International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-9 Issue-4 November 2020

Design of Bio-retention Filter Basin for Conservation and Purification of Storm water runoff in Urban Areas

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Abstract*: *Urban areas are more susceptible to water logging and subsequent flood conditions because of reduced rate of infiltration arising from construction activities particularly during the monsoon season. However, if the storm water runoff is conserved and purified, it will be useful to cater to the needs of the huge population in urban areas during the periods of less rainfall or non-monsoon season. Bio-retention basins are best management practices that use a biogeochemical process within a vegetative eco-system to provide soil moisture retention and purification of storm water. While this structure has been implemented in many countries around the world, it is yet to be implemented in Indian cities with necessary modifications considering the topography, population pressure, hydrological characteristics of a basin, and the soil and water management practices. This project work is oriented to design a bio-retention filter basin in the parking lots or roadsides or streetscapes in Indian urban cities.

Keywords: Storm water runoff, Bioretention filter, Purification, Urban areas, Water conservation

I. INTRODUCTION

Economic development and rapid urbanization process leads to the expansion of urban landscape and also causes a series of problems, such as impervious land surface, low infiltration rates, water logging, sediment transport and deterioration of water quality. The suspended solids, organic matter, nitrogen, phosphorus, heavy metals, oils, and other pollutants directly enter to the rivers and lakes by storm water runoff which is predominant sources of water pollution [9], [16]. Many researchers have worked on GIS based models to estimate the sediment transport and other pollutants [1]. Bio-retention basin is a manmade landscaped depression that receives run-off from the nearby impervious regions, treats the storm water at the site and reduces the peak discharge. The rainfall and run-off Control in urban areas by using bio-retention system depends on the infiltration capacity, extension and detention depths of the bio-retention system, filter media, hydraulic conductivity of the soil used in the bio-retention system, storm event that occurs and filter surface area.

Revised Manuscript Received on November 20, 2020.

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The use of bio-retention system can ensure the reduction in rainfall run-off process, filtration of water thereby enhancing the pre-development hydrologic condition and quality of water of an area. These systems highly depend on the ecological functionalities of a terrestrial system including soil, plants and microbes to retain and treat storm water [20]. The most important feature of bio-retention basin is its ability to preserve the natural hydrologic conditions and to maintain the natural hydrologic cycle of a region. It can be readily implemented into green spaces, streetscapes, median strips and parking islands because of its flexible design layout. They provide storm water volume control. They utilize a native forest ecosystem structure and landscape processes to enhance storm water quality. They can also remove the sediments, heavy metals, and nutrients efficiently to enhance the water quality [17], [18], [19]. They are relatively low maintenance and cost effective, effective in removing urban pollutants, reduce volume and rate of runoff. A bio-retention system is effective in capturing and treating the “first flush” of storm water runoff from impervious surfaces that carries the highest amount of pollutants. Storm water pollutant control at their source leads to the reduction in hydraulic loading, increased ability to attenuate flows, and reduction of pollutant loads to downstream storage facilities, such as reservoirs and ponds. In particular, a storm water bio-retention system is an open, vegetated drainage system that aims to improve storm water quality by filtering water through biologically influenced media. Runoff from storm water is diverted from the kerb or pipe into the bio-retention basin and gets filtered through the vegetation and temporary ponding provided in the system. The filtered water then slowly infiltrate vertically downwards through the filter media.

II. BIO-RETENTION BASINS

Many studies have been carried out by researchers and scientists on the applications of bio-retention filters and its design aspects. Some of them are discussed in this section. Some studies [15] had focused on the provision of drainage systems and storm water management strategies in low income urban settlements. The authors had stated that although engineered infrastructure is a necessary component for drainage of urban runoff, non-structural approaches are also important as complementary measures to prevent and mitigate problems related to flooding, as well as those related to pollution and deterioration in environmental health conditions.

