清華大學
Tsinghua University

Technology of Dual-media Filtration for Treatment of Stormwater Runoff of Building Subdistrict under Rapid Filtration Conditions

Zhenghao Yuan, Yi TAO

Graduate School at Shenzhen, Tsinghua University

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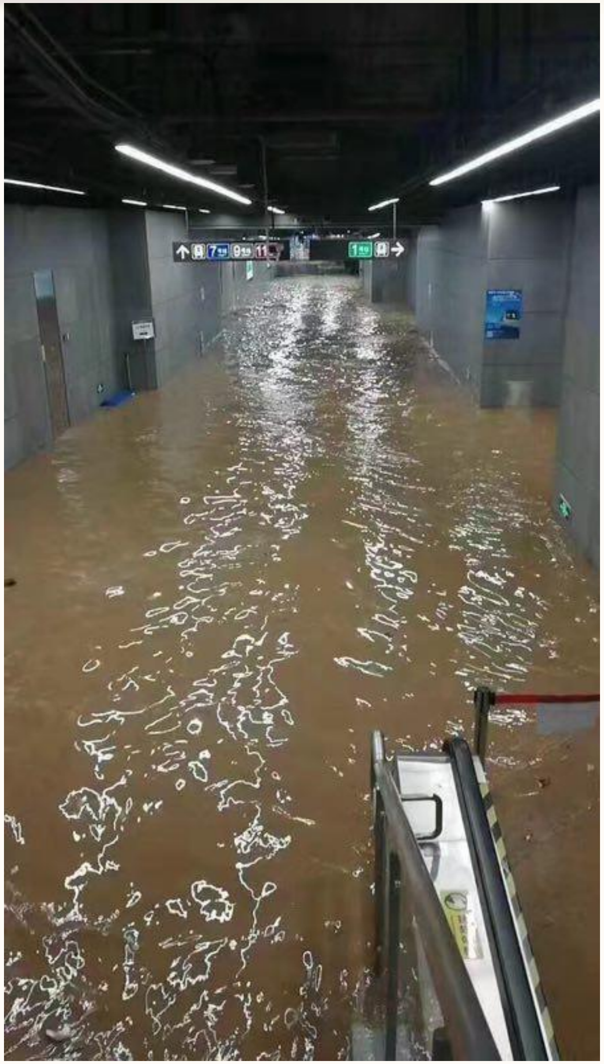
Contents

Stormwater in Shenzhen



(http://news.china.com/socialgd/10000169/20170613/30718133_2.html)

Heavy pollution of Dasha River by runoff

Runoff always contains contaminants

Characteristics of pollutants in rainwater runoff of building districts

Building districts	pH	SS mg/L	Turbidity NTU	COD_{cr} mg/L	NH_4—N mg/L	TN mg/L	TP mg/L
Tianjin	6.9-7.9	134.2-445.5	31-154	-	-	-	-
Xi‘an	-	18.4-138.2	-	-	2.67-5.13	3.32-9.38	0.13-0.26
Chongqing	-	128.5-192.3	-	90.8-125.5	1.57-2.21	2.82-.82	0.362-0.469
Average	6.5-8	50-200		90-130	1.3-5.5	2.0-10	0.10-0.50

Pollutants in runoff of building districts

	SS	COD_{Cr}	BOD_5	TN	TP
Roof	102.7	114.1	40.1	6.20	0.38
Road	512.6	286.1	57.5	7.84	0.78
Municipal sewage of residential area	155-180	455-600	230-300	-	-

- Particles and the related COD and TP are the major pollutants, which can be effectively removed by filtration process.

- The stormwater runoff in building districts is an alternate water source for reclamation and reuse in China.

Characteristics of pollutants in rainwater runoff of building districts

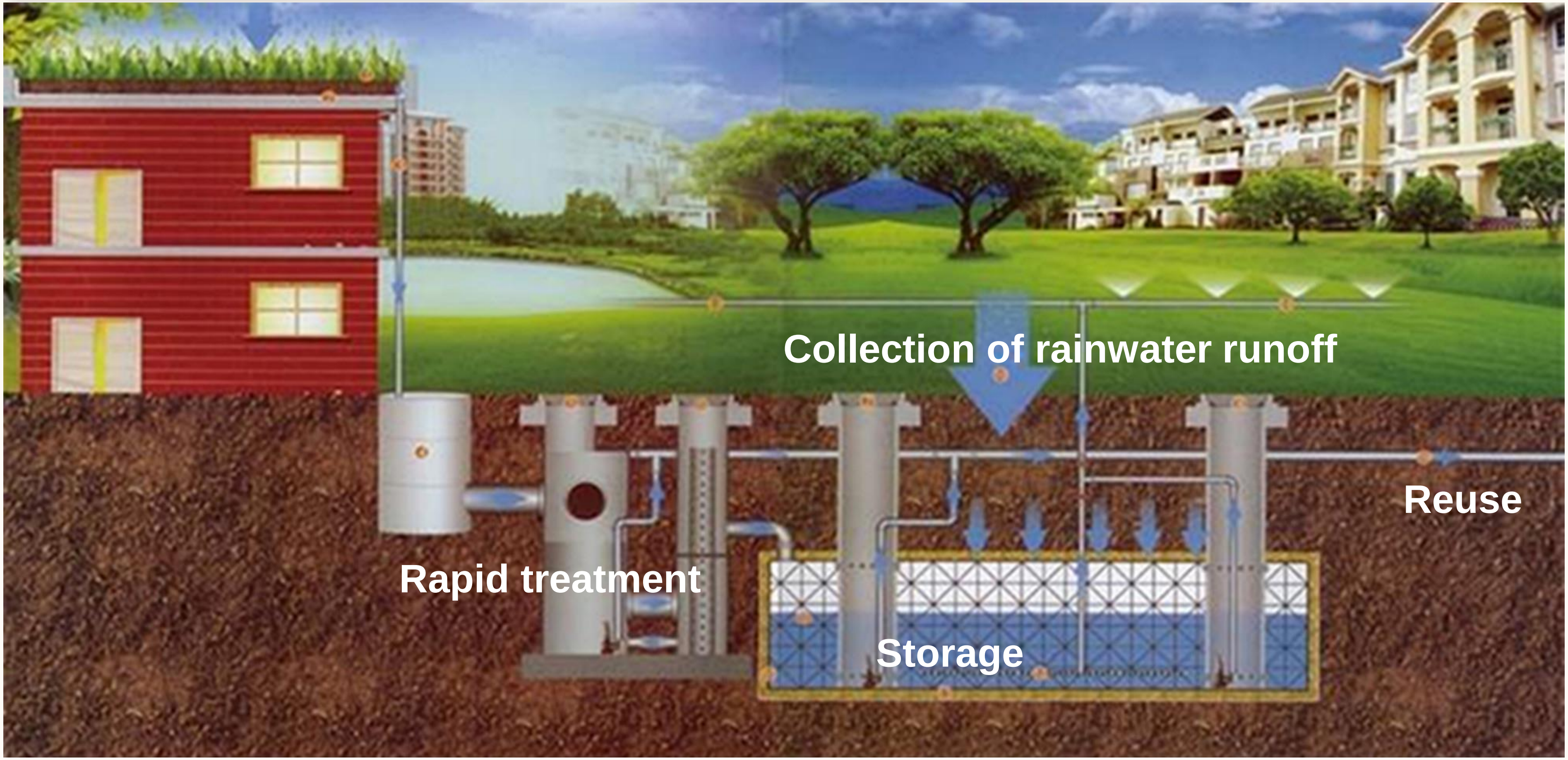
Particles, especially small particles, are the major pollutants in rainwater runoff.

