Experimental study on filter media using locally available materials in bioretention

Feikai Yang, Rajendra Prasad Singh and Dangfang Fu

ABSTRACT

Bioretention systems and selection of effective filter media are very important in implementation of sponge cities. The current study was carried out to find proper composition of filter media using locally available materials, which acclimate to the special/local climate, environmental and geographical conditions in Yangtze River Delta region. Results revealed that sand with discontinuous gradation and containing a certain amount of clay led to unsatisfactory hydraulic performance (hydraulic conductivity ranged from 423 mm/h to 1,054 mm/h, and 1,500 mm/h to 29 mm/h). In contrast, a mixture of locally available sand, which consisted of continuous gradation of coarse sand (40–70%, by mass), fine sand (0–40%, by mass), very fine sand (10–60%, by mass) and nutrient soil (0–3%, by mass), had a hydraulic conductivity ranging from 200 to 400 mm/h and relatively stable structure. During the 70 days' flooding test, the hydraulic conductivity changed in the first 20 days due to the migration of particles (mainly <0.6 mm) and then became stable; the stable value was close to the initial. Moreover, easy access and simple production processes made it easier to promote. Findings could be used as a guideline for implementation of bioretention systems and selection of locally available and effective filter material.

Key words | bioretention, filter layer gradation, hydraulic conductivity, sponge city, stormwater control

Feikai Yang
Rajendra Prasad Singh
Dangfang Fu (corresponding author)
School of Civil Engineering,
Southeast University,
Nanjing 210096,
China
E-mail: *fdf@seu.edu.cn*

INTRODUCTION

Stormwater management concepts have been proposed and developed around the world to deal with water-related issues caused by rapid urbanization (Liu *et al.* 2017). Dominant concepts with respect to the performance include low-impact development (LID – USA and Canada), water-sensitive urban design (WSUD – Australia) and sustainable urban drainage systems (SUDS – UK) (Zhang *et al.* 2016; Ariza *et al.* 2019). Low-impact development or best management practices (BMPs) have been widely adopted and proven successful in addressing hydrologic and water quality issues (Eckart *et al.* 2017). In 2013, the government of China proposed and called for the comprehensive promotion of the construction of sponge cities, which emphasized the importance of integrated management of water-related issues. Moreover, bioretention with good adaptive mechanisms for runoff reduction (Charlesworth *et al.* 2013; Haile *et al.* 2016; Gao *et al.* 2018; de Macedo *et al.* 2019) and water quality improvement (Li *et al.* 2014; de Macedo *et al.* 2019; Hermawan *et al.* 2019; Singh *et al.* 2019) is a common stormwater control measure used to mitigate the impacts of urban runoff, and an important technology for the construction of sponge cities.

A bioretention system is a low energy treatment technology with the potential to provide both water quality and quantity benefits. The typical structure of bioretention is composed of a detention layer, filter layer, transition layer

doi: 10.2166/aqua.2019.210

and drainage layer, from top to bottom. Stormwater is diverted from a kerb or pipe into the bioretention system, where it flows through dense vegetation temporarily ponding on the surface, before slowly filtering down through the filter media, followed by purification through physical and biological processes (Archer *et al.* 2002; Hatt *et al.* 2009). Filter media is an important factor affecting the operation and efficiency of bioretention systems (Hunt *et al.* 2006; Bratieres *et al.* 2008). Permeability of the filter material affects total runoff reduction rate, peak flow reduction rate, peak time of the entire system (Tahvonen 2018) and, as well, as the pollutant removal efficiency. However, the surface soil type varies from region to region, and choosing the mixing ratio also differs accordingly.

The fillers in the current study were initially selected with respect to the hydraulic conductivity of the filter layer and its removal impact on the contaminants. In existing designs, it is recommended to use a mixture of filler with good permeability, soil-based and certain organic matter. The recommended mixing ratio of fillers in North Carolina (85–88% sand, 8–12% clay and silt, and 3–5% organic matter) seems economically viable. However, the recommended filler ratio in Maryland (50% sand, 30% topsoil and 20% organic matter: wood chips, leaves compost (MDE 2000)) is relatively expensive. The Facility for Advancing Water Biofiltration (FAWB), Australia has recommended the use of sandy loam as filler and suggested that it is better to have all gradation particles in the filler to prevent system collapse caused by loose particles. At the same time, it is also suggested that the hydraulic conductivity of filter layer fillers should be between 100 and 300 mm/h. The optimal value ranged between 100 and 200 mm/h after the system has stabilized (Hatt *et al.* 2009).

Based on the FAWB guidelines, the current study attempts to develop a composition of the filter layer suitable for climate and soil conditions in the Yangtze River Delta region of China by using locally available materials. Considering the difference in climate between Australia and local conditions, Australia has relatively clean stormwater runoff and low mean annual rainfall, while in the Yangtze River Delta region, the rainfall is abundant and stormwater runoff is highly contaminated. Therefore, permeability of the filter layer should not be very low for effective flood protection. Severe runoff pollution in China and other countries also leads to a serious clogging problem in the filter (Xu *et al.* 2016; Zhao *et al.* 2017; Yi *et al.* 2019; Yang *et al.* 2019; Zhou *et al.* 2019). Due to clogging, it is very hard for many pollutants to be fully removed from the treatment systems and advanced technologies or new materials for further treatment are needed (Ali *et al.* 2015, 2016; Basheer 2017, 2018; Burakova *et al.* 2018).

Research studies have mainly focused on the composition of the filter layer in recent years. Winston *et al.* (2018) found that higher underlying soil K_{sat} directly affected the volume reduction and peak flow mitigation in bioretention. Wang *et al.* (2011) found that the hydraulic conductivity of silty sand decreases with the increase of the fines' content. It is also noteworthy to mention that the climatic, economic and geographical conditions in countries like Australia or America are different from China. Therefore, design guidelines developed in these countries cannot be implemented directly in China or other developing countries. Moreover, locally available filter media are also different from the materials used in developed countries which have already been investigated for their quality and pollutant removal capacity. Hence, the current study aimed to find out the proper composition of filter media using locally available materials, which are suitable for the specific/local climate and environmental conditions in the Yangtze River Delta region. Another goal was to meet the requirements of sponge city construction in China, and not only focusing on effective performance but also considering the cost issues.