Bio-retention systems are promising storm water BMPs which have shown great potential for the reduction of influent storm water volumes and peak flow rates, as well as the retention of a large array of important storm water pollutants [4], [7] , [10]. A number of studies have identified processes that significantly influence phosphorus removal in bio-retention systems but the lack of understanding of the overall phosphorus cycle in bio-retention systems and the relative importance of different bio-retention processes remains to be addressed.

Many researchers had focused on the efficiency of different filter media in pollutant removal process in a bioretention basin. Limestone sand showed significantly higher removal efficiencies, especially for the removal of heavy metals [5]. In this study, the hydraulic head in the gutter and the orifice flow rates were monitored throughout the experiment to maintain consistency, and the feed tank was refilled during experimental runs to sustain the desired injection rate and total volume, which were 150 mL/min and ~10 gallons, respectively. Rain gauges were installed at outlet of the columns to monitor the effluent volume and flow rate. The objective of this study was to compare the removal efficiency of four different media by conducting column experiments using synthetic storm water. Of the four tested media, sand performed better in removal of phosphorus while Bio Filter seems to perform better in removal of nitrogen, High phosphorus content of Bio filter lead to leaching of phosphorus. Additionally, phosphorus and nitrate removal require sufficient contact time and saturation, thus small infiltration rate was essential for effective treatment. Therefore, the media with high hydraulic conductivity showed poor treatment performance, especially in nitrate removal. Bio-retention is one of the most recognized LID practices for mitigating the hydrologic impacts of urbanization development and improving water quality in urban areas [12], [13], [14]. Extensive research work has been conducted on bio-retention to understand its function, improve its performance, and lengthen and predict its lifecycle. The physical and biological processes that occur within bio-retention mimic ecological processes similar to those that occur in nature. Bio-retention systems can control the runoff by increasing the infiltration of water into the ground. The design area of the bio-retention system should be compared with urban areas in order to get more benefits and to enhance the performance of this system, good plants should be selected that can perform better. Sometimes, due to clogging problems at the filter media of the bio-retention system, it does not perform well. In bio-retention, filter media and soil media have great influence on the water quality. Sometimes, the nutrient removal efficiency of the bio-retention system is decreased after a period of time. It was found in some studies that Bio-retention system enables the mitigation of the hydrologic impacts of urbanization development and improves water quality in urban areas. The storm water detention facilities are often used in modern drainage systems for the reduction of the hydraulic load on existing sewers, due to increase of impermeable surfaces and more frequent extreme rainfalls as a consequence of climate changes [2] and [3]. Some studies were focused on the probability analysis of retention times to provide guidance to engineers for the design of storm water detention facilities[2]. The influence on retention time of the possibility of water mixing from consecutive rainfall events, due to the pre-filling of the storage capacity from previous runoffs events has been investigated specifically in this study. The probabilistic methods enable estimation of the probability distribution function of average retention times in a storm water detention facility. The resulting formulae mentioned in the above study can also be used to design a storm water detention facility for estimation of the storage capacity with a guaranteed sufficient average retention time for removal of pollutants and also to understand the effect of storage volume on retention times. A storm water detention tank should be designed effectively to ensure a sufficient retention time for the sedimentation of suspended solids, uptake of nutrients and the die-off of bacteria carried in rainwater. In this paper, an analytical probabilistic approach, has been proposed to estimate the probability distribution function of the average retention time and the also to calculate efficiency in pollutant removal of storm water tanks [3]. In this study, the possibility of storm water mixing from successive runoff events and existing storage facilities due to successive rainfall events has also been considered. Proposed approach relates the efficiency of a storm water detention tanks in pollutant removal with the retention time. Moreover, they can be used to size storm water detention tanks to analyze the influence of outflow rates and storage volumes on the probability distribution of the average retention time that is on probability distribution of the efficiency of the storage in pollutant removal. Storm water runoff from industrial sites is often subject to a higher level of treatment than municipal “non-point” source runoff due to its unusually high concentrations of pollutants [11]. Typically, samples from these sites must be taken quarterly and analyzed for pollutants such as zinc, copper and total suspended solids (TSS). Selecting a treatment option for these industrial sites can be complicated by several environmental factors related to runoff chemistry as well as physical makeup. The research work presents a program of bench-scale and full-scale tests that are used to generalize a model of system performance. Using multivariable regression analysis, a predictive model is identified that can be used to screen applications for appropriate media selection. The results indicate that rule-of-thumb performance predictions such as “percent removal” are likely not accurate enough to be used to confidently select a media. Regression models built from multiple input variables produce a closer correlation and indicate a better predictive model. Due to high runoff volumes and peak flows, and significant contamination with (inter alia) sediment, metals, nutrients, polycyclic aromatic hydrocarbons and salt, urban storm water is a major cause of degradation of urban water ways. [6], [8]. The effects of various ambient factors, storm water characteristics and modifications of filter design on the removal of metals, nutrients and total suspended solids (TSS) in bio filters, and pollutant pathways through them, have been investigated in the above research work. The authors had stated that prolonged drying especially impaired their removal efficiency, but variations in temperature and filter media variations had little effect on metal removal rates. However, in initial stages phosphorus was washed out from the filter media, indicating that filter media that do not have high levels of labile phosphorus should be used to avoid high effluent concentrations.