	Source	Particle size distribution	Reference
1#	Sidewalk sediment	<104 μm for 15%， 104~246 μm for 28%、246~840 μm for 25%、846~2000 μm for 8%	Sartor 1974
2#	Sediments	<75 μm for10%， 75~250 μm for 32%，250~420μm for 24%， 420~850 μm for 19%, 850~3350 μm for 15%。	Shaheen 1975
3#	Motorway rainwater runoff	<100 μm for 90%, <50 μm for 78%	Roger 1998
4#	Road runoff	0.45~75 μm for 85%， >300 μm for 22%	Herngren 2005
5#	Road runoff	<100 μm for 10%， 100~400 μm for 25~60%，>400 μm for 40~70%	Sansalone 1998

Characteristics of pollutants in rainwater runoff of building districts

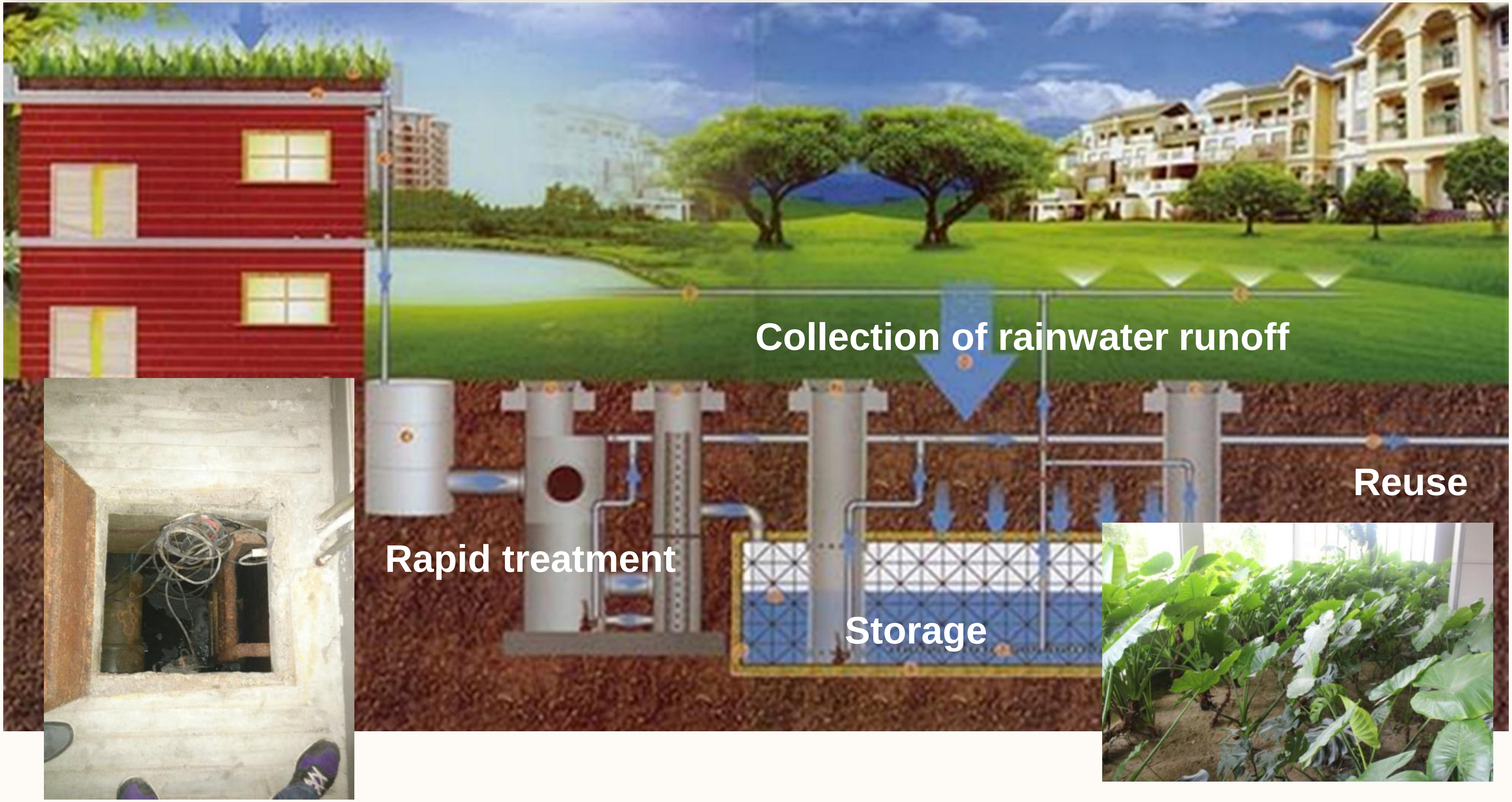
	Runoff	Particle size distribution	Reference
1#	Garden, Road, Roof	COD, BOD_5, Heavy metal（Cd、Cu、Pb、Zn）, and TP were largely incorporated into filterable partcles	Gromaire -Mertz M C 1999
2#	Road	60~80% TP and Pb，50~60% TN，30~40% Zn were particulate	Hvitved-Jacobsen 1991
3#	Road	More than 60% of TP, 40% of TN were adsopt on the particles with 11~150 μm	Vaze J 2004
4#	Highway	50% of Zn, Pb and Cu were adsopt on the small particles with size less than 100 μm	Sansalone 1997

Treatment and reuse system for rainwater in building districts



（https://baike.so.com/doc/5606070-5818679.html）

Treatment and reuse system for rainwater in building districts



（https://baike.so.com/doc/5606070-5818679.html）

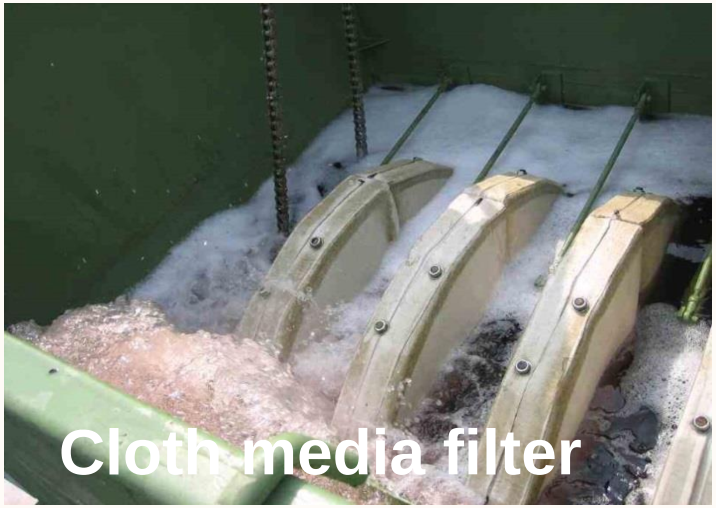
Characteristics of pollutants in rainwater runoff of building districts

1. Heavy particulate pollution
2. COD_{Cr}, TP, and heavy metal were mainly in particle form
3. Large rainfall runoff

Filtration is suitable for runoff treatment
1. Well retention effects for particles
2. Large hydraulic load

1. Physical-chemical filtration process：hydrocyclone, filtration、sedimentation、permeable pavement；
2. Biological filtration process: artificial wetland, rainwater garden, glassed swales

Normal filtration processes



Effectiveness of the normal filtration processes

Process	**SS (%)**	**Turbidity (%)**	**TP (%)**	**NH_4-N (%)**	**TN (%)**	**CODcr (%)**	**Hydraulic load $m^3/(m^2*h)$**	**Advantages**	**Disadvantages**
Sand filter	58-95	55-90	27-91.3	31-93	5-71	35-69	0.6-9	Wildly used, high hydraulic load, good for SS removal	Poor effects for removal of microbes and TN
Wetland	-98-97.3	10-78	-47.6-96.5	86	-39.6-85.9	-47.6-96.5	0.01	Good for NP removal	Low hydraulic load, large land use
Membrane	97	>95	≥80	-	Poor	80-84	0.05-0.1 (metal)	Good for SS removal, stable, easy for maintenance	High cost
Filter cloth（20μm）	70-80	-	-	-	-	-	5-25	high hydraulic load、Good for SS removal	Less case for rainwater

Effectiveness of the normal filtration processes

Items	Parameters	Remove efficiency
Particulate pollutants	SS	Membrane＞Sand filter＞Filter cloth＞Artificial wetland
	Turbidity	Membrane＞Sand filter＞Artificial wetland
Solable pollutants	TP	Membrane＞Sand filter＞Artificial wetland
	NH_4-N	Artificial wetland＞Sand filter＞Membrane
	TN	Sand filter＞Artificial wetland＞Membrane
	CODcr	Membrane＞Sand filter＞Artificial wetland
Hydraulic load		Filter cloth＞Sand filter＞Membrane＞Artificial wetland

