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A SELECTION OF PLANTS FOR BIORETENTION SYSTEM IN THE TROPICS

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CONTENTS

ACKNOWLEDGEMENT

This Research Technical Note (RTN) is the work of a team from NParks (CUGE Research) and SDWA-NUS (Singapore Delft Water Alliance – National University of Singapore), led by Dr. Tan Puay Yok and managed by Benjamin Loh. The aim of this RTN is to document and disseminate the knowledge gained from a vegetation trial conducted by SDWA-NUS at Pasir Panjang Nursery using biofilter columns. While the experiment successfully shows that more than 30 plant species chosen for the trial exhibited recovery with rewatering at the end of 4-week drought and some species are more effective than others in pollutant removal, further trial test in field conditions is essential.

This RTN was authored by Benjamin Loh (NParks), with significant contributions from Carol Han (SDWA-NUS), Reuben Sheela (SDWA-NUS) and Joshi Umid Man (SDWA-NUS).

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Concept design by Kenneth Khoo (CUGE Research)

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PREFACE

As cities develop, more and more land is converted into impervious surfaces, which do not allow water to infiltrate. These include shopping malls, civic squares, parking lots, homes, offices, schools, vehicular roads, and pedestrian walkways. Most of this expanding infrastructure is required to maintain a desired quality of life. However, without careful urban planning, impermeable land can alter the hydrologic cycle and affect the water quality of the catchment area, adjacent waterways and receiving waterbodies such as reservoirs, ponds and lakes.

Rainwater that once soaked into the ground or infiltrated is now running on top of roads or through concrete channels, often discharged straight to nearby canals, reservoirs and ponds carrying potentially harmful pollutants. Often a network of continuous impermeable surfaces serves as a "stormwater superhighway" that conveys stormwater and associated pollutants into downstream of the urban water cycle.

There are techniques that can attenuate peak flow and reduce the amount of metals, nutrients, and bacteria that enter the urban water cycle. These measures are called stormwater Best Management Practices (BMPs), which is almost equivalent to the Active, Beautiful, Clean (ABC) Waters Management in Singapore. Some examples of ABC Waters features are vegetated swale, bioretention system, sedimentation basins, constructed wetland and cleansing biotopes. In areas where land is scarce, where aesthetics are an important concern of the community, where safety is a major issue, bioretention system may prove to be the best ABC features to install.

This Research Technical Notes (RTN) is not about introducing new bioretention system technology nor is it an engineering procedure guidelines for bioretention system. Rather, it showcases a selection of plants that are suitable for bioretention system in the tropics. This publication also provides a summary of how the plants screening study was carried out and results obtained from the study. Readers seeking more scientific information can refer to the subsequent scientific papers from this study.

Background

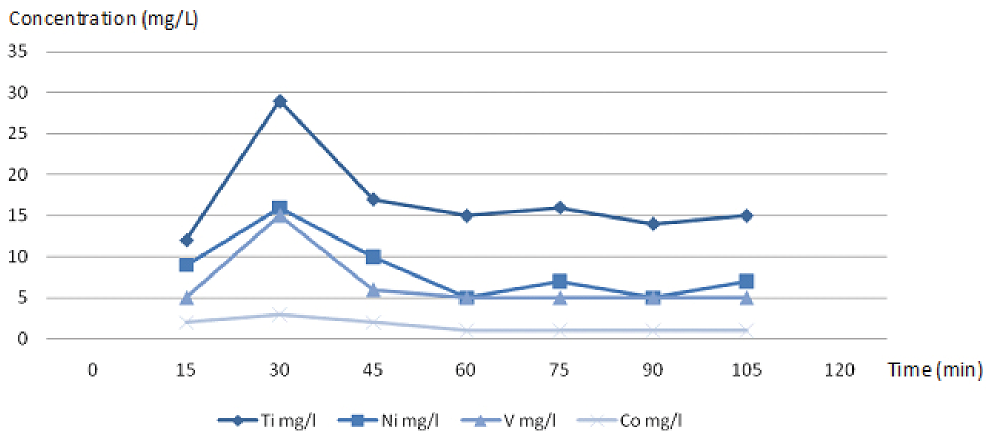


Figure 1 Trace metals in a storm event (edited from Joshi et al. 2010)

Urban sprawl and daily human activities adversely impact both surface water and groundwater resources by changing the hydrologic cycle. The introduction of new impervious surfaces increases the amount of stormwater runoff, while the construction of pipe and channel networks increases the rate at which this excess runoff is delivered to reservoirs and storage ponds.