The study indicated that ability of the bio-retention boxes to treat snowmelt from roadside snow was good overall with respect to achieving suitable concentration outflow levels and reducing mass loads.

III. DESIGN CONSIDERATIONS OF BIO-RETENTION BASIN

Two main considerations are adopted in design of bio-retention filter; firstly landscape design and secondly, hydraulic design.

A. Landscape Design

Bio-retention basins are predominantly located within public areas, such as open space or within streets, which provide a primary setting for people to experience their local community and environment. It is therefore necessary for bio-retention basins to be given an appropriate level of landscape design consideration to compliment the surrounding landscape character and to adequately address potential aesthetics issues such as weeds and sustaining perennial plants during the dry season. The landscape design of bio retention basins must address storm water quality objectives whilst also being sensitive to other important landscape objectives such as road visibility, public safety, community character and habitat.

B.Hydraulic Design

The correct hydraulic design of bio-retention basins is essential to ensure effective storm water treatment performance, minimize damage by storm flows, and to protect the hydraulic integrity and function of associated minor and major drainage systems. Usually three design flows are required for bio-retention basins i.e minor flood rates (2-10 years ARI) to size the overflow to avoid flood, major flood rate (50-100 year ARI) to ensure that the flow velocities should not exceed the rated velocity and the maximum infiltration rate through the filter media to allow for the under drainage system to freely drain. The finished surface of the bio retention filter media must be horizontal (i.e. flat) to ensure even flow dispersion across the filter media surface (i.e. full engagement of the filter media by storm water flows) and to prevent concentration of storm water flows within depressions and ruts resulting in potential scour and damage to the filter media as shown in figure 1. Temporary ponding (i.e. extended detention) of up to 0.3 m depth over the surface of the bio-retention filter media created through the use of raised field inlet pits (overflow pits) can assist in managing flow velocities over the surface of the filter media as well as increase the overall volume of storm-water runoff that can be treated by the bio-retention filter media.

C. Bio-retention Filter Media

Selection of an appropriate bio retention filter media is a key design step that involves consideration of the following four inter-related factors:

- Saturated hydraulic conductivity required to optimise the treatment performance of the bio-retention basin given site constraints and available filter media area.
- Depth of extended detention provided above the filter media.
- Surface area of the filter media
- Suitability as a growing media to support vegetation (i.e. retains sufficient soil moisture and organic content).