MATERIALS AND METHODS

Experimental design

Information regarding bioretention filter layers was highly available from previous studies, but they all had their own drawbacks such as inadaptability and inaccessibility of materials in different areas, which makes it hard to replicate a certain design in practice. Thus, three typical sand samples from the Yangtze River were chosen to find the optimal composition for filter layers in bioretention. The experiment was divided into four parts (Figure 1).

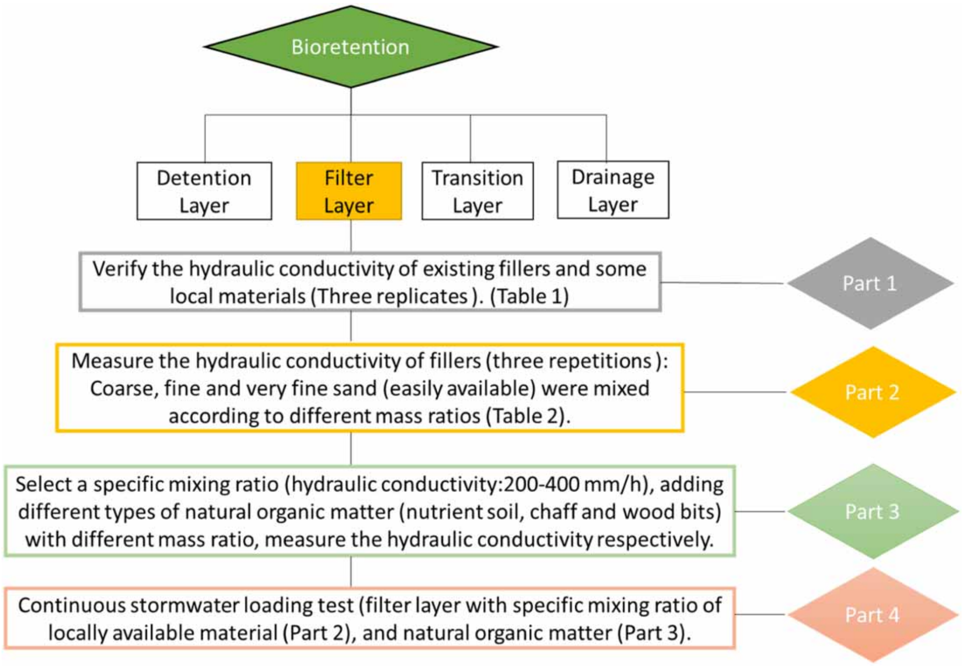

Figure 1 | Flow chart of the experiment.

Previous studies have suggested that some plant species are very useful in maintaining the infiltration capacity in bioretention due to their thick roots, which can be extended into the drainage layer (Hatt *et al.* 2009). This study further stated that a strong root system can increase the hydraulic conductivity while fine roots do not necessarily increase. Plants with thick roots (e.g., *Melaleuca*) demonstrated an ability to maintain hydraulic conductivity over time. Other species studied, with finer roots, had no such beneficial effects (Le Coustumer *et al.* 2012). Mainly, vegetation with fine roots is often used in bioretention in the Yangtze River Delta. Although plants may have some constraints on the bioretention performance they are not considered in this experiment because the main goal was to find an optimal mixing ratio of locally available materials to get a suitable initial hydraulic conductivity. Schematic diagrams of lab-scale experimental units designed and implemented in the current study and TST-70 analyser (Nanjing Soil Instrument Co., Ltd, Nanjing, China) are presented in Figure 2. TST-70 analyser was used to determine the permeability coefficient of sand and gravel non-cohesive soil under the unchangeable water pressure during the experiment.

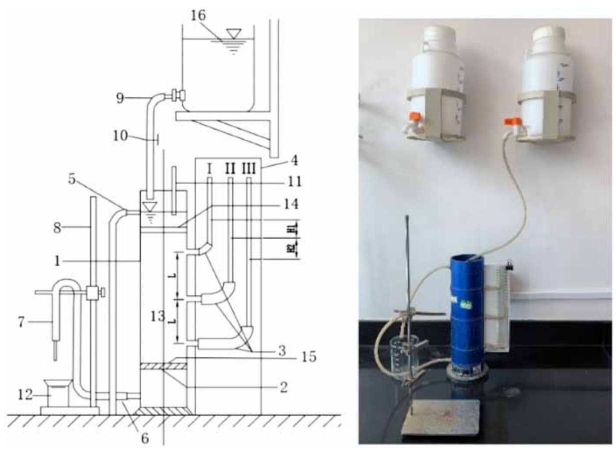

Figure 2 | Schematic design and lab-scale set-up of the TST-70 soil hydraulic conductivity tester (1. metal cylinder; 2. metal orifice; 3. pressure tap; 4. piezometer pipe; 5. spillway hole; 6. infiltrating hole; 7. regulating tube; 8. sliding support; 9. water supply pipe; 10. flatjaw pinchcock; 11. thermometer; 12. measuring cup; 13. sample; 14. gravel layer; 15. copper wire gauze; 16. water bottle).

Water quality

The inflow for the experiment was stormwater runoff collected from the roof of the laboratory. The average pollutant concentrations were as follows: total suspended solids (TSS) 3 mg/L; NH_3-N 0.8 mg/L; total nitrogen (TN)

1.5 mg/L and total phosphorus (TP) 0.34 mg/L. Nutritive soil (1 g) was added into 500 mL of water and soaked for 24 hours. The mean pollutant concentrations were as follows: NH_3-N, 0.58 mg/L; TN, 3.01 mg/L and TP, 0.22 mg/L. Therefore, the nutritive soil had little effect on the effluent quality, and only occurred in the early operation of the bioretention system (Hatt *et al.* 2009).