It is recognised that for urban areas, pollutants are mobilized early in an event due to the wash off of pollutants from impervious surfaces (Chua et al., 2009). It is observed that concentrations of TSS, TP and TN are higher during the first flush periods (Chua et al., 2009). Some of the trace elements from urban runoff such as Co, Ni, Ti, V, and Zn also exhibited first flush phenomena. Although concentrations of most of the metals/metalloid were below the discharge limit, statistics show that some of the elements exceeded the limit during the first flush periods (Joshi et al., 2010) (Figure 1).

Bioretention system is effective at capturing and treating the "first flush" of stormwater runoff from impervious surfaces that carries the highest amount of pollutants. It is one example of a source control method that can be integrated into the urban landscapes or even rooftops to treat the runoff prior to discharging to receiving waters. Controlling stormwater pollutants at their source has the advantages of reduced hydraulic loading, greater ability to attenuate flows, reduced pollutant loads to downstream storage facilities such as reservoirs and ponds.

What is a Bioretention System?

Stormwater bioretention is the process of improving stormwater quality by filtering water through biologically influenced media.

Stormwater bioretention system (also known as biofiltration system, biofilter and rain garden) is just one of the stormwater mitigation measures of Active, Beautiful, Clean Waters (ABC Waters) Programme in Singapore. It is a low energy consumption treatment technology with the potential to increase water quality while reducing peak discharge. A typical bioretention system can be configured as either a basin or a longer, narrower vegetated swale overlaying a porous filter medium with a drainage pipe at the bottom. Surface runoff is diverted from kerb or pipe into the biofiltration system, where it physically filtered through dense vegetation and temporarily ponds on the surface of filter media (also a planting media) before slowly infiltrate vertically downwards through the media. Depending on the design, treated water (effluents) are either exfiltrate into the underlying or surrounding soils, or collected in the underdrain system (subsoil perforated drain) for conveyance to downstream waterways or receiving waterbodies. This system can vary in size and can receive and treat runoff from a variety of drainage areas within a land development site. They can be installed in parks, roadside planting verge, parking lot islands, commercial areas, civic squares and unused lot areas (Figure 2 - 5).