- Sand filter is a good candidate for the treatment of rainwater runoff in building districts

Research progress on filtration process of rainwater runoff

	Process	Item	Turb. (NTU)	SS (mg/L)	COD (mg/L)	TP (mg/L)	NH4-N (mg/L)	TN (mg/L)	Bac. count cells	Heavy metal	Reference
1#	Sand	Influent	6-93	14-56	-	0.08-0.15	-	1.0-1.4	500-11000	-	Aryal, 2010
		Effluent	-	-	-	-	-	-	-	-	
		Removal efficiency	55-90%	60-90%	-	40-70%	-	30-50%	-25-90%		
2#	Underground sand filtration	Removal efficiency	-	70-90%	-	43-70%	-	30-50%	-	22-91%	Shen, 2009
	Surface sand filtration	Removal efficiency	-	75-92%	-	27-80%	-	27-71%		33-91%	
3#	Hydrocyclone + rapid filter	Influent	-	207-958	38.5-90.0	0.12-0.6	0.39-1.18	2.16-3.79	-	-	Jin, 2011
		Effluent 1	-	110-854	4.1-97.0	0.10-0.64	0.35-1.11	1.75-3.06	-	-	
		Effluent 2	-	＜10	-	-	-	-	-	-	
		Removal efficiency	-	95%	52-58%	60-80%	70-90%	30%（SV)	-	-	
4#	Sand	Influent	-	-	108.5-165.9	0.09-0.62	2.49-3.61	-	-	-	Chen, 2012
		Effluent	-	-	39.5-87.0	0.04—0.19	0.19—0.59	-	-	-	
		Removal efficiency	-	-	48-64%	57-89%	84-93%	-	-	-	

Research progress on filtration process of rainwater runoff

5#	Zeolite filtration	**Influent**	-	-	95.7-122.1	0.07-0.21	1.66-2.09	-	-	-	
		Effluent	-	-	32.6-79.6	0.02-0.07	0.19-0.45	-	-	-	
		Removal efficiency	-	-	35-66%	78-89%	66-73%	-	-	-	
6#	Coagulation + Sand	Influent	54.4	-	87.3	0.80	5.34	-	-	-	Wu, 2008
		Effluent	7.5	-	27.0	0.07	3.68	-	-	-	
7#	filtration	Removal efficiency	-	87%	-	59%	-	32%	-	Cu：49% Zn：80%	US EPA2000
8#	Vertical sand filtration	Effluent	-	74	-	0.14	-	1.3	-	Cu：5.5 Zn：20.0	
		Removal efficiency	-	58%	-	45%	-	5%	-	Cu：32% Zn：56%	

Research gap

1. Effectiveness at large hydraulic load was less assessed
2. The optimization of materials, particle size, depth, velocity of filter

Objective

The objective of the present study is to develop the technology of rapid filtration for treatment of stormwater runoff.

Four works:

(1) The effects of filters with single media of quartz sand or ceramsite, as well as dual media of both, on removal of particulate matter, organic matter, nitrogen and phosphorus in stormwater runoff were evaluated under high hydraulic loadings.

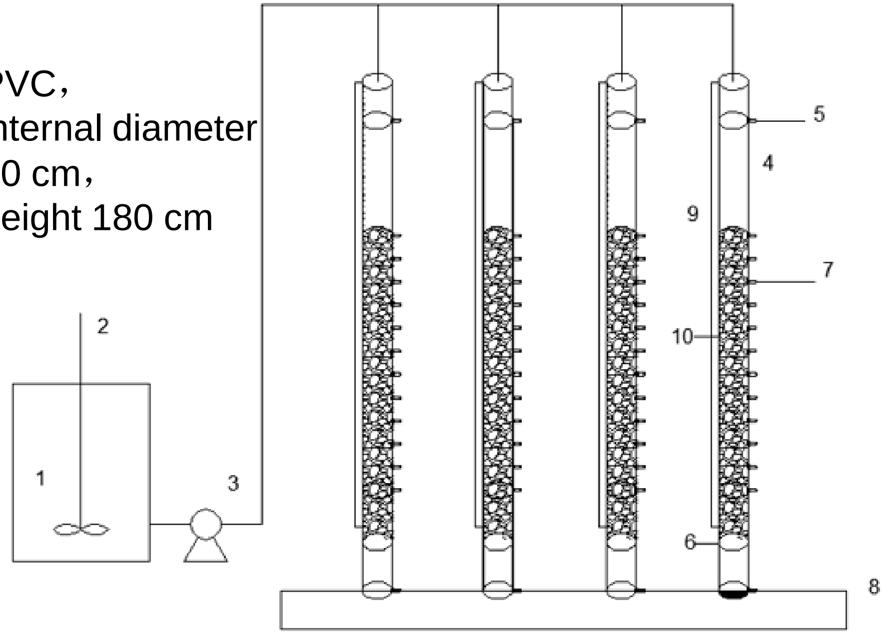
(2) Long-term operation test of dual-media filter was performed to assess the effectiveness and stability of pollutants removal and to determine suitable filtration period through head loss analysis.

(3) The effectiveness of a rapid filtration device was assessed to treat real stormwater runoff collected in rainy days.

(4) The improvements in removal efficiency on both particulate and dissolved pollutants were estimated by combination of rapid filtration and artificial wetland.

Filtration experiment device

PVC，
internal diameter 10 cm，
height 180 cm



1.水箱 2.搅拌浆 3.蠕动泵 4. 滤柱 5. 溢流口 6. 穿孔筛板 7. 出水阀 8. 基座 9. 测压管 10. 测压管

Design of filtration experiment device

Picture of filtration experiment device

- Quartz sand or ceramsite with size of 3-5, 5-8, and 8-12.5 mm
- The particle size distribution in effluents at different media depth were estimated.
- The effective media depths as well as suitable filtration rate were determined.

Feed water

Simulated rainwater:

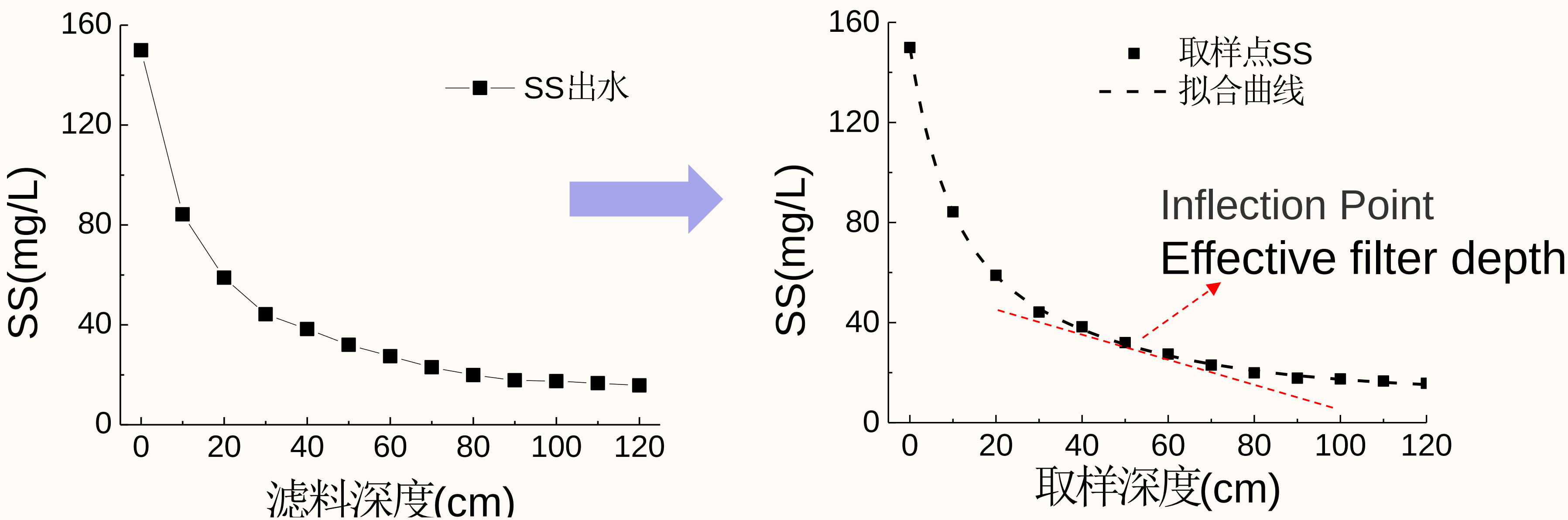
SS: Surface earth sampled at Tsinghua campus with screening

