

EVALUATION OF THE LONG-TERM POLLUTION REMOVAL PERFORMANCE OF ESTABLISHED BIORETENTION CELLS

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ABSTRACT: Over the last two decades bioretention (biofiltration) systems have been commonly constructed in urban areas to manage stormwater runoff by moderating peak flows and reducing downstream pollution loads. Bioretention systems are generally soil-plant based systems which typically include a filter medium above a drainage layer. They are often either lined with a geofabric to support infiltration, or with an impermeable membrane to prevent infiltration and/or to allow stormwater harvesting and reuse. Bioretention systems are known to treat a range of stormwater pollutants through physical, chemical and biological processes such as mechanical filtering, sedimentation, adsorption, and plant and microbial uptake. However, the long-term pollution removal performance, particularly of heavy metals, remains largely unknown. It is generally accepted that the filter media used in bioretention systems has a finite life span, after which time it should be replaced. However, there is only very limited information available on when this should occur, or how to assess this. It is also recognised that contaminated filter media may require regulated disposal. This study presents results from a series of controlled field experiments conducted over two years which evaluated the pollution removal performance of a series of 10 year old bioretention systems located in an industrial estate in Australia.

Keywords: Stormwater Pollution, Bioretention Systems, Heavy Metals, Filter Media

1. INTRODUCTION

The increase of impervious surfaces that comes with urban development has caused both the volume of stormwater runoff, and the amount of pollution flowing downstream to rise, often causing environmental harm [1], [2]. Consequently, stormwater management in urban areas has become a priority for those responsible for planning and construction of new developments, and maintenance of existing stormwater infrastructure [3].

Bioretention (biofiltration) systems have been used widely over the past 20 years to manage stormwater in urban areas, they reducing peak flows and downstream pollution loads [4] – [6]. The flexibility in their design helps with easy retrofitting into existing urban areas [7] raising their popularity. They also contribute to a range of other benefits beyond stormwater quality and quality functions, including aesthetic and social benefits [8], [9]. Small bioretention systems are often incorporated into existing roadways in place of a traditional grass street verge [3].

Bioretention systems are generally soil-plant based systems that typically consist of a filter medium (usually sandy), underlain by a gravel drainage layer [1], [8]. Bioretention systems may be lined with geofabric to allow infiltration, or include an impermeable liner to assist in stormwater capture and reuse [10]. Bioretention systems treat stormwater via a range of chemical, physical, and biological processes. These include

sedimentation, filtration, adsorption, and plant and microbial uptake [8]. Despite a number of previous studies on the performance of bioretention systems, the mechanisms through which pollutants are removed or treated are yet to be fully understood [8]. There have also been few studies on the long-term performance of bioretention systems regarding heavy metals [11].

Clogging of bioretention systems over time and depth and sizing of the filter media [11] have been seen as the cause of heavy metal accumulation or breakthrough [6], [12]. Heavy metal breakthrough may occur even faster in sub-tropical locations (such as Brisbane) that experience higher rainfall intensities. It has also been suggested that if the filter media needs replacement during regular maintenance of these systems, it may need to be classified as contaminated waste due to the build-up of pollutants over time and necessitating special disposal procedures [11].

Laboratory scale studies have been the predominant form of analysis of many previous studies investigating the performance of bioretention systems [6]-[8], [11], [12]. Field-based studies have reported varied results, particularly regarding soluble forms of nitrogen and phosphorous, and areas subject to high contaminant loading such as fuel stations or waste recycling sites [1].

This paper presents the pollution removal performance results of a series of field-based experiments undertaken on five, 10-year old street-side bioretention systems. The bioretention basins,

located on the Sunshine Coast in Australia, were subjected to a series of simulated rainfall events using synthetic stormwater. Four different synthetic stormwater pollutant concentrations were used in the study. Tests were undertaken to determine the levels of contaminant and heavy metals build-up that occurred in the filter media over the 10 year operational life of the bioretention systems.

2. METHODOLOGY

2.1 Site Description

The bioretention systems evaluated in this study were installed in 2005 to treat stormwater road runoff from a mixed commercial and industrial catchment of approximately 0.6 ha in area. There are five individual bioretention basins located directly adjacent to the roadway, which runs centrally through the catchment (Figure 1). The bioretention basins were designed to have an operational hydraulic conductivity of 180 mm/h and achieve the recommended regulatory pollution reduction objectives of 80% of Total Suspended Solids (TSS), 60% of Total Phosphorous (TP), and 45% of Total Nitrogen (TN) [13] (ANZECC, 2000).