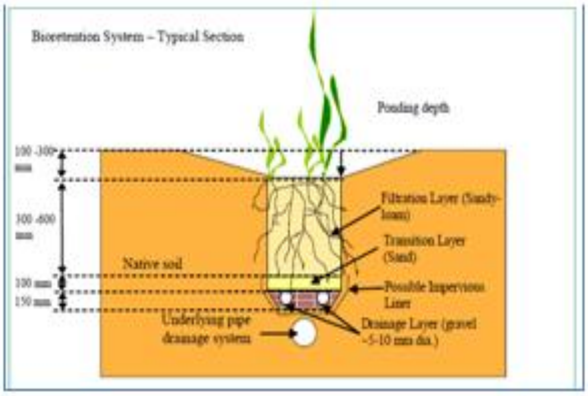

Figure 1 Typical cross-section of bio-retention filter (Source: Water sensitive urban design guidelines bio-retention basins)

Bio-retention media can consist of three or four layers. In addition to the filter media required for storm water treatment, a saturated zone can also be added to enhance nitrogen removal and to provide a source of water for vegetation over the dry season. A drainage layer is also essential to move the treated water from the base of the filter media or saturated zone into the perforated under-drains. The drainage layer surrounds the perforated under-drains and can be either coarse sand (1 mm) or fine gravel (2- 5 mm). If fine gravel is used, a transition layer of sand must also be installed to prevent migration of the filter or saturated zone media into the drainage layer and subsequently into the perforated under-drains.

IV. DESIGN PROCESS

The design process for the bio-retention basin is mentioned in the methodology flowchart below (figure 2). The detailed design procedure is mentioned in this section.

A. Estimation of Design flows

With a small catchment area, the rational formula of flood flow estimation is appropriate but for large catchment areas a detailed flow analysis should be done. Initially the time of concentration is calculated using any standard empirical formula and then the rainfall intensity can be computed based on the time of concentration or from the IDF curves of a particular region. A suitable runoff coefficient must be chosen based on the material of the drainage area. The design flow can be estimated using the formula

$$\mathbf{Q = CIA/360} \qquad (1)$$

Where Q = Design flow (m^3/s)
C = Runoff coefficient
I = Rainfall intensity in mm/hr.
A = Catchment area in ha.