Hydraulic conductivity was obtained by Darcy seepage formula (Equation (1)), calculating the hydraulic gradient of the filter layer between each two piezometer pipes and the flow rate of the whole infiltration system.

$$v = ki \quad (1)$$

where v is the infiltration velocity; k is the hydraulic conductivity; $i = \frac{h}{L}$ hydraulic gradient, which is the head loss per unit distance along the seepage direction; h is the water heads at both ends of the filter layer; and L is the length of the seepage path.

The flow was measured by a measuring cylinder and a stopwatch. After the flow was determined, the flow rate was calculated according to the cross-section area of the infiltration column. The filler experiments were carried out with the location of each piezometer pipe as the boundary, and the thickness of the filler L was calculated according to the type of fillers. The head difference was determined according to the reading data of the piezometric pipe in each layer, and then the hydraulic gradient was calculated according to Darcy seepage formula (Equation (1)).

RESULTS AND DISCUSSION

Analysis of different existing materials

Considering that the permeability of surface soil in Kunshan is extremely poor, a filter layer with low hydraulic conductivity has very little impact on alleviating flooding. The fillers are also prone to clogging due to the highly polluted storm runoff. Details on the locally available materials, previous designs in Kunshan and FAWB design requirements are presented in Table 1. However, the original filter media used in Kunshan included the surface soil, coarse sand (particle size between 1 and 2 mm) and

Table 1 | Different types of filter layer

No.	Type of filter layer
#1	Composition of the filter layer in FAWB
#2, 3	Composition of filter layer used in Kunshan, China
#4	Coarse sand
#5	Fine sand
#6	Very fine sand

medium sand (particle size between 0.25 and 1 mm), and the proportion was 2:3:15 (by volume). The average hydraulic conductivity of different fillers is shown in Figure 3. Findings presented in Figure 3 and Table S1 (Supplementary material) reveal that material of the filter layer recommended by FAWB is not continuous graded sand, although the hydraulic conductivity in engineering application meets the requirements. However, secondary screening of raw materials prolong the production process and escalate the production cost. Similarly, the original fillers in Kunshan were mixed with 10% surface soil. The initial hydraulic conductivity was estimated as >1,500 mm/h, and after a 20-day operation, the hydraulic conductivity decreased to 29 mm/h. This may be due to the low permeability of the surface soil, which is easy to agglomerate, resulting in a sharp drop of hydraulic conductivity which may affect the life cycle of the whole bioretention system.

A continuous gradation of fine sand was chosen as the basic filler of the filter layer, and a certain ratio of coarse

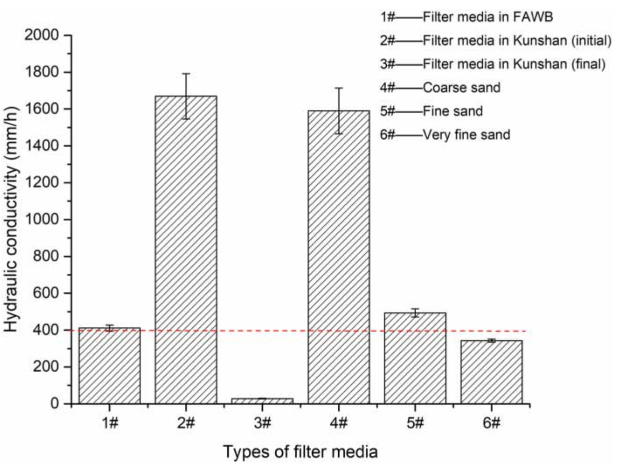

Figure 3 | Mean hydraulic conductivity of local and previously used filter layer.

sand (1.18–2.36 mm) and medium sand (0.3–1.18 mm) which are not continuous graded were added. The test results revealed that the hydraulic conductivity was 423 mm/h after the addition of 5% coarse sand and 25% medium sand, which is close to the required composition recommended by FAWB. The hydraulic conductivity increased sharply to 1,054 mm/h at day 20 of the continuous stormwater loading test. Gradation curves and the hydraulic conductivity of different compositions are shown in Figure 4(a) and Table S2 (Supplementary material). Results revealed that the filler volume (#10) greatly reduced after the continuous flooding, due to the gap gradation of sand, which affected the structural stability of natural sand. Because fine sand was the main part of the filler, the structural stability of the filter layer was consequently insufficient. The change of the filler structure is the key reason for the rapid increase of hydraulic conductivity. It is evident from Figures 3 and 4(b) that it was difficult for locally available materials to meet the requirements of FAWB, except fine sand which has a similar hydraulic conductivity and gradation curves. However, for local fine sand, particle size in the range of 0.15–0.6 mm accounted for >85%. The proportions of big particles were too low to stabilize the filler, and the long-lasting stormwater loading may lead to the collapse of the system.

Earlier, Water by Design (2014) recommended a 100% sand and loam mix while Australian guidelines recommended 100% sandy loam. However, Davis *et al.* (2009) highlighted the fact that when the use of loam was more than 30% (by volume), it may lead to collapse of the system due to the high clay content. Because of the lower average annual rainfall in Australia, the loam-based filter media may be applicable. As China has higher average annual rainfall, this filter media might not be suitable for application. Therefore, the previous design (local or international) may not adapt to the special conditions in the Yangtze River Delta region, China.

