A new installation for treatment of road runoff: up-flow filtration by porous polypropylene media

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Abstract We installed a new device on a paved road to treat runoff from a roadway surface. All the stormwater runoff was transferred into the device and the runoff equivalent to 10 mm/hr or less was treated. The treatment method consists of sedimentation and up-flow filtration with porous polypropylene (PPL) processes. The treated runoff was discharged into the existing storm drainage pipe. The average removal efficiency of the initial runoff at the beginning of rainfall which has high pollution intensity was about 90% for SS, about 70% for COD, about 40% for total phosphorus (T-P), about 80% for Pb and Cd, about 70% for Zn, Cu, Mn and Cr, and about 60% for polycyclic aromatic hydrocarbons (PAHs). The overall removal efficiencies of the experiment that ran for four months remained $>60\%$ of SS, $>40\%$ of COD, $>60\%$ of heavy metals, and $>40\%$ of PAHs. The PPL is excellent for removing smaller size particulates of suspended solids, which originate basically from diesel exhaust, as well as larger size particulates from automobile tires, asphalt roads, and other accumulated source(s) of clay and sand, *etc.*

Keywords Non-point source pollutants; particle size distribution; porous polypropylene; road runoff; up-flow filtration

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Introduction

Stormwater runoff is one of the major sources of pollution in urban areas and may be discharged directly, in most cases without any treatment, into the receiving environments. The majority of pollution in urban stormwater runoff originates from non-point sources. Road runoff, as one of the urban non-point sources, contains various pollutants including COD, heavy metals and polycyclic aromatic hydrocarbons (PAHs), which are either dissolved or particulate-bound (Boxall and Maltby, 1995; Sansalone and Buchberger, 1997; Gromaire-Mertz *et al.*, 1999). The pollutants tend to accumulate in the receiving environments where particulate materials are deposited and remain over a relatively long period of time, since many of the pollutants are associated with suspended particulate materials for road runoff. The first flush of road runoff can harm the ecology of the receiving environment, and then more extensive rainfall would have less impact due to the large dilution of pollutants in the road runoff (Mungur *et al.*, 1995). The runoff pollutants from paved roadway surfaces have increased along with urbanization. In addition, the traditional drainage systems appear insufficient for the treatment of these runoff pollutants, and it is far too expensive to completely manage the stormwater runoff.

The input and accumulation of pollutants from stormwater runoff in receiving environments can be reduced by treatment technology such as detention ponds and constructed wetlands (Shutes *et al.*, 1999; Sriyaraj and Shutes, 2001). These systems can reduce many pollutants in stormwater runoff including COD, suspended solids, nitrogen, phosphorus and heavy metals. They are, however, unsuitable in urban areas because the treatment

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system needs a large land space for the road runoff treatment. Therefore, in order to reduce the amount of pollutants in road runoff, some new forms of treatment are necessary with low construction and maintenance costs. A field experiment of an installed new device in the draining grid sink was undertaken in this research in order to evaluate the treatment efficiency of the device for reducing the road runoff pollutants.

Description of the new treatment device

Designed maximum road runoff

According to the data of 80 major weather observation stations in Japan from 1961 to 1990 (National Astronomical Observatory, 2000), the average number of days with rainfall greater than 1 mm/day and 10 mm/day was 124.7 days/year (34.2% in a year) and 49.2 days/year (13.5% in a year), respectively. About 60% of the rainy days were between 1 and 10 mm/day. Therefore, if the rainfall that is less than 1 mm/day is included, most of the rainfall in a year may be less than 10 mm/day. Moreover, this value was converted to rainfall per hour as the first flush, in which the pollution intensity is high, and limited to about 2 or 3 hours from the beginning of rainfall. Although the patterns of rainfall were variable, excluding the special cases such as typhoons, the amount of rainfall per hour during first flush or at the beginning of rainfall was generally regarded to be small. Therefore, the designed maximum rainfall intensity was determined as rainfall of 10 mm/hr in order to come up with the design treatment capacity of the device.