Fig.1 One of the bioretention basins evaluated in the study.

Figures 2 and 3 show the design and construction plans of the bioretention basins. The design comprised an impermeable plastic liner, a 200 mm gravel drainage layer base surrounding a 100 mm diameter, perforated drainage pipe. A 100 mm thick sand transition layer was laid above the gravel base and a 900 mm sandy-loam filter media was included above the sand (Figure 3). An indigenous plant species *Lomandra longifolia* (Matt Rush) was planted into the filter media at a typical spacing of one plant per square metre. Outflow pipes from the bioretention systems were diverted through the nearest downstream drainage gully within the standard underground stormwater

drainage system.

A purpose built metal spout was attached to the wall of the pit to collect outflows and direct them through the measurement equipment installed in the pits.

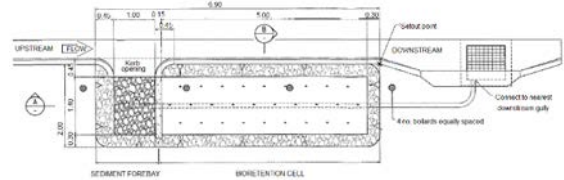


Fig.1 Plans of the bioretention basins evaluated in the study.

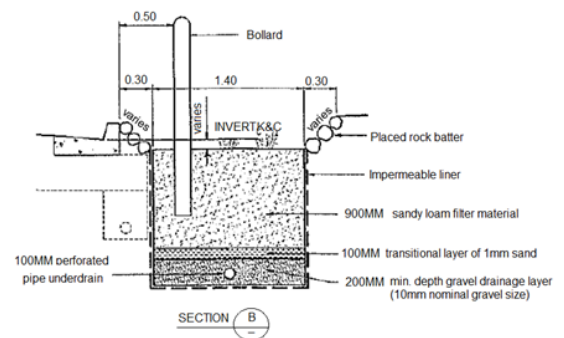


Fig.2 One of the bioretention basins evaluated in the study.

2.2 Sampling Equipment and Testing

2.2.1 Water quality sampling

Owing to the different existing pit locations, it was only possible to effectively evaluate three of the five bioretention basins. The three identically-sized basins were fitted with flow monitoring and water sampling equipment including 50 mm diameter flow meters (Octave Ultrasonic Water Meter DN50) to measure flowrates. An ISCO GLS auto-sampler was used to collect outflow samples in each pit. Sampling equipment also included a Datataker (DT80) datalogger, battery pack and battery charger.

In order to reduce the potential variability and difficulty in monitoring pollution removal performance during natural rainfall events, simulated rainfall runoff techniques were used in this study. Using a purpose-built stormwater simulation test rig (Figure 4), each bioretention basin was subjected to the equivalent runoff inflow rate that would be generated from a 54.8 m² roadway catchment emanating from a 30 minute duration, two year average recurrence interval (ARI) rainfall intensity event (Figure 5) at the test location based on procedures outlined in Australian Rainfall and Runoff [14]. Two 1,000 litre tanks with adjustable outlet control were used to simulate the inflow volumes (total inflow

volume = 2,000 L). In order to replicate typical stormwater pollution loads found in urban runoff, the synthetic stormwater was dosed with contaminants using a similar methodology to that used by [15] and [16].



Fig.4 Stormwater supply rig used to simulate test inflow rates used in the study.

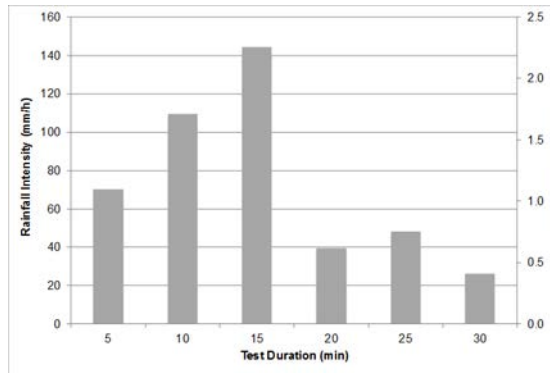


Fig.5 Rainfall intensities and equivalent test inflow rates used in the study to simulate the roadway runoff volumes from a two year, 30 minute storm event.