Analysis of fillers with different mixing ratio

As recommended by Australian guidelines (Hatt *et al.* 2009), initial hydraulic conductivity of filter media should be between 100 and 300 mm/h. Considering the difference of climate and environment conditions between China and Australia, this study selected the filter media with hydraulic conductivity that ranged between 200 and 400 mm/h. The experiment result shows that local materials cannot be directly used as filter layers in bioretention. Moreover, the filler, which is mixed with soil, will significantly affect the service life of the bioretention. Payne *et al.* (2014) suggested that sand with different particle size (between 0.05 and 3.4 mm) would provide sufficient infiltration rate and hold enough water to support the growth of plants. Therefore, local coarse, fine and very fine sand were used and mixed with a certain ratio in this section (Table 2). The mean hydraulic conductivity of these compositions is shown in Figure 5. It revealed that the hydraulic conductivity was

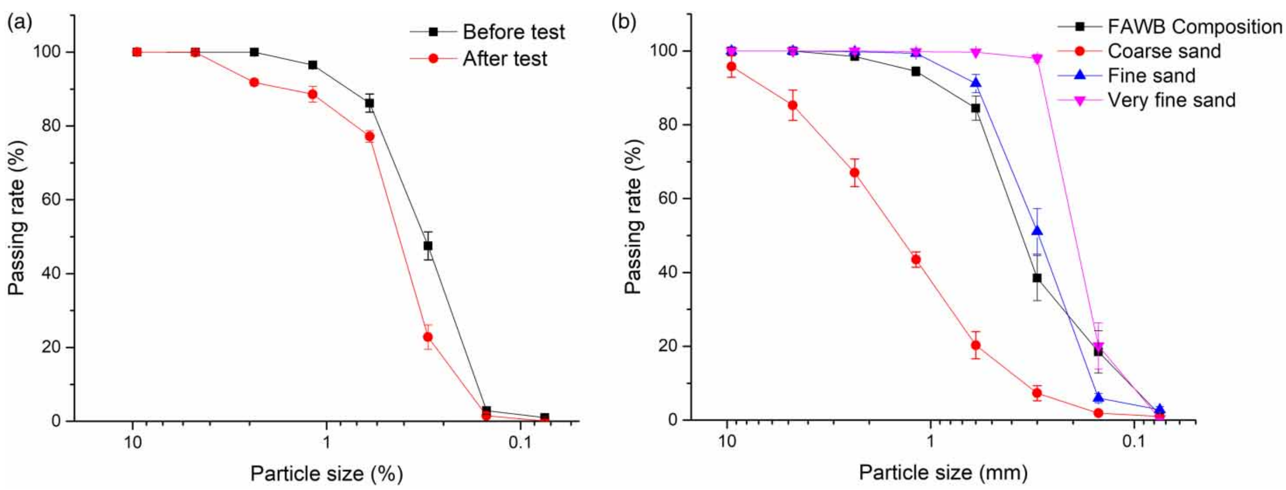

Figure 4 | (a) Gradation curves of #10 filler and (b) #3 locally available materials and filter layer in FAWB.

Table 2 | Mixing ratio of the filter layer using locally available materials

	Types (%)		
No.	Coarse sand	Fine sand	Very fine sand
#1	90	0	10
#2	90	10	0
#3	80	0	20
#4	80	10	10
#5	70	0	30
#6	70	10	20
#7	60	0	40
#8	60	10	30
#9	60	20	20
#10	60	30	10
#11	60	40	0
#12	50	50	0
#13	50	40	10
#14	50	30	20
#15	50	20	30
#16	50	0	50
#17	40	0	60
#18	30	0	70

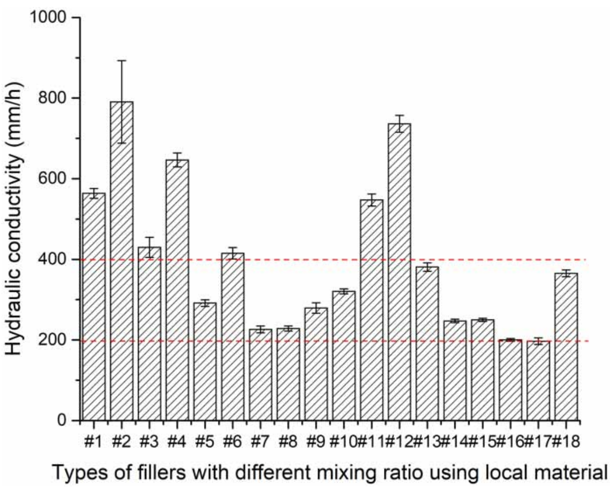

Figure 5 | Mean hydraulic conductivity of fillers with different mixing ratio using locally available materials.

appropriate in fillers #5 #7, #8, #9, #10, #13, #14, #15, #16, #17 and #18. The mixing ratios of the coarse, fine and very fine sand were estimated at 70:0:30, 60:0:40, 60:10:30, 60:20:20, 60:30:10, 50:40:10, 50:30:20, 50:20:30, 50:0:50, 40:0:60 and 30:0:70, respectively. Out of these, coarse sand ranged from 30 to 70%, fine sand ranged from 0 to 40% and very fine sand ranged from 10 to 70%. The grading range is presented in Table S3 (Supplementary material).

It can be seen from Figure 6(a) that when there are only two local materials involved in the filter layer and the coarse sand is fixed, if another local material is very fine sand, the hydraulic conductivity of the mixed filler is far lower than that of fine sand. This indicated that very fine sand is the key content to control the hydraulic conductivity of the whole layer. The reason is that very fine particles continuously fill the pores of the coarse sand while the fine particles will create their own pores beyond a certain ratio. In unison with Figure 6(b), it can be seen that, with the increase of the mixing ratio of very fine sand, the hydraulic conductivity of the filler tends to decline. As the very fine sand mixing ratio reached 60%, the hydraulic conductivity reached its lowest point, then it started to increase and reached close to the values of the original very fine sand. This result showed that coarse sand does not contribute much to the hydraulic conductivity of the mixed composition, and that the very fine sand plays the leading role, which leads to a poor structure stability. Therefore, the coarse, fine and very fine sand should be controlled between 40 and 70%, 0 and 40% and 10 and 60%, respectively, to meet the requirements of hydraulic conductivity from 200 to 400 mm/h and a relatively stable structure. This composition can meet the local requirements.