Traditionally in Japan, a draining system includes draining grid sink installed at generally about 20 m intervals on both sides of road for the drainage of stormwater (Japan Society of Road, 1987). The structure of the road depends on the road type, traffic condition and regions. The maximum lane width is 3.5 m, except in certain cases, and the number of lanes depends on traffic conditions. In this research, runoff from a road consisted of four lanes (two lanes on each side) was considered as the runoff amount. Therefore, the designed catchment area (A) of road runoff is calculated as follows (Figure 1):

$$A = 20\,m \times 3.5\,m \times 2\,\text{lanes} = 140\,m^2 \quad (1)$$

The designed maximum runoff flow rate (Q_{max}), based on the road engineering and drainage guideline is as follows:

$$Q_{max} = C \times I_{max} \times A/\gamma/3,600 = 0.389\,L/sec \quad (2)$$

In Equation (2), C is the coefficient of runoff (= 1.0), I_{max} is the designed maximum rainfall intensity (= 10 mm/hr), A is the designed catchment area (= 140 m^2), and γ is the drop coefficient to drainage equipment (= 1.0).

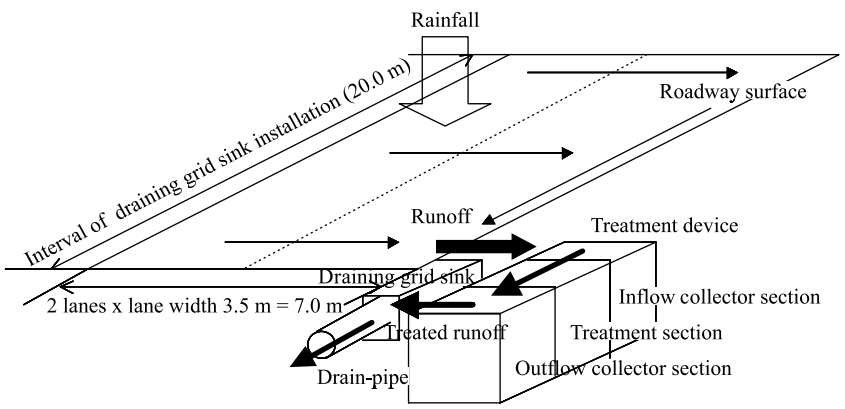

Figure 1 Schematics of a road runoff treatment

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Structure of the treatment device

Since the treatment device is installed on site to take measures for pollutants in road runoff, it must be compact and be connected at a draining grid sink. The treatment device consists of two collector sections (inflow and outflow) and treatment section (Figure 1). After the road runoff of first flush is continuously collected and treated by the treatment device, the flow is discharged into the drainage pipe. The structure of the treatment section for sedimentation and up-flow filtration processes is shown in Figure 2. The inlet of the treatment section is large enough to receive the amount equal to or less than the designed maximum runoff flow rate (Q_{max}). The runoff exceeding Q_{max} is not treated but directly discharged to the drainage pipe as excess overflow. The road runoff collected in the inflow collector section of the device flows downward to the treatment section, and large particulates settle down and deposit there (*i.e.*, sedimentation). Then, the flow passes upwards through the treatment media that is porous polypropylene (PPL) particles, while pollutants are removed by filtration and adsorption (*i.e.*, up-flow filtration). The treated runoff is discharged into the drainage pipe. The particles accumulated in the deposition space remain at the bottom until the sludge collection maintenance.

Materials and methods

Field experiments

The experimental site where the treatment device was installed was located along the roadway of Route 161 (in Otsu, Shiga, Japan), which consists of four lanes that have two lanes on each side. The average traffic density between 7 am and 7 pm at this experiment site was 38,086 vehicles/12 hrs during the study period. In the treatment device, the cylindrical filter column in the treatment section had dimensions of 30 cm diameter and 50 cm high, and polyethylene mesh (opening: 500 μm) was set at each end of cylinder to hold the treatment media (Figure 2). PPL particles of 1–3 mm diameter were filled as treatment media. The head loss by the PPL media was almost negligible, since the apparent density and the bulk specific gravity were 0.65 g/cm^3 and 0.2, respectively. At eight rainfall events between October 2000 and January 2001 (Table 1), the samples were collected at the inflow and outflow collection sections of the treatment device by using the solvent-cleaned bottles. The total amount of rainfall and maximum intensity for the eight rain events ranged from 7 to 51 mm and from 2 to 10 mm/hr, respectively.