Group	pH	SS（mg/L）	COD_{Cr}（mg/L）	TN (mg/L)	NH_4-N (mg/L)	TP (mg/L)
Normal level	6~8	150	150	6	3	0.45
High level	6~8	300	300	12	6	0.90

Real rainwater runoff sample

Sampled at Building L of Tsinghua campus

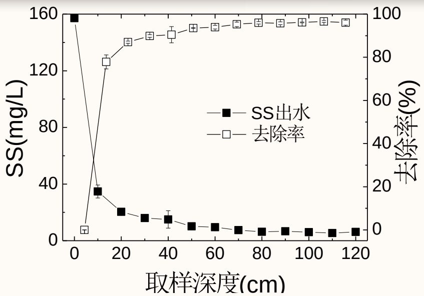
Effectiveness of single filter on SS removal



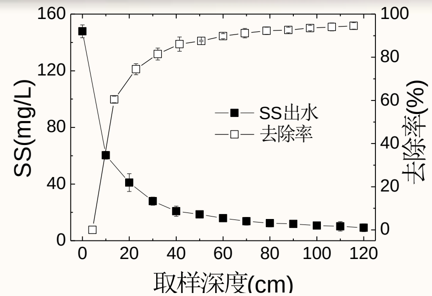
Filtration curve of 5-8 mm sand at V=10 m/h. Left is measured value and Right is simulated curve.

- Inflection Point: for each filter of 1 cm, increase in SS removal was less than 0.3%

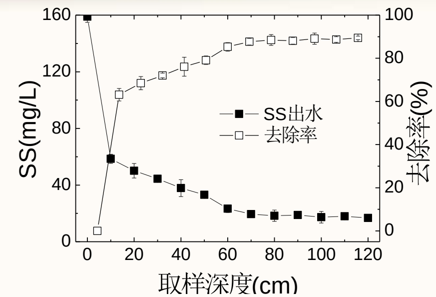
Effectiveness of single filter on SS removal



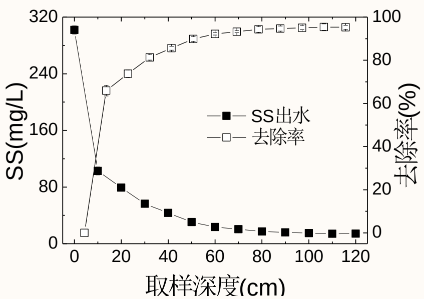
SS=150 mg/L V=5 m/h 3-5mm石英砂



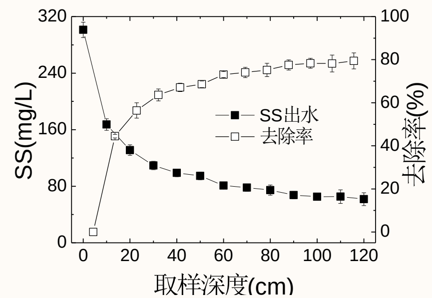
SS=150 mg/L V=10 m/h 3-5mm石英砂



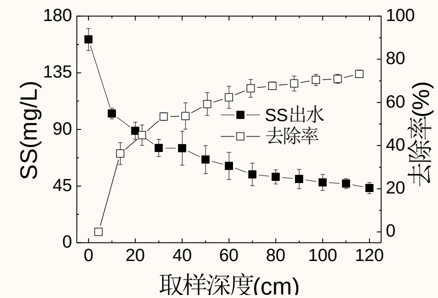
SS=150 mg/L V=5 m/h 8-12.5mm石英砂



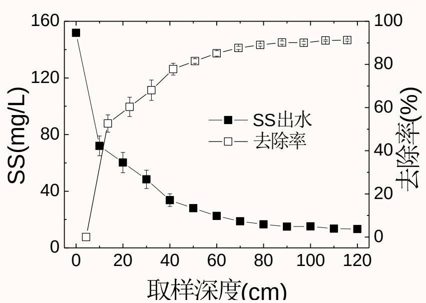
SS=300 mg/L V=5 m/h 3-5mm石英砂



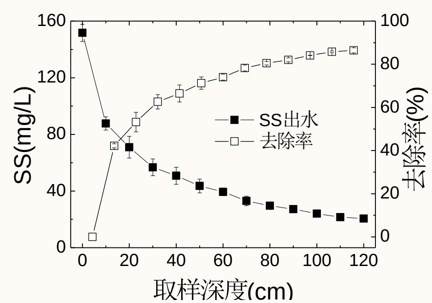
SS=300 mg/L V=20 m/h 8-12.5mm石英砂



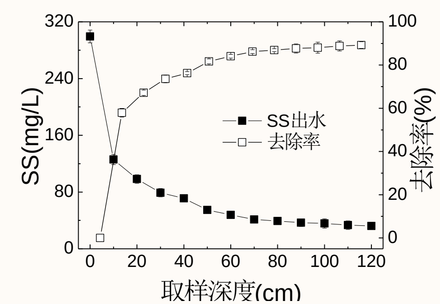
SS=150 mg/L V=20 m/h 8-12.5mm陶粒



SS=150 mg/L V=15 m/h 3-5mm陶粒



SS=150 mg/L V=20 m/h 3-5mm陶粒



SS=300 mg/L V=10 m/h 5-8mm陶粒

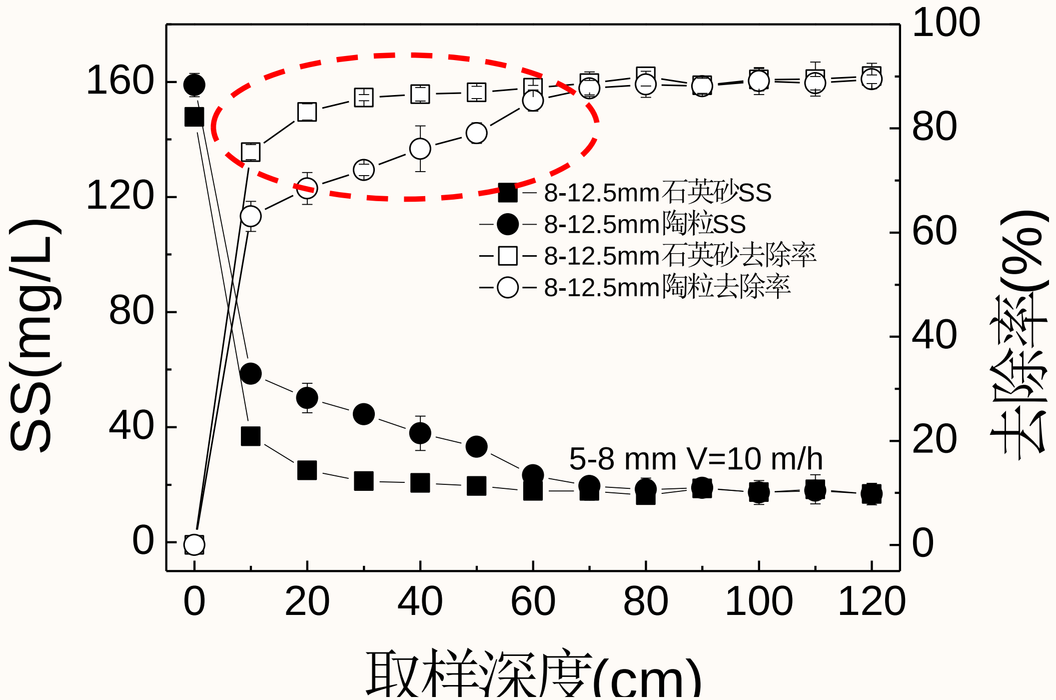
Effectiveness of single filter on SS removal

Hydraulic load	5 m/h	10 m/h	15 m/h	20 m/h
Sand size	Effective filter depth (EFD, cm)			
3-5 mm	28	49	60	67
5-8 mm	41	56	53	52
8-12.5 mm	25	32	35	49