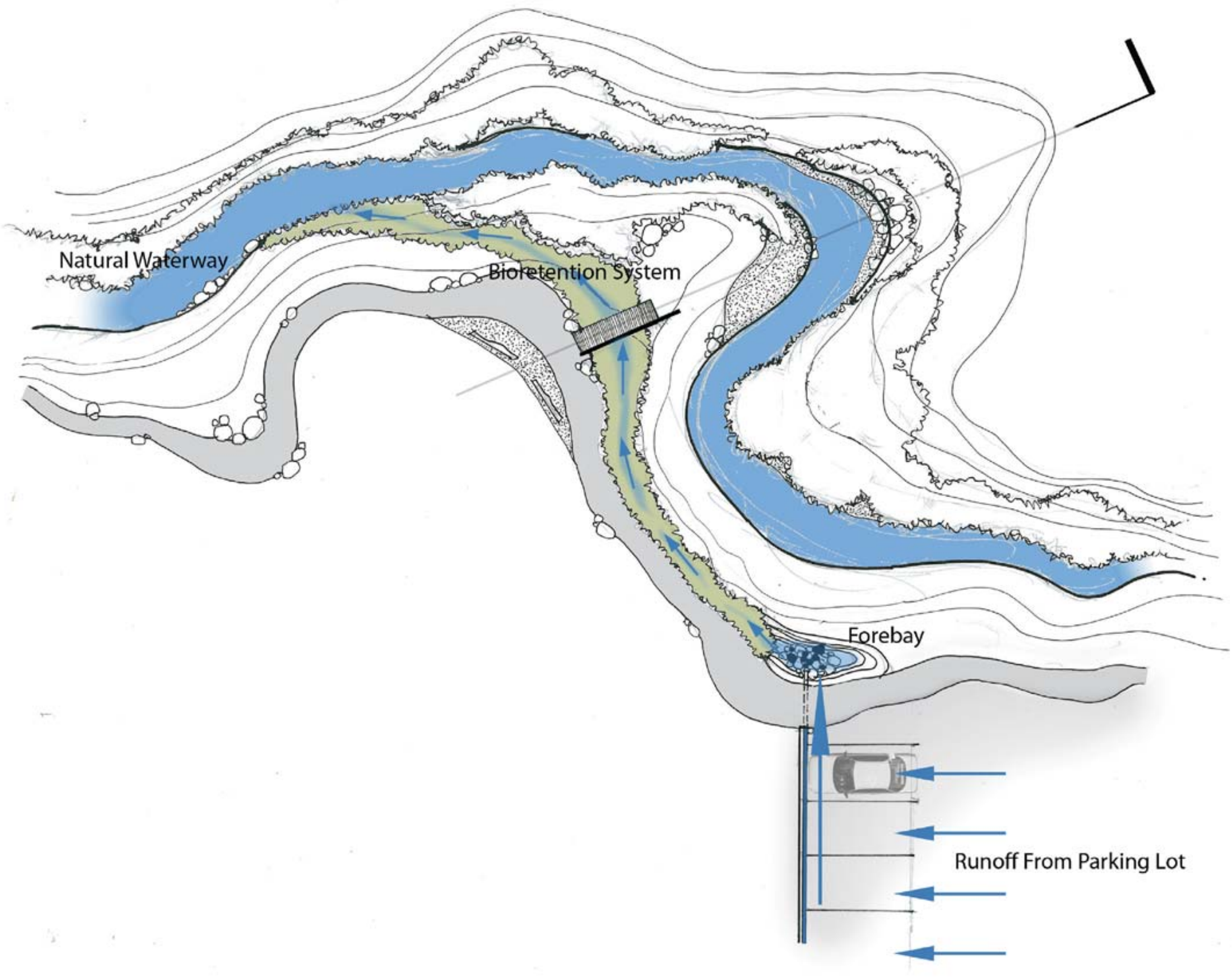


Figure 2 Runoff from the impervious surfaces such as carpark area can be diverted into drain and channelled into bioretention system for treatment before it is being discharged into the receiving waterway

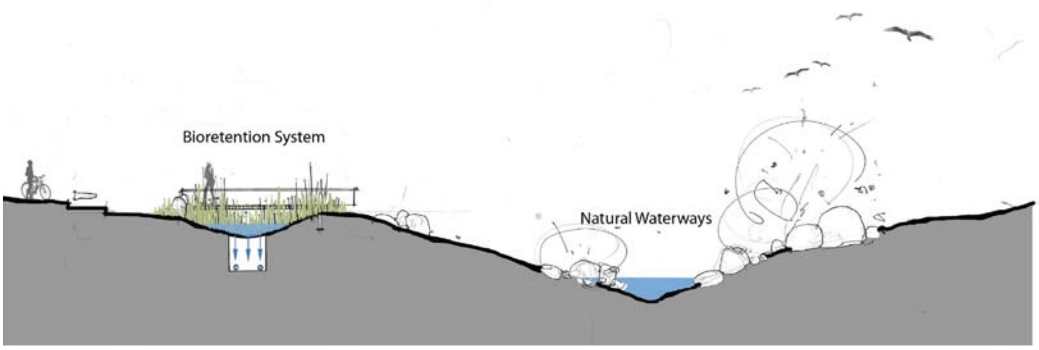


Figure 3 Cross section view of the parkland with a bioretention system integrated into the design of the space