Analytical methods

The SS was determined by using glass fiber filters (GF/B, Whatman). The COD was analyzed according to *Standard Methods* (1998) using $K_2Cr_2O_7$. The pH and EC were determined with a potable water analyzer (U-10, HORIBA, Japan). In addition, the particle

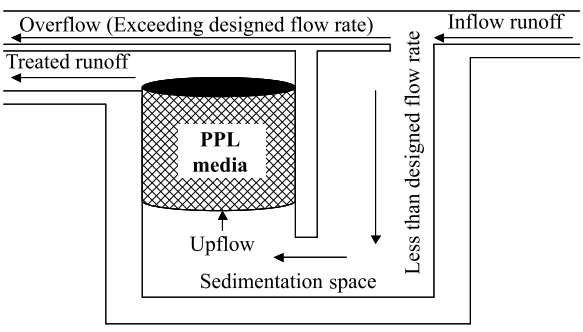

Figure 2 Structure of treatment device

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Table 1 Characteristics of each rainfall event

Rainfall event	Total rainfall (mm)	Rainfall duration (hr)	Maximum rainfall intensity (mm/hr)
R-1	28	19	7
R-2	26	14	6
R-3	36	14	6
R-4	51	23	10
R-5	7	6	2
R-6	14	9	5
R-7	22	17	3
R-8	27	19	4

size distribution (PSD) was measured with a laser diffraction particle size analyzer (SALD-2100, Shimadzu, Japan).

For the measurement of heavy metals, the samples (100 mL) were first digested by concentrated nitric acid (1 mL) in acid-washed beakers, and then evaporated to dryness in an oven at 100 °. After cooling, the solutions were transferred to volumetric flasks and diluted to 50 mL with 1% (v/v) nitric acid. The heavy metals and total phosphorus concentrations were determined using a inductively coupled plasma with mass spectroscopy (HP4500, Yokogawa Analytical Systems, Japan).

For the measurement of PAHs concentrations, the PAHs in samples (50 mL) were liquid–liquid extracted by ultrasonication (10 min) with acetonitrile (15 mL) and then by rotary shaker (30 rpm, 20 min) with *n*-hexane (30 mL). The extracts (in *n*-hexane solution) were, after dehydration by unhydrous sodium sulfate, concentrated to 1 mL using a rotary evaporator. The *n*-hexane extracts (1 mL) were fractionated with 5 g of silica gel column (Supelclean LC-Si, 40 μm, 20 mL, Supelco). The PAHs was eluted with 20 mL of 20% (v/v) dichloromethane in *n*-hexane. The fraction containing PAHs was concentrated to 1 mL under reduced pressure at 30 ° using a rotary vacuum evaporator and stored at − 20 ° until further analysis. One μL of the extracts with internal injection standards (*i.e.*, acenaphthene-d_{10}, phenanthrene-d_{10}, chrysene-d_{12}, and perylene-d_{12}) was injected into a gas chromatography (GC-17A, Shimadzu, Japan) equipped with a mass spectrometer (QP-5000, Shimadzu, Japan), which was operated under selected ion monitoring (SIM) mode. The GC was also equipped with an auto-sampler (AOC-20i, Shimadzu, Japan). In order to test recovery efficiency, PAH standards were added to the runoff samples and analyzed. The recovery efficiency for phenanthrene, pyrene, benzo[a]pyrene and benzo[ghi]perylene ranged from 65 to 79%.

Results and discussions

Water quality of the road runoff inflow

The average pollutant concentrations of road runoff inflows for the eight events are summarized in Table 2. The pollutant concentrations of initial runoff at the beginning of rainfall, except pH, were higher than those of total runoff. The average values of pH in road runoff inflow are 7.84 in initial runoff and 7.98 in total runoff, remained weakly alkaline. Heavy metals were presented in varying concentrations (Zn > Mn > Cu > Pb > Cr > Cd). The heavy metals with higher concentrations (*i.e.*, Zn, Mn and Cu) may be originated from surface soils, since these three heavy metals are common in surface soils. The Mn concentration was generally higher than Zn concentration in the surface soils (Bowen, 1979). However, among 6 heavy metals Zn was the highest concentration in the road runoff inflow. This result indicates that much tire debris may be contained in the road runoff inflow, since Zn was derived from not only surface soils but also tire debris. Normally, Pb and Cd do not exist in clean surface soils. Therefore, they may be originated from human activities.