Hydraulic load	5 m/h	10 m/h	15 m/h	20 m/h
Ceramsite size	Effective filter depth (cm)			
3-5 mm	46	65	80	108
5-8 mm	54	63	75	72
8-12.5 mm	43	65	62	62

1. More than 90% SS were removed by the sand at 0-60 cm or the ceramsite at 0-80 cm;
2. Larger sand size, smaller EFD
3. Larger hydraulic load, larger filter depth
4. Hydraulic load should be lower than 15 m/h as SS removal at 20 m/h were lower than 80%

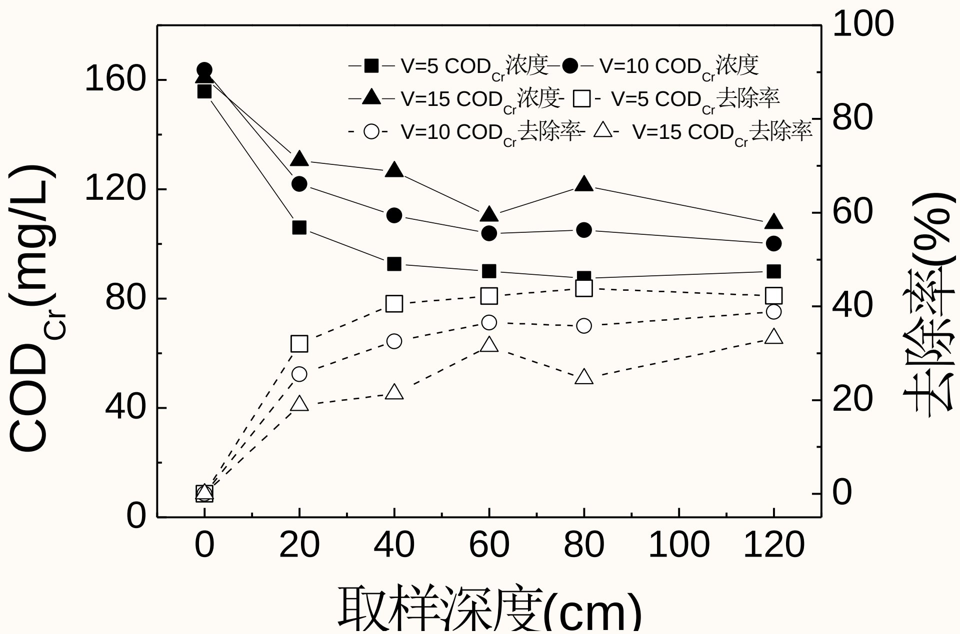
Effectiveness of single filter on SS removal

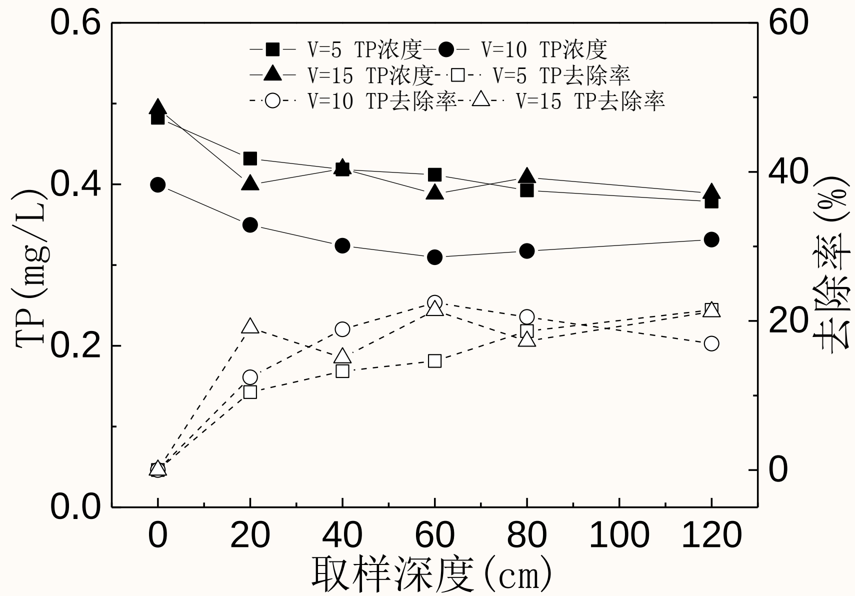


(8-12.5 mm, SS=150 mg/L, V=10 m/h)

For filter depth within 0-60 cm, sand filtration is better；

Effectiveness of single filter on COD and TP removal

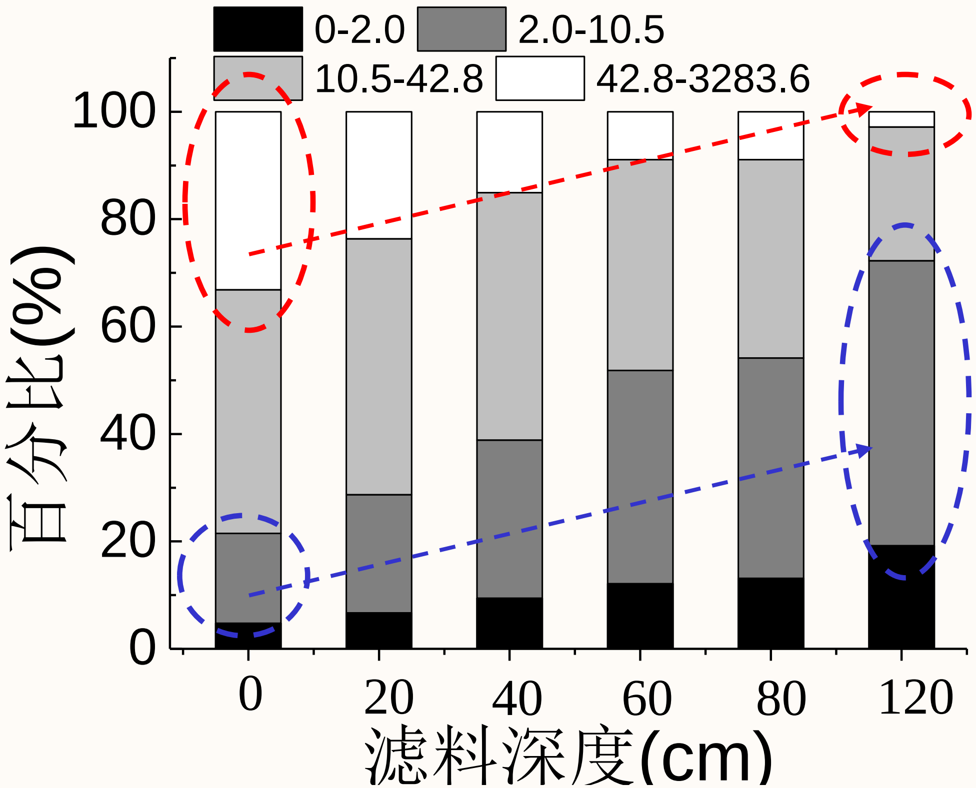




SS=150 mg/L 5-8 mm sand

- ✓ 35-50% COD_{Cr} and 15-30%TP were removed, over 90% removed within the filter depth of 0-60 cm
- Less effects for ammonia and TN removal

Particle size distribution of effluent of single filter



5-8 mm Sand
SS=150 mg/L V=10 m/h

- Large particles were mainly retained by the surface filter
- The percentage of small particles with size <10.5 μm increased in the effluent