Analysis of different organic matter and mixing ratios

Fillers are usually filled with nutrients to keep the plant growing. In this section, a certain mixing ratio of coarse, fine and very fine sand (50:20:30) was chosen to start the experiment for screening the optimal mixing ratio of natural organic matter (Figure 7). Findings revealed that different types of organic matter have specific impacts on the hydraulic conductivity of the filler. In respect to nutrient soil and wood chips, the hydraulic conductivity at first decreased and then increased with addition of their respective content. It reached the lowest point when the content of nutrient soil was 4% while that of wood chips was 1%. The hydraulic conductivity of the lowest point was 189.8 mm/h and

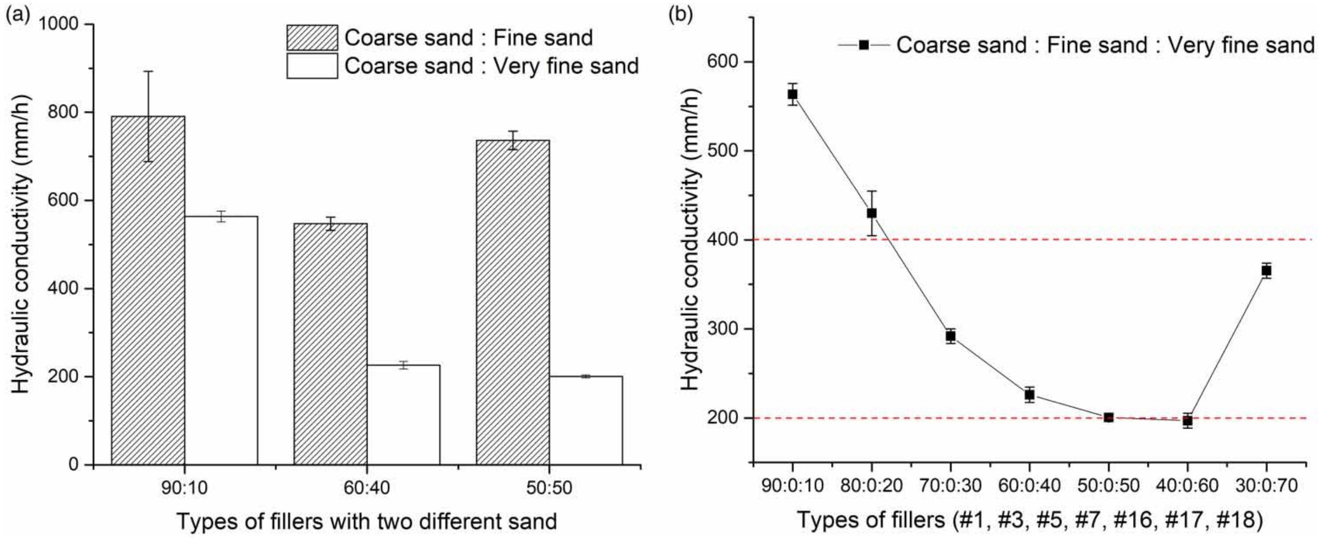

Figure 6 | Comparison of hydraulic conductivity of fillers.

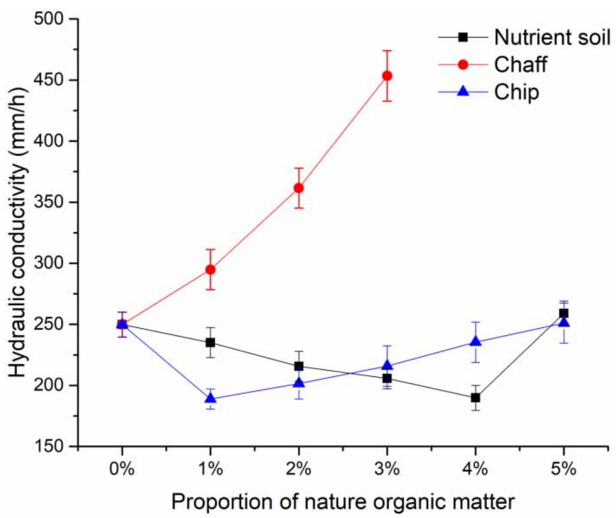

Figure 7 | Mean hydraulic conductivity of filler with the increase of natural organic matter.

188.8 mm/h, respectively. It showed a tendency towards rapid increase with the increase of chaff content. This was highly attributed to the nature of the organic matter added into the filler.

The nutritive soil used in the experiment was a fermentation product of animal excrement and litter compost, and its actual organic matter content was >85%. At the same mass ratio, the volume of the nutritive soil was low because of the grinding process before addition. Therefore, the nutritive soil continuously fills the pores of the original media at the beginning and the hydraulic conductivity declines. When the content of the additive exceeds 4%, the porosity of the nutritive soil itself begins to contribute to the porosity of the entire filler, resulting from its fleecy structure, which leads to the rise of the hydraulic conductivity of the fillers. Wood chips have small density, and their volume under the same mass percentage is much larger than that of nutrient soil. Therefore, when the content of wood chips was 1%, the hydraulic conductivity of the composition reaches its lowest point. The original, ending and lowest points of the mixing ratio are basically the same as that of the filler mixed with nutrient soil, except that the lowest point comes earlier. Different from nutrient soil and wood chips, chaff particles are larger and cannot fill the pores of the original filler. Therefore, the hydraulic conductivity increases at the beginning. In addition, due to the large size and low density of chaff particles, volume ratio of the filler was also increased, resulting in a sharp increase in the hydraulic conductivity.

In comparison to the filler mixed with nutrient soil, the actual organic matter content of wood chips and chaff varied from 70 to 80%. Hydraulic conductivity of filler mixed with chaff also exceeded the control range, because the chaff particle could not enter into the pores of coarse sand. Therefore, nutrient soil is more suitable as a natural organic matter added to the composition of the filter layer in bioretention. The hydraulic conductivity was lower than

200 mm/h when nutrient soil addition was 4%, and it does not meet the requirements. Therefore, the range of the nutrient soil content should be controlled within 0–3%. Results presented in Figure 7 revealed that when the addition ratio of nutrient soil exceeded 4%, the hydraulic conductivity started to increase, because the filler pores were filled up and new pores came into being. While this mixing ratio cannot meet the requirements (>3%) of FAWB (Hatt *et al.* 2009), considering that road runoff in China is rich in organic matter (Xu *et al.* 2016; Zhao *et al.* 2017) and the mean annual rainfall is high, the organic matter content of the filter layer would fulfil the requirements of plant growth in the respective periods.