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Table 2 Water quality of the road runoff inflow for eight rainfall events

		Initial runoff inflow[a]			Total runoff inflow		
Parameter	**Unit**	**Min**	**Max**	**Average**	**Min**	**Max**	**Average**
pH		7.23	8.45	7.84	7.23	9.16	7.98
EC	(μS/cm)	88	557	172	24	557	108
SS	(mg/L)	9	167	78	3	219	60
COD	(mg/L)	41	124	81	5	130	49
T-P	(mg/L)	0.03	0.20	0.10	0.01	0.21	0.09
Cr	(μg/L)	2.1	17.3	8.4	1.2	21.5	7.0
Mn	(μg/L)	25	168	89	13	178	66
Cu	(μg/L)	22	75	46	7	98	36
Zn	(μg/L)	180	1,644	532	47	1,644	286
Pb	(μg/L)	3.3	38.4	18.0	1.8	45.6	14.4
Cd	(μg/L)	0.1	0.3	0.2	0.1	0.4	0.2
Phenanthrene	(μg/L)	0.08	1.50	0.60	0.02	1.50	0.43
Pyrene	(μg/L)	0.17	7.83	3.26	0.01	9.33	2.13
Benzo[a]pyrene	(μg/L)	0.12	5.50	2.07	0.05	5.90	1.43
Benzo[ghi]perylene	(μg/L)	0.14	5.75	2.24	0.05	6.65	1.74

[a]Initial runoff inflow is the runoff inflow at the beginning of each rainfall event

The PAHs concentrations are in the order of pyrene > benzo[ghi]perylene > benzo[a]pyrene > phenanthrene. Pyrene is ubiquitous in soils and sediments, and frequently high concentration is observed, which accords to the observation in this research.

The relationships between SS and toxic pollutants in the road runoff inflows are shown in Figure 3. Figure 3a indicates good linear relationship between SS concentration and heavy metal concentrations. Pb has the highest correlation to SS with correlation coefficient (R^2 = 0.876). Also, Cr, Cu and Mn have good correlations to SS with R^2 of 0.840, 0.836 and 0.833, respectively. Among these heavy metals, Zn shows the lowest

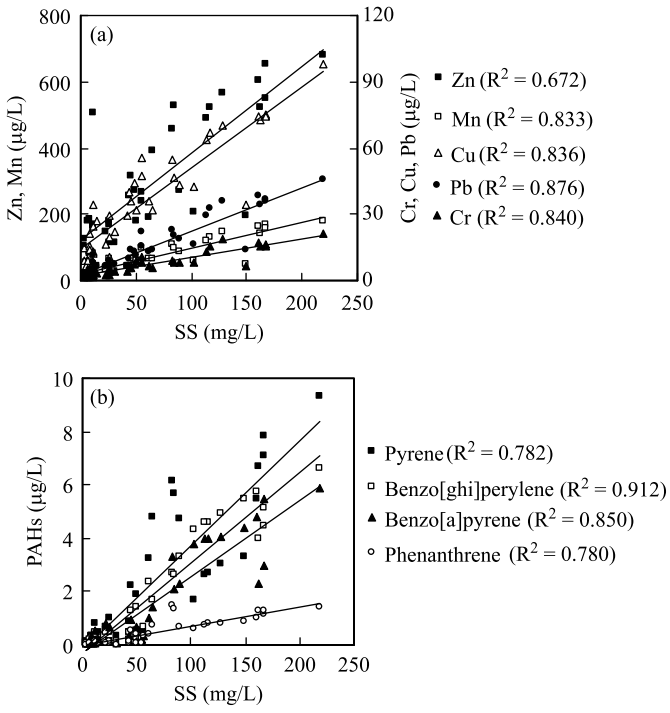

Figure 3 Relationship between SS and toxic pollutants in road runoff inflows: (a) heavy metals, (b) PAHs

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correlation to SS with R^2 of 0.672, although the concentration is the highest. Figure 3b shows good linear relationships between SS concentration and PAHs concentrations. Individual PAH has a good correlation to SS with R^2 above 0.780: benzo[ghi]perylene (0.912) > benzo[a]pyrene (0.850) > pyrene (0.782) > phenanthrene (0.780). The PAHs of high molecular weight shows stronger correlation to SS concentration than PAHs of low molecular weight. These results of heavy metals and PAHs clearly indicate that the removal of micropollutants from the road runoffs, which are important for urban stormwater runoffs, can be attained with the removal of SS.