Optimal filter depth for pollutants removal

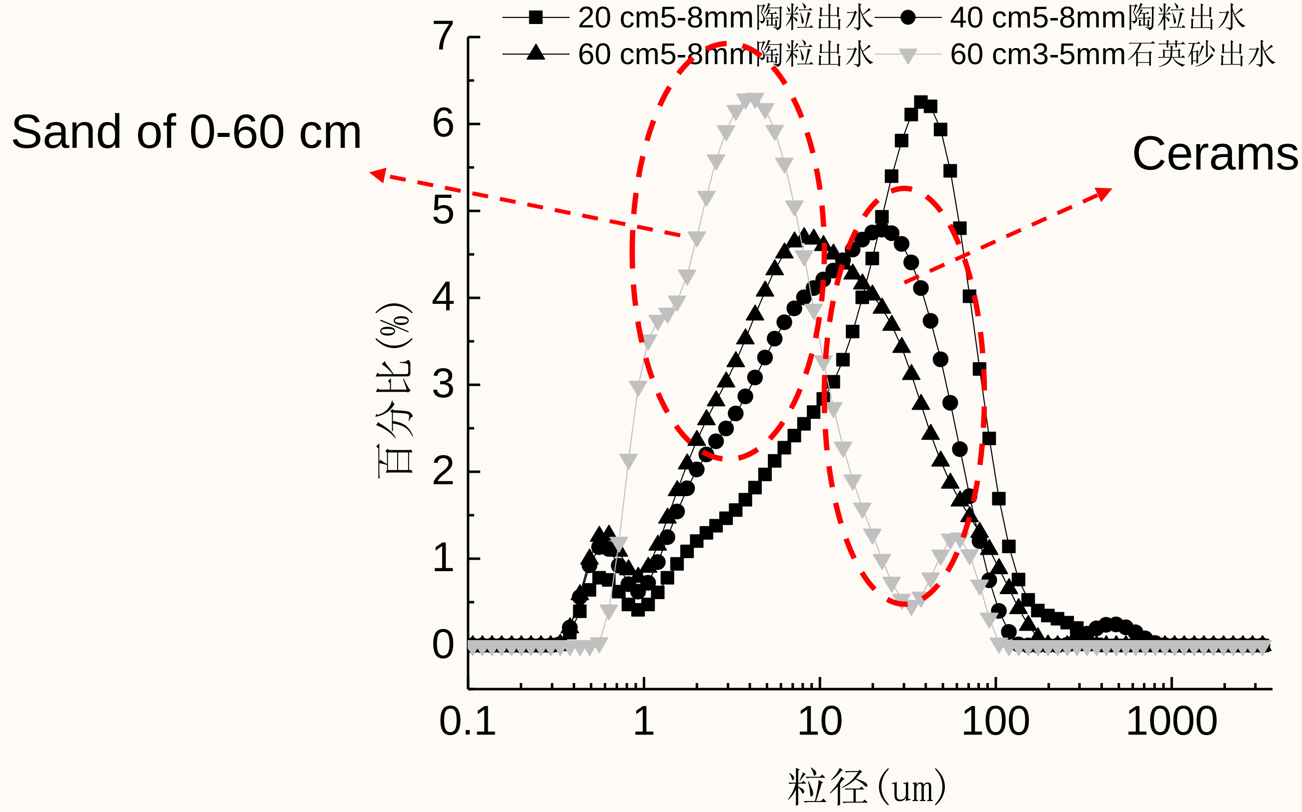
原水SS mg/L	Size mm	HL mg/L	SS mg/L	COD_{Cr} mg/L	TP mg/L	EFD mm
150	3-5	5	20	40	60	60
		10	40	120	40	120
		15	60	60	60	60
	5-8	5	50	40	80	80
		10	60	60	40	60
		15	60	80	60	80
	8-12.5	5	20	40	60	60
		10	30	60	40	60
		15	50	40	60	60
300	3-5	5	50	40	40	50
		10	50	60	40	60
		15	60	60	80	80
	5-8	5	40	40	40	40
		10	50	40	40	50
		15	50	60	60	60
	8-12.5	5	30	40	40	40
		10	30	40	80	80
		15	50	40	80	80

Optimal sand filtration

- 5-8 mm
- <10 m/h
- 60 cm

Similar results for ceramsite filtration

Hypothesis for dual-media filtration



How about to combine the two filters together ?

Hypothesis for dual-media filtration

Column	Upper layer	Lower layer
1#	5-8 mm ceramsite for 40 cm	3-5 mm sand for 60 cm
2#	5-8 mm ceramsite for 60 cm	3-5 mm sand for 60 cm
3#	5-8 mm sand for 40 cm	3-5 mm sand for 60 cm

Effectiveness of dual-media filtration

SS

HL	Effluent of dual-media filtration			Effluent of single media filtration	
m/h	1#	2#	3#	Sand	Ceramsite
5	92.9%	96.2%	93.4%	92.6%	91.8%
10	92.4%	92.7%	91.0%	89.5%	88.2%
15	90.6%	91.0%	91.3%	82.9%	82.7%

COD

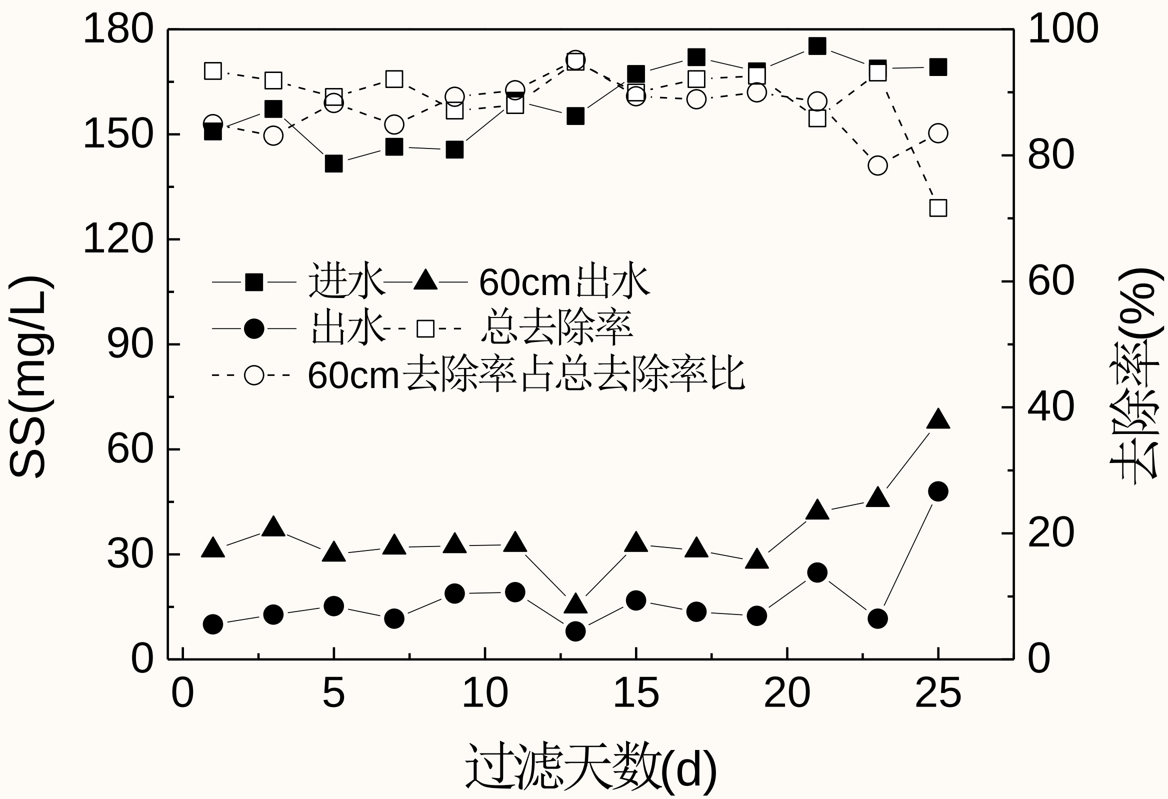
m/h	1#	2#	3#	Sand	Ceramsite
5	44.2%	46.6%	41.6%	42.3%	39.6%
10	44.7%	43.3%	40.9%	37.6%	43.0%
15	40.3%	41.6%	35.9%	28.8%	27.3%

TP

m/h	1#	2#	3#	Sand	Ceramsite
5	25.1%	28.8%	26.1%	17.9%	24.2%
10	23.5%	26.8%	23.8%	17.0%	21.1%
15	22.9%	24.5%	21.3%	15.1%	21.3%