After a prolonged operation, pollutants in runoff mainly maintained the plant growth and development. The moisture content of the nutrient soil in the experiment was around 43% without dry process. Average particle size distribution is presented in Table S4 (Supplementary material). According to FAWB (Hatt *et al.* 2009), the filter layer should contain some organic matter which has low nutrient content for increasing water holding capacity. Otherwise, leaching would occur if the nutrient contents (TN and PO_4^{3-}) were high, which would lead to deterioration of the water quality. In this study, organic matter content in the filter layer was <3%, and has a slight effect on effluent quality; de Macedo *et al.'s* (2019) research findings revealed that the soil organic matter did not affect contaminant concentrations, and also suggested that filter media with higher organic matter reduced the mass flux of contaminants more than that with lower organic matter.

Analysis of filter stability with long-term operation

The stability of the filter layer directly affects the service life of the bioretention system. In this experiment, the selected mixing ratio of coarse, fine and very fine sand was 50:20:30. Nutrient soil (2%, by mass) was chosen as natural organic matter. After mixing, it was loaded into a TST-70 analyser for continuous flooding test. Following that, the change in hydraulic conductivity was monitored and results are presented in Figure 8(a).

Results revealed that during the first 4 days, the hydraulic conductivity of the filler showed a sharp increase (Figure 8(a)). The possible reason could be that in the early stage, part of sand in the filler migrates with the flow, and in the process, the originally dense pores may have temporary capillary channels which can increase hydraulic conductivity. Later, it began to fall, by process of recomposing and stabilizing of some of the fillers. Under continuous flooding condition, it takes nearly one month for the filter layer to reach a stable structure. After one month, the hydraulic conductivity of the filler remained

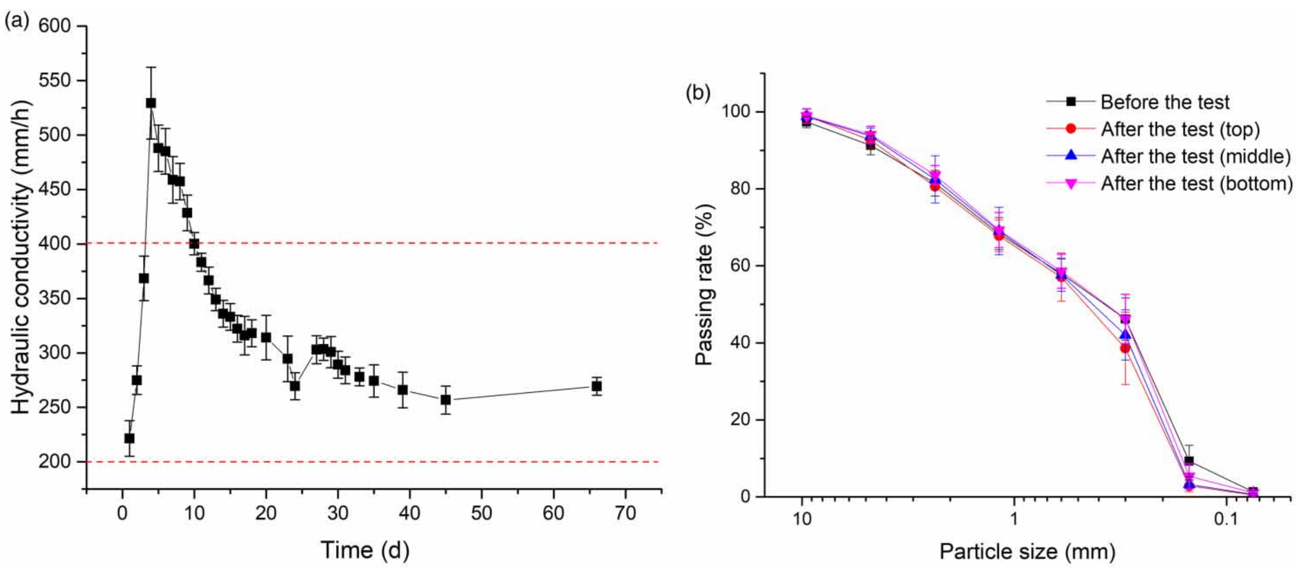

Figure 8 | (a) Hydraulic conductivity of the filter layer with time and (b) gradation curve before and after the experiment.

almost stable, slightly larger than the initial value, indicating that the initial hydraulic conductivity of the filter layer is an important factor. It can be concluded from the results that the stable hydraulic conductivity was close to the initial value.

At the final stage of the experiment, the sand column in the hydraulic conductivity tester was completely removed, and the original state was maintained. The top, middle and lower parts of the filler were taken for screening, and the grading curve before the test was compared, as shown in Figure 8(b). Results revealed that when the particle size was >0.6 mm, the four curves practically coincided, indicating that the sand in this particle size rarely moved with the flow. However, fillers with particle sizes <0.6 mm have different degrees of loss. The grading curve of the bottom filler was closest to the hydraulic conductivity of the initial one, followed by the middle and top filler. Also indicated was that the bottom filler controlled the hydraulic conductivity of the whole filter layer.

