soil filters with throttled or regulated outlet discharges also work by the processes of sorption, precipitation and indeed biological processes. This can be seen very clearly at table 4 below. For TSS removal all systems show a good performance. The heavy metals are removed very effective by the new unit system and by the soil filters. For phosphates the tested units presented in this paper also shows a very good efficiency, comparable with soil filters. The same high efficiency can be found for ammonia and for mineral oil type hydrocarbons. It is apparent that the new system’s performance is comparably as efficient as soil filters, with one difference. It is not possible to treat nitrate, because the contact time of the water is too short for biological processes to take place.

However, for all other parameters tested the filter system presented here may offer a viable small scale, small footprint, decentralised alternative to central retention soil filters for smaller catchments.

Table 4. Comparison of the Efficiency of different stormwater treatment systems.

	TSS	Zn	Cu	Pb	PO_4	NH_4	HC
Treatment system at B 75	94	86	84	82	81	91	91
Sedimentation tank (Hahn et al. 2000)	-	12	5	36	(34)	(5)	-
Sedimentation tank (Fischer et al. 2000)	-	40	45	48	(16)	(8)	-
Sedimentation tank (Krauth 1982)	85	50	73	79	32	36	-
Soil filter (Hahn et al. 2000)	-	79	55	43	(53)	(31)	-
Soil filter in Laboratory (Kasting 2002)	85	91	87	54	4	90	31

CONCLUSIONS

Inflow and outflow of the treatment unit were monitored over a period of one year. Water samples were analysed for key parameters, heavy metals (Zn, Cu, Pb, and Cd), hydrocarbons, ammonia and phosphorous. The following results could be observed:

- TSS were reduced by 94 % from 425 mg/L to 27 mg/L.
- The efficiency for the removal of heavy metals varied between 82 % for lead and 86% for zinc.
- Ortho-phosphate was removed by 81 %, ammonia by 91 % from the measured runoff.
- More than 90 % of mineral oil type hydrocarbons were retained in the tested system.
- Most project water quality objectives for the final discharge were taken from the permissible limits for seepage of the German Soil Restoration law. To date all the target parameters have been achieved, even though the connected area for the system is higher (2.3 times) that recommended.

The flat catchment shows positive effects to the treatment process. By this and the storage volume in the system itself peak flows are reduced significantly which decreases the flow rate through the filters and increases the contact time of the water with the filter media.

One further question to be examined is how long the performance of the filter will be sufficient hydraulically and hydro-chemically, and at which time the filters have to be exchanged. From observed chemical data to date, exceedance of the filter capacity has not been observed. At least two years of operation seem to be possible without maintenance. Furthermore, the flow rates and pressure data show that the filters are not clogged.

The system is still being monitored and samples are being taken regularly to monitor the performance during the next months.

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