Particle size distribution of the road runoff inflow

The average particle size distributions (PSD, expressed as volume%) of road runoff inflows for eight rain events are shown in Figure 4a for the initial (at the beginning of rainfall) and post runoffs (after about 300 min from the beginning of rainfall). The particulate size in the initial runoff was relatively smaller (over 90 vol% of particulates had a diameter smaller than approximately 100 μm) than that in the post runoff. The average d_{10}, d_{50} and d_{90} of PSD were 4.3, 14.9 and 38 μm, respectively. These indicate that the smaller particulates dominate in initial runoff. In the post runoff, over 90 vol% of particulates had a diameter smaller than approximately 350 μm. In addition, 71.3 vol% of the particulates were the diameters less than approximately 100 μm. The values for d_{10}, d_{50} and d_{90} of PSD were 25.6, 70.2 and 168.8 μm, respectively. These results indicate that the smaller particles flow faster with runoff than the large particles. Particulate-bound pollutants such as heavy metals and PAHs tend to be adsorbed on the smaller particulates

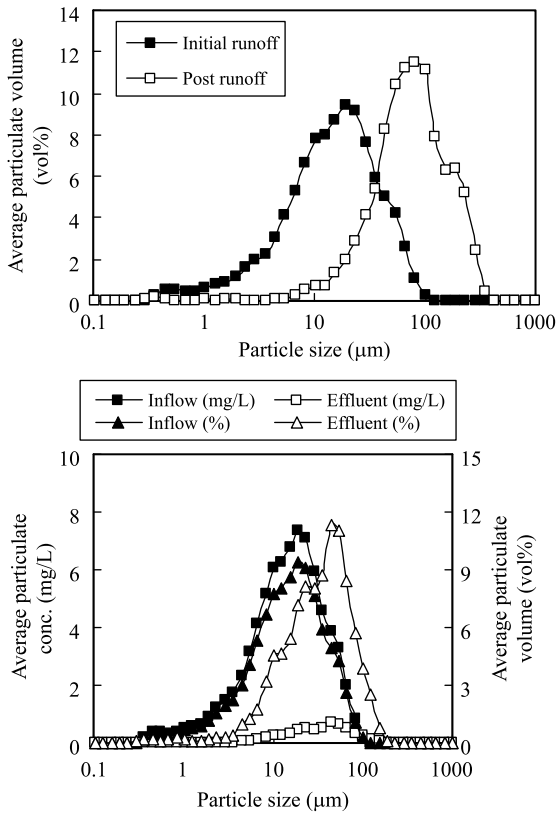

Figure 4 (a) Particle size distribution (vol%) of road runoff inflows (the average of eight rainfall events). (b) Particle size distribution in road runoff inflows and treated effluents (the average of eight rainfall events)

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due to higher specific surface area and higher organic carbon content. This is also verified for stormwater runoffs (Xanthopoulos and Augustin, 1992). Therefore, for the further removal of these micropollutants, the smaller particulates must be efficiently removed. This is especially true for the initial road runoffs.

Removal of particles from road runoff

Figure 4b shows the average PSD of eight rainfall events in inflows and effluents of treatment device for initial runoff expressed in vol% and mg/L. Sedimentation and up-flow filtration caused a shift in PSD towards larger. The median diameter (d_{50}) of the particles was shifted from 14.9 μm (in inflow) to 30.9 μm (in effluent). The removal efficiency of particle concentration was above 80% for all size ranges. These results indicate that relatively smaller particles as well as larger particles in the runoff inflow were removed during their percolation through the treatment device.