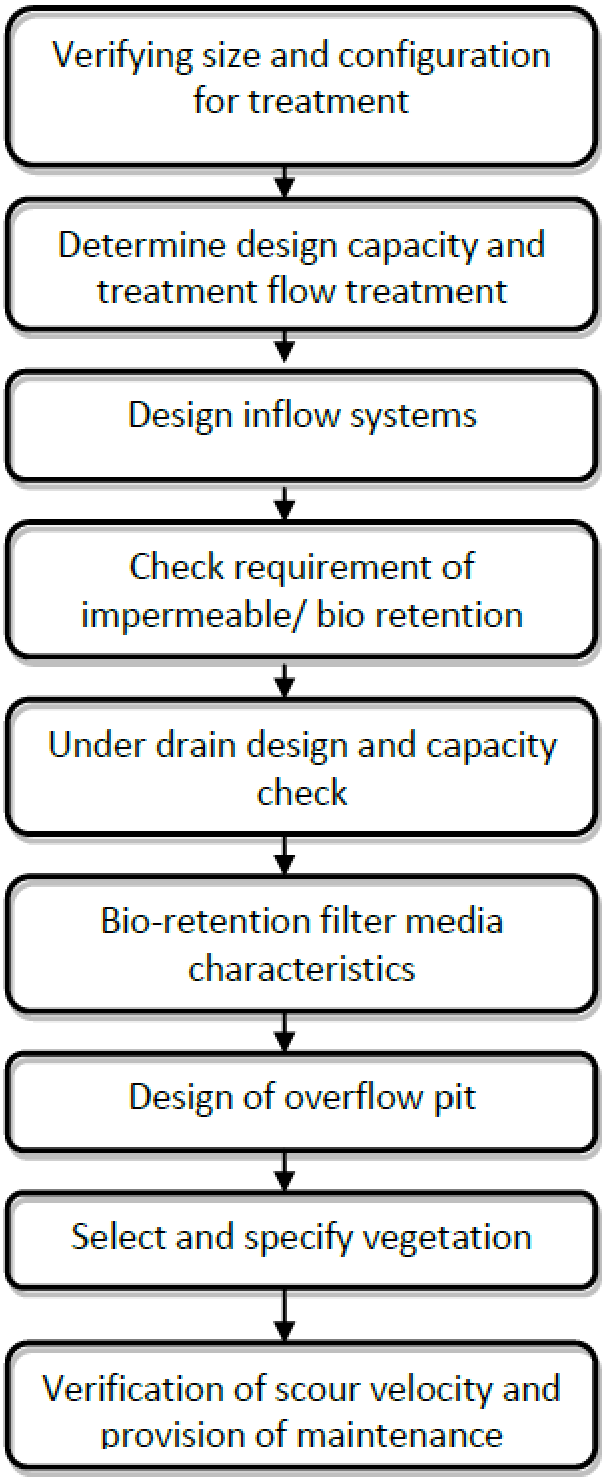

Figure 2 Methodology flow chart for design of bio-retention filter

4.2 Estimation of Maximum Infiltration rate

The maximum infiltration rate can be estimated using the following formula

$$Q_{\max} = k \cdot A \cdot \frac{h_{\max} + d}{d} \qquad (2)$$

Where, k = Hydraulic conductivity of sand, m/s
A = Surface area of sand filter, m^2
h_{max} = depth of pondage above sand filter, m
d = depth of the sand filter, m

B. Flow width at entry

A check of the flow capacity of the system and the width of the flow across the road needs to be performed to ensure the road is protected for a minor (5 year ARI) flood. In this case there is a criterion of having less than 2 metre wide flow in the gutter, which facilitates one trafficable lane during a minor flood. A longitudinal gradient of 1% along the gutter can be assumed and the flow and depth estimates can be made using the Manning‘s equation. The flow depth in the gutter estimated is used to determine the required width of opening in the kerb to allow for flows to freely flow into the bio-retention system. For this, we can assume a broad crested weir condition through the slot using the following equation.

$$\mathbf{Q = BCLH^{3/2}} \qquad (3)$$

Where Q = Flow, m^3/s
C= 1.7
H = Flow depth, m

C. Vegetation scour velocity check

The scouring of the vegetation should be checked to ensure that the velocities are below 0.5m/s during Q5 and 1.0 m/s for Q100.

D. Size of perforated collection pipes

The inlet capacity of sub-surface drainage system (perforated pipe) should be estimated to ensure there is no choke in the system. It is assumed that 50% of the holes are blocked. A standard perforated pipe may be selected that is widely available. To estimate the flow rate an orifice equation is applied using the following parameters:

Head = 0.85 m [0.6 m (filter depth) + 0.2 m (max. pond level) + 0.05 (half of pipe diameter)] (4)

Discharge capacity of each slot can be calculated using the orifice flow equation

$$Q_{perforation} = C \cdot A_{perforation}\sqrt{2gh} \qquad (5)$$

Where, h is the head above the slotted pipe, m
C is the orifice coefficient = 0.6
A blockage factor 0.5 may be assumed

The Colebrook-White equation is applied to estimate the flow rate in the perforated pipe. A slope of 0.5% is usually assumed and commonly a100 mm perforated pipe may be used. Should the capacity not be sufficient, either a second pipe could be used or a steeper slope. The capacity of this pipe needs to exceed the maximum infiltration rate.