The excellent stability of this composition enables a longer service life, which also improves its economic efficiency. Compared with recent studies on filter layers in bioretention, this study provides an adaptable composition by using locally available materials in the Yangtze River Delta, which have suitable hydraulic conductivity, stable structure and a simple mass production process. Jiang *et al.* (2018a, 2018b) used four types of modifiers, which they mixed with traditional bioretention soil (65% sand +30% soil +5% sawdust, by mass), and ended up with a hydraulic conductivity of around 120–2,300 mm/h. However, that is too large a range and economically unviable. Liu & Fassman-Beck (2018) measured the saturated hydraulic conductivity of 14 engineered media with different compositions, mixed with fine pumice, coarse pumice, pumice sand, marine sand, compost, zeolite and topsoil. Their hydraulic conductivities varied between 468 and 9,612 mm/h, and although the mixing materials were simple, the hydraulic conductivity was too high to maintain plant growth and development. However, the effect of filter layer on plants was not investigated in this study. Tirpak *et al.* (2018) noted that, when bioretention was coupled with suspended pavement systems, which provide tree roots with an uncompact soil matrix that enhances root access to oxygen and water, the transpiration of plants was enhanced. This can lead to a better hydrological effect of the whole bioretention system. However, it is not clear whether plant transpiration has an effect on the hydraulic conductivity of the filter layer in a bioretention implemented in fields under long-term operation and thus needs further research.

PRACTICAL APPLICATIONS AND FUTURE RESEARCH PERSPECTIVES

The research results have been applied as a standard guideline in the construction of a sponge city in Kunshan, China. Current findings have also been used as reference by some other cities in China (Nanjing, Zhenjiang, etc.). Some bioretention units constructed in Kunshan city under the current project (bioretention units in Kunshan Lab, Xiaolin Road, Boshi Road and Fortune Plaza) are presented in Figure 9. The results of the current study are very significant and applicable to the Yangtze River Delta region and other regions with similar geophysical, climatic and soil conditions. The current study provides more accurate information on suitable particle size and hydraulic conductivity of filter media materials. It also helps to improve the construction quality to a certain extent and provides a basis for the detection unit. Finally, it contributes towards reduction of production difficulties and improving cost efficiency to make it economically viable, which is a key problem in the promotion of sponge city construction in China. Considering that the studied filler has not yet been used in a specific project in Kunshan for a long time, the actual service life needs to be further studied. In future research, the removal effect of pollutants will be taken into consideration to optimize the composition.

CONCLUSIONS

The performance of established filter materials in bioretention (used in developed countries) showed poor hydraulic performance in local conditions. Therefore, the current study aimed to find proper filter materials adapted to local climatic, environmental and soil conditions. Results revealed that optimal hydraulic conductivity ranged

Figure 9 | Bioretention implemented in Kunshan, China.

between 200 and 400 mm/h and had stable structure under continuous flooding when the mixing ratios of coarse, fine, very fine sand and nutrient soil were 40–70%, 0–40%, 10–60% and 0–3% (by mass), respectively. Easy access and simple production processes make these materials more economic and easier to promote their utilization in the construction of sponge cities in China.

ACKNOWLEDGEMENTS

This work was financially supported by the National Key Research & Development Program of China (Grant No. 2018YFC0809900).

SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at https://dx.doi.org/10.2166/aqua.2019.210.

REFERENCES

Ali, I., Al-Othman, Z. A. & Al-Warthan, A. 2015 Removal of secbumeton herbicide from water on composite nanoadsorbent. *Desalination and Water Treatment* **57** (22), 1–13.

Ali, I., Alothman, Z. & Al-Warthan, A. 2016 Sorption, kinetics and thermodynamics studies of atrazine herbicide removal from water using iron nano-composite material. *International Journal of Environmental Science & Technology* **13**, 733–742.

Archer, N. A. L., Quinton, J. N. & Hess, T. M. 2002 Below-ground relationships of soil texture, roots and hydraulic conductivity in two-phase mosaic vegetation in south-east Spain. *Journal of Arid Environments* **52** (4), 535–553.

Ariza, S. L. J., Martinez, J. A., Munoz, A. F. & Baron, J. P. Q. 2019 A multicriteria planning framework to locate and select Sustainable Urban Drainage Systems (SUDS) in consolidated urban areas. *Sustainability* **11** (8), 2312.

Basheer, A. A. 2017 Chemical chiral pollution: impact on the society and science and need of the regulations in the 21st century. *Chirality* **30**, 402–406.

Basheer, A. A. 2018 New generation nano-adsorbents for the removal of emerging contaminants in water. *Journal of Molecular Liquids* **261**, 583–593.

Bratieres, K., Fletcher, T. D., Deletic, A. & Zinger, Y. 2008 Nutrient and sediment removal by stormwater biofilters: a large-scale design optimization study. *Water Research* **42** (14), 3930–3940.

Burakova, E. A., Dyachkova, T. P., Rukhov, A. V., Tugolukov, E. N., Galunin, E. V., Tkachev, A. G., Basheer, A. A. & Ali, I. 2018 Novel and economic method of carbon nanotubes synthesis on a nickel magnesium oxide catalyst using microwave radiation. *Journal of Molecular Liquids* **253**, 340–346.

Charlesworth, S. M., Perales-Momparler, S., Lashford, C. & Warwick, F. 2013 The sustainable management of surface water at the building scale: preliminary results of case studies in the UK and Spain. *Journal of Water Supply Research and Technology-AQUA* **62** (8), 534–544.

Davis, A. P., Hunt, W. F., Traver, R. G. & Clar, M. 2009 Bioretention technology: overview of current practice and future needs. *Journal of Environmental Engineering* **135** (3), 109–117.

de Macedo, M. B., do Lago, C. A. F. & Mendiondo, E. M. 2019 Stormwater volume reduction and water quality improvement by bioretention: potentials and challenges for water security in a subtropical catchment. *Science of the Total Environment* **647**, 923–931.

Eckart, K., Mcphee, Z. & Bolisetti, T. 2017 Performance and implementation of low impact development – a review. *Science of the Total Environment* **607–608**, 413–432.

Gao, J., Pan, J., Hu, N. & Xie, C. 2018 Hydrologic performance of bioretention in an expressway service area. *Water Science and Technology* **77** (7), 1829–1837.

Haile, T. M., Hobiger, G., Kammerer, G., Allabashi, R., Schaerfinger, B. & Fuerhacker, M. 2016 Hydraulic performance and pollutant concentration profile in a stormwater runoff filtration systems. *Water Air and Soil Pollution* **227**, 34.