Four different pollution concentrations were tested on each of the three bioretention basins (Table 1). The four concentrations tested were: A) no pollution; B) typical Australian urban pollutant loads (TSS 150 mg/L; N 2.6 mg/L, and; P 0.35 mg/L) [17] - [19]; C) double the typical pollution loads, and; D) five times the typical pollution loads. The higher pollution loads were included to help identify any trends that may otherwise be difficult to measure. Silica sediment (Sibelco 60G, Table 2), phosphorus (KH₂PO₄) and nitrogen (KNO₃) was added to 2,000L of municipal water to produce the simulated pollutant concentrations [20], [21].

Table 1 Pollution concentrations used in study (A - Nil pollution; B - typical Australian pollutant loads; C - 2 X typical loads; D - 5 X typical loads).

Test	TSS	TP	TN	Stormwater
A	0	0	0	2000L
B	300g	8.79g	14.44g	2000L
C	600g	17.58g	28.88g	2000L
D	1500g	43.95g	72.2g	2000L

Note: Synthetic additives include: TSS- 60G Silica; TP- KH₂PO₄; TN- KNO₃.

Table 2 Particle size distribution (PSD) of Sibelco 60G synthetic sediment used during testing

Particle size (µm)	% finer
<250	99
<150	94.1
<106	86.2
<75	65
<45	60
<20	33.7
<10	19.1
<2	5.9
<1	5.1

2.2.2 Soil Testing

The study site land use was classified as commercial/industrial, and subject to high traffic volumes over the last decade. It was therefore anticipated that the bioretention filter media would contain significant heavy metal and hydrocarbon pollution loads. In order to evaluate the pollution build-up in the filter media, soil core samples of 500 mm depth were taken at three different locations in all five bioretention basins (Figure 6). Each of the core samples was separated into three distinctive sub-sample depths (0 - 50 mm, 50 - 100 mm and 100 - 500 mm) and these were sent to a soil testing laboratory for pollutant analysis. The sub-samples were analysed to determine their concentration levels across the entire range of measurable heavy metal and hydrocarbon pollutants.



Fig.6 Soil core sampling

Sub-sample pollutant concentrations were compared with health investigation levels (HIL) for soil contaminants contained within the Australian Government regulation National Environment Protection Measure [22]. Levels specified under Recreational Land Classification (C) were applicable as the basins were located on public open space as defined by this legislation, and exceedances have been noted.

Sample collection and testing was undertaken in accordance with test methods specified in Standard Methods for the Examination of water and Wastewater (APHA, 2005) [23]. Sample collection, storage and transport complied with AS/NZS 5667.1:1998 [24]. Heavy metals and hydrocarbons were extracted using standards methods (Table 3). The results presented in this study focused on the four main heavy metals recognised as being particularly harmful to aquatic ecosystems, namely: chromium (Cr), lead (Pb), copper (Cu), and zinc (Zn) [25].

Table 3 Test descriptions and methods used during laboratory analysis of soil

Test	Method
Total Recoverable Hydrocarbons (1999 NEPM Fractions)	TRH C6-C36 - LTM-ORG-2010
Total Recoverable Hydrocarbons - 2013 NEPM Fractions	TRH C6-C40 - LTM-ORG-2010
BTEX (Benzene, Toluene, and Xylenes)	TRH C6-C40 - LTM-ORG-2010
Polycyclic Aromatic Hydrocarbons	USEPA 8270 PAH
Metals	USEPA 6010/6020 Heavy Metals & USEPA 7470/71 Mercury
Percentage Moisture	LTM-GEN-7080 Moisture

2.2.3 Data analysis

Concentration Reduction Efficiency (CRE) was calculated for each simulated event as the percentage reduction in concentration with respect to inflow concentration for each pollutant (TSS, TN, and TP). Average CRE was calculated as shown in Eq. (1) below. Total pollutant loads and Event Mean Concentrations (EMCs) were determined for each test flow event, and efficiency ratios (ER) calculated using Eq. (2).

$$\text{Avg. CRE} = \frac{\sum \left[\frac{(EMC_{\text{inf low}} - EMC_{\text{outflow}})}{EMC_{\text{inf low}}} \right]}{\text{number of events}} \quad (1)$$

$$\text{ER} = \frac{EMC_{\text{inf low}} - EMC_{\text{outflow}}}{EMC_{\text{inf low}}} \quad (2)$$

3. RESULTS

3.1 Nutrient Pollution Removal Performance

Pollution removal performance as measured by event mean concentrations (EMC) for the three regulated pollutants varied significantly between inflow and outflow for TSS ($p < 0.03^*$) and TP ($p < 0.01^*$) but not for TN ($p < 0.18$) across pollution dosage concentration treatments (Table 4).