Estimate applying the Colebrook-White Equation

$$\mathbf{Q = -2(2gDSf)\ 0.5 \times \log[(k/3.7D) + (2.51v/D(2gDSf)0.5)] \times A} \qquad (6)$$

Where D = pipe diameter ,m
A = area of the pipe,m^2
S_f = pipe slope
k = wall roughness
v = viscosity
g = gravity constant

Typically flexible perforated pipes are usually installed using fine gravel media to surround them. In order to reduce the risk of washing the filtration later into the perforated pipe, a transition layer is to be used. This may be of 100 mm of coarse sand.

E. Impervious liner requirement

If the conductivity of the filter media is > 10times the conductivity of the surrounding soils, then impervious liner is not considered to be required. In some cases, a bentonite liner or clay may be used as liner.

F. High flow route and by-pass design

The overflow pit is required to convey 5 year ARI flows safely from above the bioretention system into an underground pipe network. Grated pits are to be used at the upstream end of the bioretention system. The size of the pits are calculated using a broad crested weir equation with the height above the maximum ponding depth and below the road surface, (i.e. 100mm). It is first checked using a broad crested weir equation and then for drowned conditions

$$P = \frac{Q_{des}}{B \cdot C_w \cdot H^{1.5}} \qquad (7)$$

P = Perimeter of the outlet pit
B = Blockage factor (0.5)
H = 0.1m Depth of water above the crest of the outlet pit
Q_{des} = Design discharge (m3/s)
C_w = weir coefficient (1.7)

$$A_o = \frac{Q_{des}}{B \cdot C_d \sqrt{2gH}} \qquad (8)$$

Cd = Orifice Discharge Coefficient (0.6)
B = Blockage factor (0.5)
H = Depth of water above the centroid of the orifice (0.1m)
Ao = Orifice area (m^2)
Qdes = Design discharge (m^3/s)

G. Soil media specification

Three layer of soil media are to be used. A sandy loam filtration media (600mm) to support the vegetation, a coarse transition layer (100mm) and a fine gravel drainage layer (200mm).

H. Filter media specifications

The filter media is usually a sandy loam with the following criteria:

- hydraulic conductivity between 50-200 mm/hr
- Particle sizes of between: clay 5 – 15 %, silt <30 %, sand 50 – 70 %
- Organic content between 5% and 10%
- pH value can vary between 6-7.5, but preferably it should be neutral.

I. Transition layer specifications

Transition layer material shall be coarse sand material such as Unimin 16/30 FG sand grading or equivalent. A typical particle size distribution is provided below:
% passing 1.4 mm 100 %
1.0 mm 80 %
0.7 mm 44 %
0.5 mm 8.4 %

J. Drainage layer specifications

The drainage layer specification can be either coarse sand (similar to the transition layer) or fine gravel having 2mm or 5 mm screenings. This layer should be a minimum of 150 mm and preferably 200mm thick.

K. Vegetation specifications

While selecting the vegetation for the bioretention filter basin, consultation with landscape architects is recommended to ensure the treatment system compliments the landscape of the area.

V. CONCLUSION

This research work is aimed at finding a solution for the conservation and purification of storm water runoff in urban areas during monsoon season so that it may be reused during water scarcity condition in summer or non-monsoon season. Bio-retention filter basin effectively purifies the impurities present in the storm water making it safe for future use in a cost effective way. The flexibility of its design layout allows it to be readily implemented into green spaces, streetscapes, median strips and parking islands.