Hatt, B. E., Fletcher, T. D. & Deletic, A. 2009 Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale. *Journal of Hydrology* **365** (3–4), 310–321.

Hermawan, A. A., Talei, A., Leong, J. Y. C., Jayatharan, M., Goh, H. W. & Alaghmand, S. 2019 Performance assessment of a laboratory scale prototype biofiltration system in tropical region. *Sustainability* **11** (7), 1–16.

Hunt, W. F., Jarrett, A. R., Smith, J. T. & Sharkey, L. 2006 Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina. *Journal of Irrigation and Drainage Engineering* **132** (6), 600–608.

Jiang, C. B., Li, J. K., Zhang, B. H. & Li, H. E. 2018a Phosphorus removal of retrofit bioretention systems on urban surface runoff. *Desalination and Water Treatment* **126** (2), 39–47.

Jiang, C. B., Li, J. K., Zhang, B. H., Ruan, T. S., Li, H. E. & Dong, W. 2018b Design parameters and treatment efficiency of a retrofit bioretention system on runoff nitrogen removal. *Environmental Science and Pollution Research* **25** (33), 33298–33308.

Le Coustumer, S., Fletcher, T. D., Deletic, A., Barraud, S. & Poelsma, P. 2012 The influence of design parameters on clogging of stormwater biofilters: a large-scale column study. *Water Research* **46** (20), 6743–6752.

Li, M. H., Swapp, M., Kim, M. H., Chu, K. H. & Sung, C. Y. 2014 Comparing bioretention designs with and without an internal water storage layer for treating highway runoff. *Water Environment Research* **86** (5), 387–397.

Liu, R. F. & Fassman-Beck, E. 2018 Pore structure and unsaturated hydraulic conductivity of engineered media for living roofs and bioretention based on water retention data. *Journal of Hydrologic Engineering* **23** (3), 04017065.

Liu, Y., Engel, B. A., Flanagan, D. C., Gitau, M. W., McMillan, S. K. & Chaubey, I. 2017 A review on effectiveness of best management practices in improving hydrology and water quality: needs and opportunities. *Science of the Total Environment* **601–602**, 580–593.

Maryland Department of the Environment 2000 *Maryland Stormwater Design Manual*, Vols. I and II. Center for Watershed Protection and the Maryland Department of the Environment, Water Management Administration, Baltimore, MD, USA.

Payne, E. G., Pham, T., Cook, P. L., Fletcher, T. D., Hatt, B. E. & Deletic, A. 2014 Biofilter design for effective nitrogen removal from stormwater – influence of plant species, inflow hydrology and use of a saturated zone. *Water Science and Technology* **69** (6), 1312–1319.

Singh, R. P., Zhao, F., Ji, Q., Saravanan, J. & Fu, D. F. 2019 Design and performance characterization of roadside bioretention systems. *Sustainability* **11** (7), 2040.

Tahvonen, O. 2018 Adapting bioretention construction details to local practices in Finland. *Sustainability* **10** (2), 1–17.

Tirpak, R. A., Hathaway, J. M. & Franklin, J. A. 2018 Evaluating the influence of design strategies and meteorological factors on tree transpiration in bioretention suspended pavement practices. *Ecohydrology* **11** (8), 1–8.

Wang, L., Li, X. & Tian, H. 2011 Effect of fines content on permeability coefficient of sand and its correlation with state parameters. *Rock and Soil Mechanics* **32**, 21–26.

Water by Design 2014 *Bioretention Technical Design Guidelines (Version 1.1)*. Health Waterways Ltd, Brisbane, Australia.

Winston, R. J., Dorsey, J. D., Smolek, A. P. & Hunt, W. F. 2018 Hydrologic performance of four permeable pavement systems constructed over low-permeability soils in Northeast Ohio. *Journal of Hydrologic Engineering* **23** (4), 04018007.

Xu, P., He, J. C., Zhang, Y. J., Zhang, J. Q. & Sun, K. P. 2016 Runoff pollutant characteristics and first flush analysis in different urban functional areas: a case study in China. *Fresenius Environmental Bulletin* **25** (7), 2444–2453.

Yang, Y., Zeng, Z. T., Zeng, G. M., Huang, D., Xiao, R., Chen, Z., Zhou, C., Xiong, W., Wang, W., Cheng, M., Xue, W., Guo, H., Tang, X. & He, D. 2019 Ti_3C_2 Mxene/porous g-C_3N_4 interfacial Schottky junction for boosting spatial charge separation in photocatalytic H_2O_2 production. *Applied Catalysis B: Environmental* **258**, 117956.

Yi, H., Yan, M., Huang, D. L., Zeng, G., Lai, C., Li, M., Huo, X., Qin, L., Liu, S., Liu, X., Li, B., Wang, H., Shen, M., Fu, Y. & Guo, X. 2019 Synergistic effect of artificial enzyme and 2D nano-structured Bi_2WO_6 for eco-friendly and efficient biomimetic photocatalysis. *Applied Catalysis B: Environmental* **250**, 52–62.

Zhang, J., Wang, Y., Hu, Q. & He, R. 2016 Discussion and views on some issues of the sponge city construction in China. *Advances in Water Science* **27** (6), 793–799.

Zhao, F., Cao, M., Fan, K. E., Liu, Z., Feng, M. & Li, W. 2017 Analysis of pollution characteristics and first flush effect in rainfall runoff in separate storm sewer system in upstream of Tangxi River, Chaohu catchment. *Journal of Lake Sciences* **29** (2), 285–296.

Zhou, C. Y., Xu, P., Lai, C., Zhang, C., Zeng, G., Huang, D., Chen, M., Hu, L., Xiong, W., Wen, X., Qin, L., Yuan, J. & Wang, W. 2019 Rational design of graphic carbon nitride copolymers by molecular doping for visible-light-driven degradation of aqueous sulfamethazine and hydrogen evolution. *Chemical Engineering Journal* **359**, 186–196.

First received 27 July 2019; accepted in revised form 17 November 2019. Available online 2 December 2019