Table 4 Student t-test results of bioretention basin nutrient pollution removal performance across basins

Pollution concentration dose	TSS (p)	TN (p)	TP (p)
Nil	<0.05*	<0.11	0.43
Single	<0.72	<0.75	<0.17
Double	<0.03*	<0.73	<0.001*
X 5	<0.001*	<0.01*	<0.05*

Note: * significant

Bioretention basin pollution removal results for Tests A-C were highly variable (Figure 7). Tests D, with five times the standard pollution concentrations, were the only tests that demonstrated significant pollution reduction performance by the bioretention basins for all three pollutants (Figure 7). During test A (Nil concentrations) results showed that the basins exported both TSS and TN, while TP was found to show a modest pollution removal performance (26.8%). This was not anticipated and may have been due to possible equipment contamination from previous tests. Although every effort was made to wash remnant contaminants from the supply tanks between tests, we found it practically impossible to achieve in the field. Therefore, it was

accepted that some of the inflow samples may have contained trace amounts of pollutants from previous tests. The measured trace contaminant concentrations however, were found to be very small for all pollutants measured. Similar issues have been found in previous studies involving synthetic stormwater (particularly involving sediment), where delivery of the polluted water is difficult during testing [11].

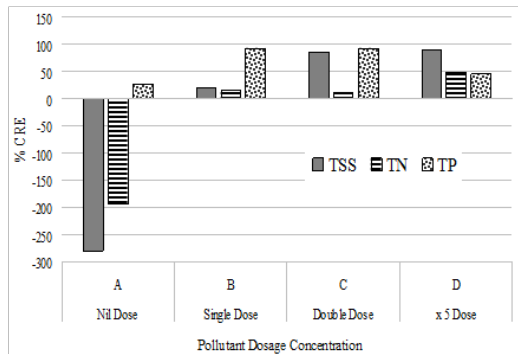


Fig.7 Bioretention pollution removal performance (CRE).

3.2 Heavy Metal and Hydrocarbon Pollution Removal Performance

Heavy metal and polycyclic aromatic hydrocarbon (PAH) pollution concentration levels in the soil core samples were found to be within acceptable limits for all pollutants analysed. Heavy metal pollution levels were found to be highest in the upper 0-50 mm soil layers of the basins. Although trace amounts of several heavy metals (most prominently Mn and Zn) were found in most of the basins, all heavy metal levels found in the soil were either below detectable limits, or within acceptable limits based on legislated health-based investigation levels (Table 5).

While remaining within acceptable limits in four of the bioretention basins, the carcinogenic BaP (Benzo(a)pyrene) was found to be higher (4.8 mg/kg) in the upper layer (0-50 mm) of the fifth basin. However, these BaP levels are comparable with similar urban and roadside locations throughout the world (Table 5). To place the relative risk into context, the highest risk to human health from BaPs is through inhalation of contaminated air, and food consumption. Although, soil and drinking water can be sources of BaPs during normal daily activities [27]. The risks to human health from PaHs contained within the bioretention basin soil are very low. The risk may be higher during activities that involve soil disturbance, including maintenance (weeding etc.),

or soil filter media replacement.

Table 5 Comparison of Bioretention Basin PAH soil content with typical global levels

Location	Typical Concentration Range (mg/kg)	Description	Ref.
	0.01-0.1	Rural soil	[26]
	0.05-0.1	Forest soil	[26]
Worldwide	0.6-3.0	Urban soil	[26]
	14.6-99.6	UK roadside soil	[26]
Europe	2.02	UK urban soil	[27]
Australia	1.2-4.8	Bioretention basins	This study

4. DISCUSSION AND CONCLUSION

Although highly variable between basins and tests, as the pollution concentrations of the simulated stormwater tests were increased, the ER performance of the bioretention basins was also found to increase. Basins were also found to export pollutants during tests where no pollutants were added to the simulated inflow water. Depending on the precise filter media used in the basin design, bioretention basins have previously been known to be occasional exporters of pollution, particularly particulate-bound phosphorous [18]. This study found that bioretention basins reduced TP loads in all tests, although the removal performance was found to be most effective during the higher pollution concentration tests, C and D.