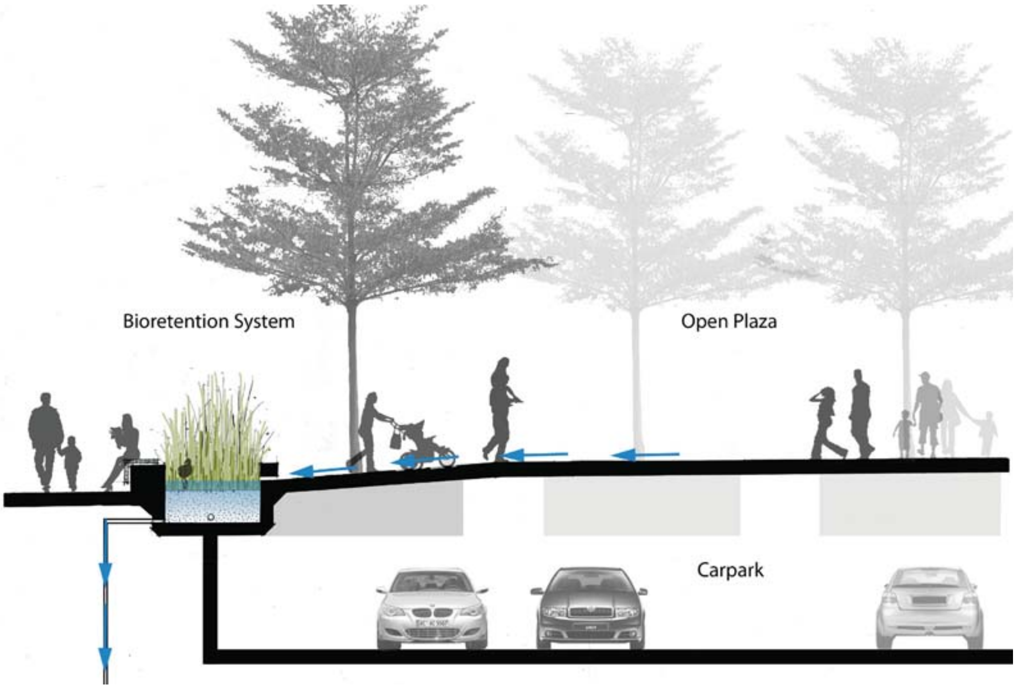


Figure 4 Bioretention system can also be designed and constructed above grade level. In this case, bioretention systems designed aboce a carpark to treat stormwater as well as to create a buffer between the open space and main pedestrain circulation path