Removal efficiency indeed improved

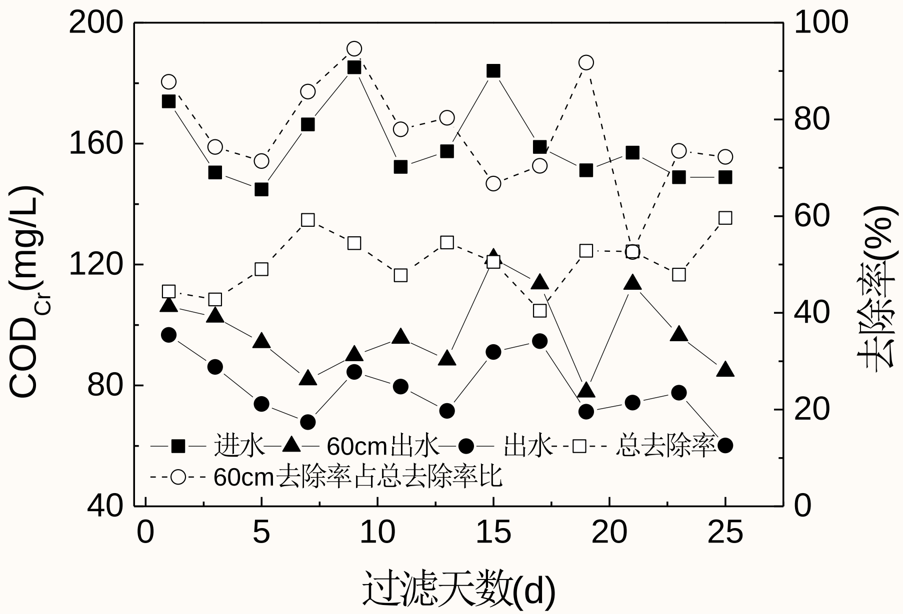
Effectiveness of dual-media filtration for long term operation

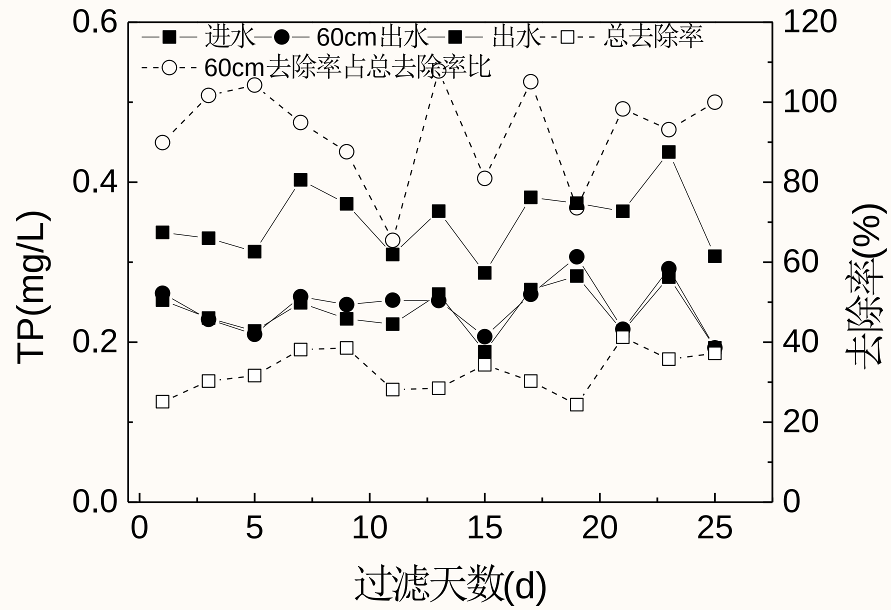


SS=150 mg/L, hydraulic load 10 m/h，
Filtration volume 120 L for each day， twice
Filtration time 1.5 h for each operation

✓ Stable effect on SS removal with removal effeciency of 85-95%

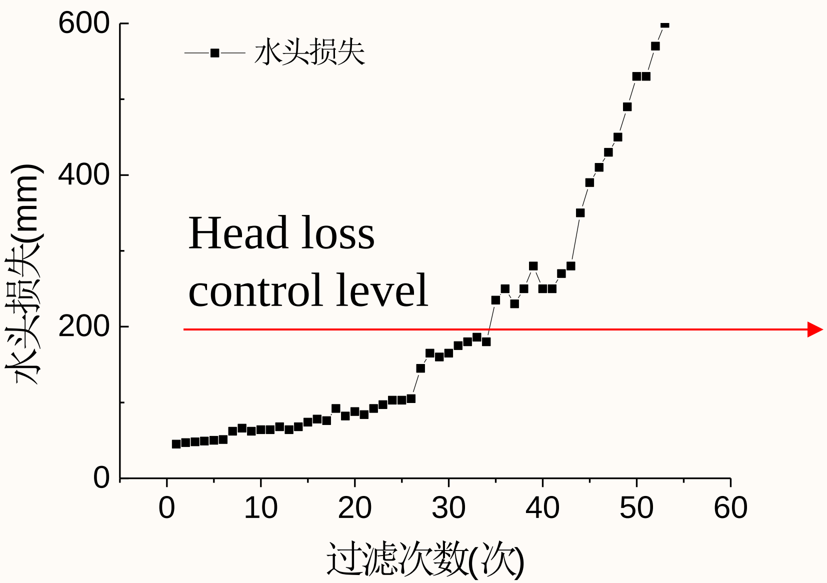
Effectiveness of dual-media filtration





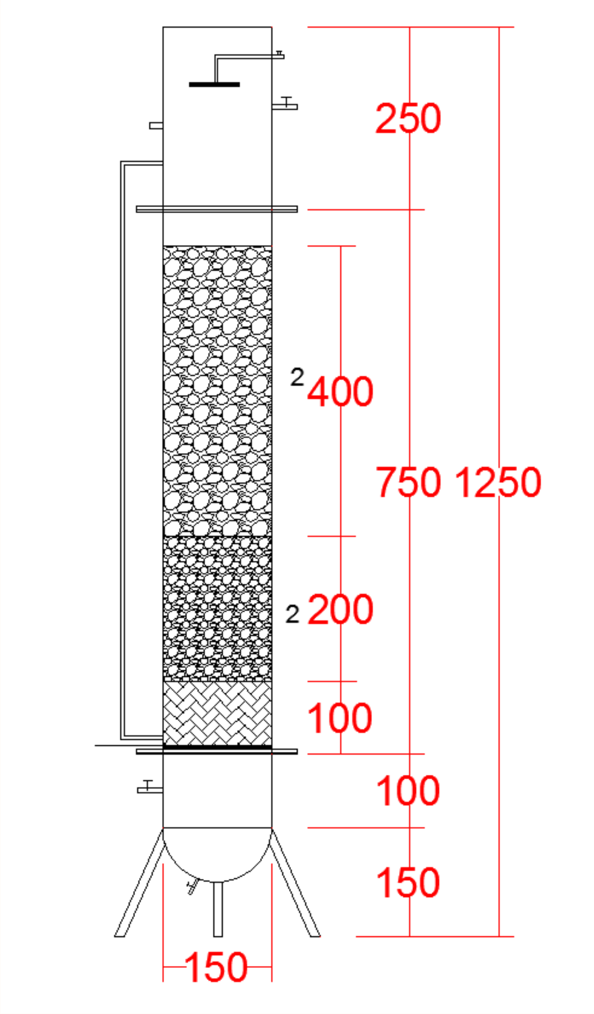
- ✓ Stable removal effects for COD and TP
- ✓ COD removal efficiency of 40-60%
- ✓ TP removal efficiency of 25-40%