Because the land was commercial/industrial, and subjected to large numbers of daily vehicle and truck movements over the last ten years, it was anticipated that the bioretention filter media would contain significant hydrocarbon and heavy metal pollution loads [12], [28]. However, results from soil core samples in this study found only minimal quantities of these pollutants in the filter media. This was not anticipated. One possible explanation may be that hydrocarbons and heavy metals were not captured by the bioretention basins during high intensity rainfall events (high flow bypass), and diverted directly to the conventional piped network. Although the basins were originally designed with a hydraulic conductivity of 180 mm/h, this may have reduced over time due to clogging leading to regular bypass conditions in the basins. If so, a higher level of maintenance

may be required to ensure effective hydrologic design performance over the longer term to maintain effective overall pollution removal performance. Further research would be required to confirm this.

Another possible reason for the absence of accumulated pollutants in the filter media may be that pollutants trapped during one storm event are then washed through the filter media during subsequent rainfall events. This has been reported as a possible explanation during previous studies [18]. The study results clearly demonstrated that pollutants were exported during pollutant-free tests (A) and this may add support to this hypothesis. Further work is required to examine this in more detail.

Analysis of the filter media used in the bioretention systems found that all pollutants were either below detectable limits, or within acceptable limits based on legislated health-based investigation levels after 10 years in operation. The filter media was not be classified as contaminated and would not require special disposal at this stage.

The results show the large degree of variability in the performance of individual bioretention basins. The authors suggest this variability may be due to a number of reasons, including the slightly different construction techniques used for each basin, and the variability of pollution loads and stormwater inflow volumes experienced between basins due to different environmental conditions.

While this study has added to the existing knowledge about the long-term pollution removal and stormwater reduction performance of street-side bioretention basins, more work is required in order to fully understand the potential stormwater management benefits of these systems.

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6. REFERENCES

- [1] Dietz, M.E., "Low Impact Development Practices: A Review of Current 17 Research and Recommendations for Future Directions." *Water Air Soil Pollution*, 2007, 186, pp. 351-363.
- [2] Lucke, T., & Beecham, S. "Field investigation of clogging in a permeable pavement system." *J. Build. Res. Inf.* 2011, 39(6), pp. 603–615.
- [3] Nichols, P.W.B., White, R., & Lucke, T. "Do sediment type and test durations affect results of laboratory-based, accelerated testing studies of permeable pavement clogging?" *Sci.Tot.Env.* 2015, (511), pp. 786-791.
- [4] Davis, A. "Field Performance of Bioretention: Hydrology Impacts." *Journal of Hydrologic Engineering* 2008, 13(2), 90-95. DOI: 10.1061/(ASCE)1084-0699(2008)13,2(90)
- [5] Hunt, W., Smith, J., Jadlocki, S., Hathaway, J., & Eubanks, P. "Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, N.C." *J. of Env. Eng.* 2008, 134(5), 403-408. DOI:10.1061/(ASCE)0733-9372(2008)134,5(403)
- [6] Le Coustumer, S., Fletcher, T.D., Deletic, A., Barraud, S., & Poelsma, P. "The influence of design parameters on clogging of stormwater biofilters: a large-scale column study." *Water Research*, 2012, 46(20), pp. 6743-6752.
- [7] Bratieres, K., Fletcher, T.D., Deletic, A., & Zinger, Y. "Nutrient and sediment removal by stormwater biofilters, A large-scale design optimisation study." *Water Research*. 2008, 42, pp.930-940.
- [8] Deletic, A., McCarthy, D., Chandresena, G., Li, Y., Hatt, B., Payne, E., Zhang, K., Henry, R., Kolotelo, P., Randjelovic, A., Meng, Z., Glaister, B., Pham, P., & Ellerton, J. "Biofilters and wetlands for stormwater treatment and harvesting". Melbourne: Cooperative Research Centre for Water Sensitive Cities, Monash University, October, 2014, pp. 67.
- [9] Mullaney, J., Lucke, T., & Trueman, S.J. "A review of benefits and challenges in growing street trees in paved urban environments." *Landscape and Urban Planning*, 2015, 134, pp. 157-166.
- [10] FAWB "Adoption Guidelines for Stormwater Bioretention Systems. Faculty for Advancing Water Biofiltration." Monash University. June 2009.
- [11] Hatt, B.E., Steinel, A., Deletic, A., & Fletcher, T.D. "Retention of heavy metals by stormwater filtration systems: Breakthrough analysis. *Water Science & Technology*, 2011, 64, pp. 1913-1919.
- [12] Hatt, B.E., Fletcher, T.D., & Deletic, A. "Pollutant removal performance of field-scale stormwater bioretention systems. *Water Science & Technology*, 2009, 59(8), pp. 1567-1576. DOI: 10.2166/wst.2009.173
- [13] ANZECC and ARMCANZ "Australian and New Zealand guidelines for fresh and marine waters. National Water Quality Management Strategy Paper No 4", Australian and New