REFERENCES

1. A. Eljamassi , ,"GIS-Based Model for the Coupled Process of Storm water Flow and Generation of Sediment" ,*Urban Ecosystem,* vol.15,2019,pp.409–435.
2. A. Raimondi and G. Becciu , " Probabilistic Analysis of the Retention Time in Stormwater Detention Facilities", *Procedia Engineering*, vol 119, 2015, pp. 1299-1307.
3. A. Raimondi and G. Becciu , "On the efficiency of storm water detention tanks in pollutant removal". *International Journal of Sustainable Development and Planning,* vol. 12 ,January 2017 , pp.144-154.
4. A.R. Poirier, P. Champagne and Y. Filion"Review of Bioretention System Research and Design: Past, Present, and Future", *Journal of Environmental Engineering,* vol. 136 (9), September 2010. DOI: 10.1061/(ASCE)EE.1943-7870.0000227.
5. A. S. Hamedani, A. Bazilio, C. Cerda, A. Manjarres and A. Hall , "Assessing the Performance of Bioretention and Sand Filter Media Using Columns and Synthetic Storm water", *Environmental Monitoring and Assessment* ,vol.190 (12),2019, pp. 1–15.
6. B. Gianfranco ,P. Alessandro ,A. Raimondi and S. Umberto , "Effects of management rules on pre-filling of storm water detention facilities", January 2011.
7. B. Sharmina , M.G. Rasul and R. Brown ,"Storm water treatment and reuse techniques: A review", *Transactions on Environment and Development,* vol. 4 , 2008.
8. G. Becciu and A. Raimondi ,"Probabilistic modeling of the efficiency of a storm water detention facility**",***International Journal of Sustainable Development and Planning*, vol. 10 , Issue 6, 2015,pp.795 - 805
9. G. Becciua, A. Raimondia , "Probabilistic analysis of the retention time in storm water detention facilities". *Procedia Engineering,* vol. 119, 2015, pp. 1299-1307
10. G. Williams , C. Murray , D.W. Zhang , "Storm water Filter Testing Procedure" *Wastewater Engineering: Collection, Treatment, Disposal, 2016.*
11. G.T. Blecken,"Biofiltration Technologies for Storm water Quality Treatment" , *Sci. Technol,* vol. 25 (2), 2010, pp. 93–139, ISSN: 1402-1544
12. H. Belinda & T. Fletcher and A. Deletic ,"Treatment performance of gravel filter media: Implications for design and application of storm water infiltration systems" , *Water research,* vol. 41, July 2007, pp. 2513-24.
13. J. Christopher, D. Booth, B. Matthew, T. Fletcher ,H. Rebecca, L. Livingston , R. Grant ,M. Roy , A. Scoggins and M. Wallace , "Principles for urban storm water management to protect stream ecosystems", *Freshwater Science,* vol. 35, March 2016 .
14. J. Liu, D. J. Sample, C. Bell and Y. Guan, "Review and Research Needs of Bioretention Used for the Treatment of Urban Stormwater", *Water,* vol. 6, pp. 1069-1099, April 2014.

15. J. Parkinson ,"Drainage and storm water management strategies for low-income urban communities*". Environment and Urbanization,* vol 15, Issue 2,2011, pp.115–126..
16. J. Wu and J. Zhang , "Development Trend and Frontier of Storm water Management", *A Bibliometric Overview Based on CiteSpace. Water , 2019.*
17. M. Julita and R. Pasela ,"Analysis of concentration trends and origins of heavy metal loads in storm water runoff in selected cities: A review," *E3S Web of Conferences,* vol. 44, January 2018 ,pp. 111-151.
18. M. Sidek , A. Ainan , N. Zakaria, A.B Ghani, A. Aminuddin and K. Ayub (2004), "Storm water Purification Capability Of Bioecods", *Advances in hydro-science and –engineering,* vol. 6, 2004, pp. 1-9.
19. M. Toor, L. Gurpal and P. Inglett, "Organic nitrogen in residential storm water runoff: Implications for storm water management in urban watersheds",*Science of The Total Environment,* vol.7, 2019.
20. N. Abdel and H. Kamel, "Purification of Storm water Using Sand Filter" , *Journal of Water Resource and Protection,* vol. 5 , January 2013, pp.1–15.
21. Water sensitive urban designguidelines-05-chapter-5-bio-retention basins, pp. 5-35., https://www.derwentestuary.org.au/assets/Water_Sensitive_Urban_Design_Guidelines_05_Chapter_5_Bioretention_Basins.pdf, accessed on 10.10.2020.

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