Removal of pollutants from road runoff

The removal efficiency of various pollutants in initial runoff, in which pollutant concentration was relatively high, is shown in Table 3 for each rainfall event. The SS removal efficiency ranged from 86.7% to 97.8% with 92.3% average removal efficiency. The COD and T-P removal efficiencies ranged from 36.7% to 87.1% and 11.9% to 96.9% with 71.9% and 43.6% average removal efficiencies, respectively. The average removal efficiencies were approximately more than 70% for heavy metals: 88.7% for Pb, 87.1% for Cd, 76.2% for Zn, 75.2% for Cu, 71.3% for Mn and 69.9% for Cr. The higher removal efficiencies of Pb and Cd suggested that this behavior correlated closely to that of SS. This result for Pb was confirmed by the stronger correlation between Pb and SS (Figure 3a). The average removal efficiency of PAHs was above 60%, ranged from 59.6% to 76.5%.

Actually, the eight rainfall events occurred continuously, one after another. The change of average removal efficiency of pollutants with operation time for the continuous eight rainfall events is shown in Figure 5. The average removal efficiencies of pollutants initially decreased with time but remained relatively constant after treatment time of 90 min. The average removal efficiencies of pollutants for all eight rainfall events were $>60\%$ for SS, $>40\%$ for COD, $>60\%$ for heavy metals and $>40\%$ for PAHs, which were almost unchanged after four months (data not shown). Furthermore, the increase of head loss (*i.e.*, pressure build-up) was negligible, and media clogging not occur.

After the filtration of PPL media was clogged, the particles accumulated in the deposition space of the device were collected by a vacuum method and then disposed in

Table 3 Removal efficiency of pollutants in initial runoff

Rainfall event	Flow rate (L/sec)	Removal efficiency (%)									
		COD	SS	T-P	Cr	Mn	Cu	Zn	Cd	Pb	PAHs[a] (S.D.)
R-1	0.020	36.7	90.9	14.3	17.3	70.0	59.9	28.9	99.0	69.7	59.6 (3.9)
R-2	0.006	53.8	90.8	11.9	54.6	78.7	64.9	89.8	92.8	84.6	59.7 (5.8)
R-3	0.012	74.5	92.3	76.9	73.8	23.3	95.2	–	69.2	99.0	67.2 (7.4)
R-4	0.021	77.1	94.8	13.3	79.8	92.4	76.5	89.8	99.0	95.9	71.5 (7.4)
R-5	0.006	81.3	97.8	28.0	74.6	45.4	62.7	91.2	62.5	83.9	75.4 (7.4)
R-6	0.028	84.4	93.5	26.8	89.1	89.0	87.1	67.9	77.2	90.6	73.4 (5.3)
R-7	0.021	87.1	91.6	96.9	90.8	86.7	78.3	82.4	98.3	96.8	76.5 (7.4)
R-8	0.024	80.3	86.7	80.4	79.5	84.6	77.2	83.5	99.0	88.9	75.8 (6.8)

[a]Average removal efficiency of 4 PAHs (*i.e.*, phenanthrene, pyrene, benzo[a]pyrene and benzo[ghi]perylene)

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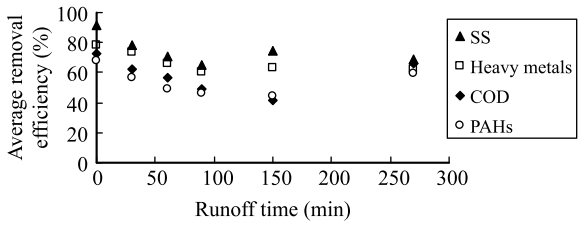

Figure 5 Removal efficiencies of various pollutants from the beginning of rainfall (the average of eight rain events)

a landfill. The used PPL media were recovered and incinerated as refuse derived fuel, because backwashing of the used media was insufficient to remove hazardous substances (*i.e.*, PAHs and heavy metals) adsorbed in the media.

Conclusions

Based on the field experiment results, it could be concluded that the new treatment device with PPL can effectively remove various pollutants in road runoff through particle sedimentation and up-flow filtration of particles. The removal efficiency did not decrease after four months. The experimental results indicated that the new device is a promising treatment technology for the road runoff. In the future, the disposal of the removed particles and the used PPL media needs further development.

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