- Zealand Environment and Conservation Council & Agriculture Resource Management Council of Australia and New Zealand, Canberra, 2000.
- [14] Pilgrim, D.H., (Ed). "Australian Rainfall & Runoff – A Guide to Flood Estimation", Institution of Engineers, Australia, Barton, ACT, 1987.
- [15] Lloyd, S.D. "Water Sensitive Urban Design in the Australian Context. Synthesis of a Conference held 30–31 August 2000, Melbourne", Australia (Technical Report No. 01/7 Cooperative Research Centre for Catchment Hydrology, Melbourne, Australia (2001)
- [16] Deletic, A. & Fletcher, T.D. "Performance of grass filters used for stormwater treatment—a field and modelling study." *Journal of Hydrology* 2006, 317(3), pp. 261-275.
- [17] Duncan, H. "Urban stormwater quality: a statistical overview" Clayton Victoria: CRC for Catchment Hydrology, 1999.
- [18] Hatt, B.E., Fletcher, T.D., Deletic, A. "Hydraulic and pollutant removal performance of stormwater filters under variable wetting and drying regimes." *Water Science & Technology*, 2007, 56(12), pp. 11-19.
- [19] Liu, J., Sample, D., Bell, C., & Guan, Y. "Review and Research Needs of Bioretention Used for the Treatment of Urban Stormwater." *Water*, 2014, 6(4), pp. 1069-1099.
- [20] Ansaf, K.M.M., Lucke, T., & Boogaard, F. "Preliminary investigation into the pollution reduction performance of swales used in a stormwater treatment train. *Water Sci. & Tech.*, 2014, 69 (5), pp. 1014-1020.
- [21] Lucke, T., Mohamed, M.A.K., Tindale, N. "Pollutant Removal and Hydraulic Reduction Performance of Field Grassed Swales during Runoff Simulation Experiments." *Water*, 2014, (6), pp. 1887-1904.
- [22] Australian Government "National Environmental Protection (Assessment of Site Contamination) Measure" (AG NEPC). National Environmental Protection Council, Adelaide, Australia, 1999. <https://www.comlaw.gov.au/>. Accessed 30 June 2015.
- [23] American Public Health Association (APHA) "Standard methods for the examination of water & wastewater." 21st edition, 2005, Eaton, A.D., Clesceri, L.S., Rice, E.W., Greenberg, A.E., Franson, M.A.H. APHA, Washington.
- [24] Standards Australia/New Zealand. "Water quality - Sampling - Guidance on the design of sampling programs, sampling techniques and the preservation and handling of samples." (AS/NZS 5667.1:1998). Retrieved from <http://www.saiglobal.com> 30 June 2015.
- [25] Feng, W.J., Hatt, B.E., McCarthy, D.T., Fletcher, T.D., & Deletic, A. "Biofilters for Stormwater Harvesting: Understanding the Treatment Performance of Key Metals That Pose a Risk for Water Use." *Environmental Science & Technology*, 2012, 46(9), pp. 5100-5108.
- [26] Menzie, C.A., Potocki, B.B., & Santodonato, J. "Exposure to carcinogenic PAHs in the environment." *Environmental science & technology*, 1992, 26(7), pp. 1278-1284.
- [27] Harrison, R.M., Smith, D.J.T., Piou, C.A., & Castro, L. M. "Comparative receptor modelling study of airborne particulate pollutants in Birmingham (United Kingdom), Coimbra (Portugal) and Lahore (Pakistan). *Atmospheric Environment*, 1997, 31(20), pp. 3309-3321.
- [28] Davis, A.P., Shokouhian, M., Sharma, H., Minami, C., Winogradoff, D. "Water quality improvement through bioretention: lead, copper, and zinc removal. *Water Environment Research*. 2003, 75(1), pp. 73–82.
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