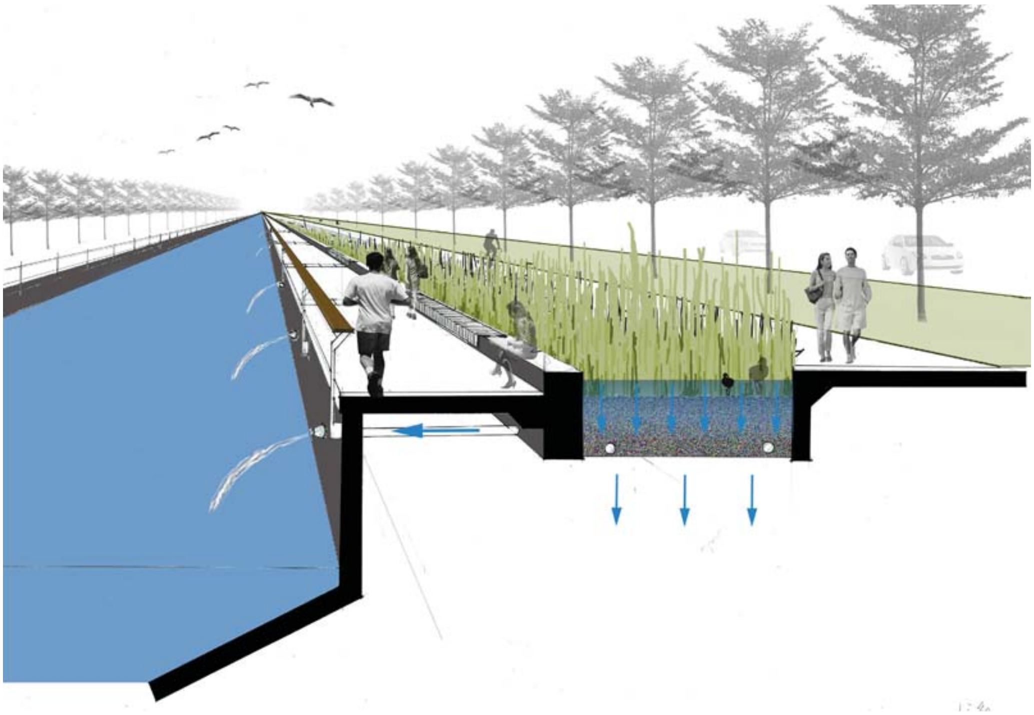


Figure 5 Bioretention system can be designed to provide visual as well as ecological connectivity within strategic open space network

Treatment Processes of a Bioretention System

Urban development adversely impacts both surface and groundwater resources by profoundly altering the hydrologic cycle and water quality. Human activities in urban watersheds produce a variety of pollutants, such as sediment, nutrients, heavy metals, oil, and bacteria that are detrimental to the health of receiving waters. If properly designed, bioretention facility can improve the quality of stormwater runoff to urban waterways. Bioretention system functions as soil and plant-based filtration devices that mimic the following natural treatment processes:

Physical: as stormwater enters the basin or conveying vegetated swale, the dense vegetation reduces flow velocities, causing deposition and retention of soil particles and particulates. Furthermore, soil particles are filtered from the water as it infiltrates downwards through the engineered mixtures of highly-permeable soil media.

Chemical: soil filter media contains minerals and other chemically active compounds that bind soluble and colloidal (fine particles held in suspension) pollutants by sorption (absorption – 'into' and adsorption – 'onto') to clays, organic matter, soil aggregates and biofilms.

Biological: plants and the associated rhizosphere microorganisms take up nutrients and some other pollutants as growth components.

Advantages of Using a Bioretention System

In the wealthy developed communities, new concepts for stormwater management such as Water Sensitive Urban Design (WSUD), Sustainable Drainage Systems (SuDS) and Low Impact Development (LID), have been applied which incorporate bioretention system.

There are numerous successful implementations of bioretention in overseas as well as in Singapore, but also many poor examples due to poor construction, operation and maintenance practices. When designed and implemented properly, bioretention system have been found to be viable and sustainable as a water treatment device. In addition to reducing peak flow generated by impervious surfaces and improving water quality, bioretention system:

- Has an acceptably small footprint in relation to its catchment area (3-5%, as in Singapore)
- Is not restricted by scale
- Is self-irrigating (and fertilizing) garden
- Provides habitat and protection of biodiversity
- Can be integrated with the local urban design (streetscape)
- Has higher level of amenity than the conventional concrete drainage system
- Serves as a tool to reconnect communities with the natural water cycle
- Has positive impact on the local micro-climate (because evapotranspiration causes cooling of the nearby atmosphere)

Considerations for Selection of Plants for Bioretention System in the Tropics

Plants are essential for facilitating the effective removal of pollutants in bioretention system, particularly nitrogen. Furthermore, the vegetations in a bioretention system also maintain the soil structure of the root zone. The plant roots throughout the root zone continually loosen the soil and create macropores, which maintain long-term infiltration capacity of bioretention system. However, some species are more effective than others in their ability to adapt to the conditions within a biofilter, along with their influence on the nutrient removal and hydraulic conductivity of the soil in the biofilter. These species are recommended in Part 2 of this RTN. Further trial test is required to cover a wider range of plant species which could also be suitable for planting in bioretention system but have not been tested in this study.

When a bioretention system fails, most commonly from failing to drain, one of the first indicators is damage to vegetations. Consequently, due to the poor aesthetics of dead plants, the health of the plants themselves becomes a key component of the landowner's perception of success. The remaining specific requirements such as ponding depth, underdrain flow rates, soil composition and thickness of the growth media (root zone) are designed to ensure plant survival.