Effectiveness of dual-media filtration

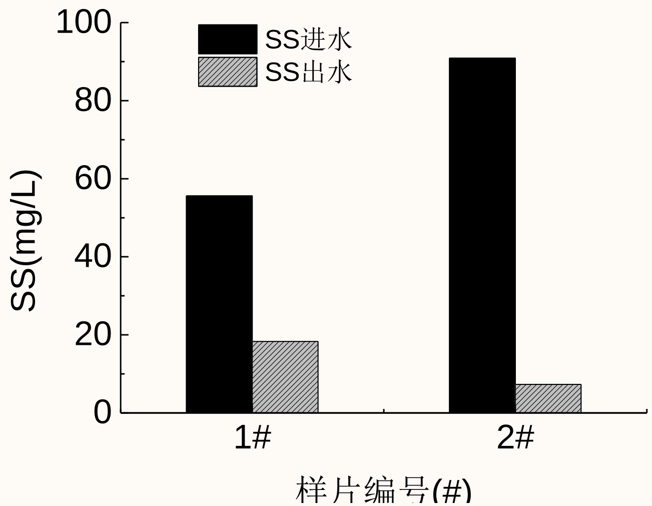


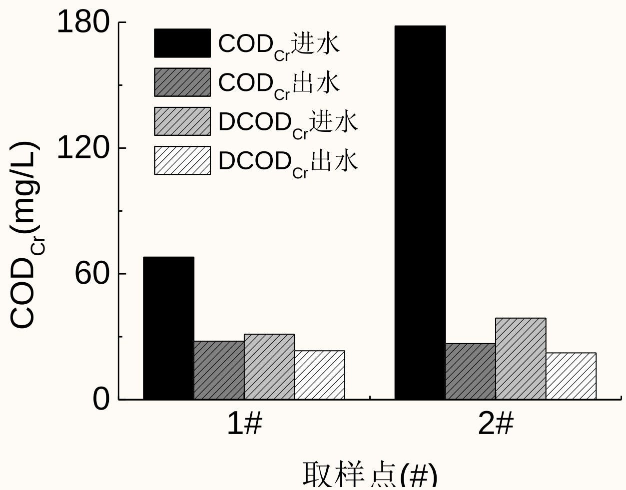
1. Head loss gradually increased during the 1st-26th filtration; no need for maintenance; the system performed well for treatment of 26 times of runoff water for rain of 45 min with 150 mg/L SS, average treatment runoff volume 199 m^3 per m^2 filter
2. Head loss rapidly increased since 27^{th}-36^{th} filtration; backwash should be operated
3. Head loss jumped to 600 mm at the 52th filtrtaion; it should be avoid.

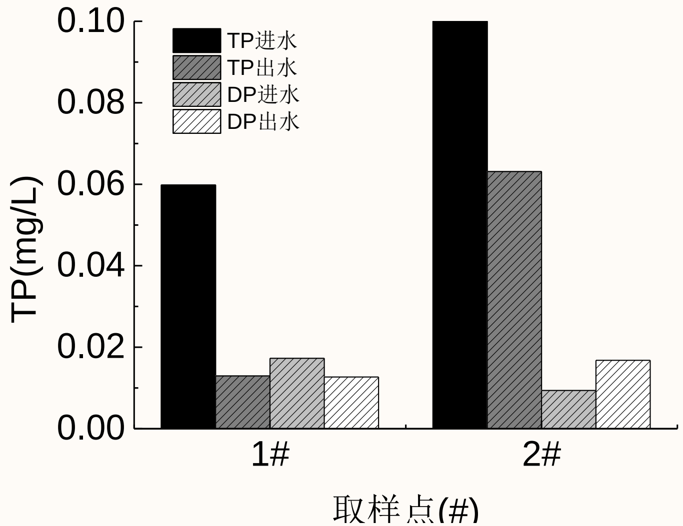
The device of rapid filtration with dual-media



Effectiveness of the rapid filtration device

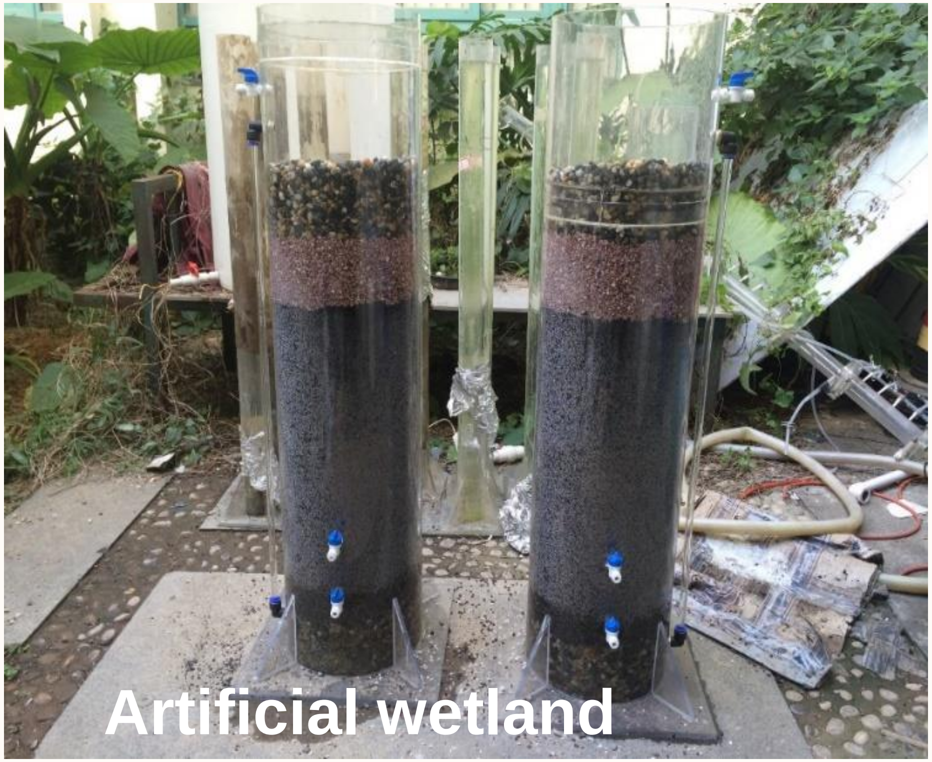






- ✓ Satisfied removal effects on SS, COD, and TP for 67.1-92.0%, 59.0-85.0%, 46.2-78.3%.
- ✓ The removal efficiencies on COD and TP were higher than the simulated feed water tests.

Combination of rapid filtration and artificial wetland



Pretreatment process
for removing SS, part of
COD and TP

Treatment process for water reuse
for removing ammonia, TN, COD, TP
0.1 $m^3/(m^2 \cdot h)$

Combination of rapid filtration and artificial wetland

Combination of rapid filtration and artificial wetland

SS	HL for wetland	No. Wetland	SS	COD_{Cr}	TP	NH_4-N	TN
mg/L	$m^3/(m^2 \cdot h)$		%	%	%	%	%
150	0.10	1	>98.0	88.2~95.7	87.4~94.9	约30	45.0~55.0
		2	>98.0	83.4~94.5	79.8~90.4	约30	45.0~55.0
	0.15	1	>98.0	90.5~92.7	76.7~87.4	21.7~25.3	40.4~48.4
		2	>98.0	83.3~94.9	58.5~79.8	24.4~30.2	41.7~45.6
300	0.10	1	>98.0	92.9~96.8	95.2~96.0	48.8~51.1	41.1~46.5
		2	>98.0	87.5~94.5	76.5~78.1	36.1~40.6	39.5~51.7
	0.15	1	>98.0	82.1~84.0	89.3~90.0	42.1~57.9	42.3~50.4
		2	>98.0	78.9~82.1	82.0	38.3~48.1	37.6~38.3

The combination of rapid filtration and artificial wetland can significantly improve removal efficiency in dissolved pollutants as well as prevent blockage of artificial wetland due to removal of particles in advance.

Conclusions

1. The filters with single media of quartz sand or ceramsite with particle sizes of 3-5, 5-8, and 8-12.5 mmunder filtration rate of 5-15 m/h can remove 73-96% of SS, 35-50% of COD_{Cr}, and 15-30% of TP.
2. The removal efficiencies of dual-media filters on SS, COD_{Cr}, and TP were 91%-97%, 35-50%, and 15-25%, respectively, which showed better and more stable performance than single media.
3. The removal efficiencies of dual-media filter within the initial 18 d, i.e. 36 times filtration of long-term filtration teston SS, COD_{Cr}, and TP were 85-95%, 40-60%, and 25-40%, respectively. The head loss was less than 180 mm and increased in less than 7.5 mm for each filtration.
4. The combination of rapid filtration and artificial wetland can significantly improve removal efficiency in dissolved pollutants as well as prevent blockage of artificial wetland due to removal of particles in advance.

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Dr. Yi TAO

Assistant Professor

Graduate School at Shenzhen,

Tsinghua University

13632759436

tao.yi@sz.tsinghua.edu.cn