The key parameters to consider for selecting plants type for bioretention system are:

- Growth form

  Suitable plant species should have extensive root structure and should not be shallow rooted. Ideally the species should have deep root system to allow its roots penetrate the entire filter media depth (but not intruding into the underdrain pipes). Dense linear foliage with a spreading growth form is desirable, while bulbous or bulbo-tuber (corms) plants should generally be avoided as they can promote preferential flows around the clumps, leading to soil erosion.

  It is recommended wherever possible that plants selected for application in biofiltration system have deep root system for optimum nutrients removal such as *Chrysopogon zizanioides* (L.) Roberty and *Ipomoea pes-caprae*.

  In terms of maintaining infiltrability of soil media, results from vegetation trial at Pasir Panjang Nursery suggests that any plant species will be useful. However, if this issue of major concern to engineer, it is advised that species with deep roots, such as *Chrysopogon zizanioides* (L.) Roberty, *Galphimia glauca* Cav. or *Ipomoea pes-caprae*, be specified.

- Water requirement

  Plant material selection should be based on the goal of simulating a terrestrial vegetated community which consists of shrubs and groundcovers materials. The intent is to establish a diverse, dense plant cover to treat storm water runoff and withstand urban stresses from insect and disease infestations, as well as the hydrologic dynamic of the system.

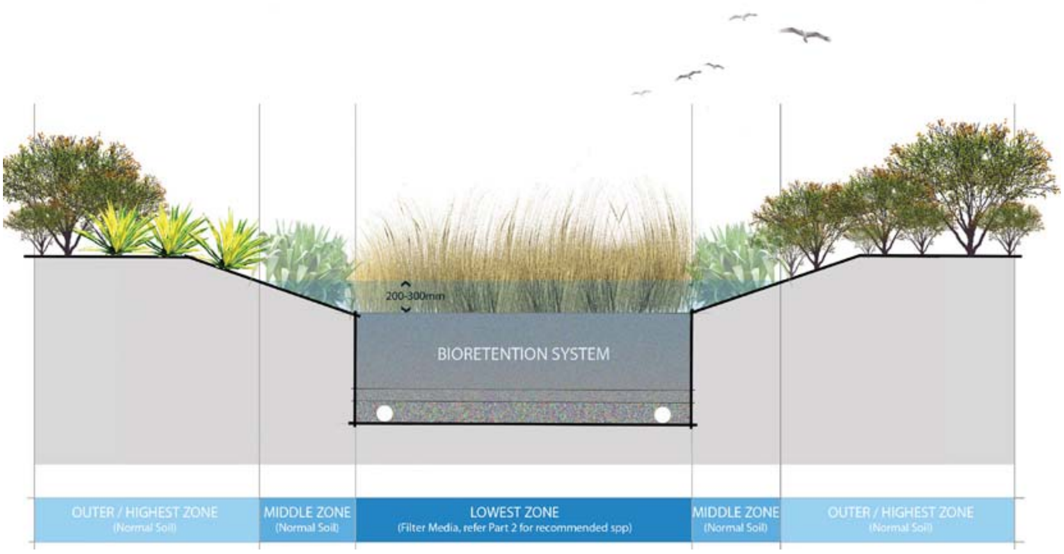
There are essentially three zones within a bioretention system (Figure 6):

The lowest elevation supports plant species, recommended in Part 2 of this book, adapted to standing and fluctuating water levels. Suitable species for application in the lowest elevation need to be tolerant of drought (unless a submerged zone is designed at the bottom of biofilter), freely draining sand based soil media and variable short periods of inundation (maximum inundation of 9 hrs).

The middle elevation supports a slightly drier group of plants that grows on normal planting media, but still tolerates fluctuating water levels.

The outer edge is the highest elevation and generally supports plants adapted to dryer conditions as it is above the ponding level.

"Wet footed" plants (obligate wetland species) are generally not recommended if the filter media used is sandy.



The key parameters to consider when designing with plants for biofiltration system are:

- Planting density

  The overall planting density should be high (Table 1) to increase root density, maintain infiltration capacity (surface porosity), ensure even distribution of flows, increase evapotranspiration losses (which assists to reduce stormwater volume and frequency), and reduce weed competition. Low density planting increases the likelihood of weed invasion (Appendix) and subsequently increases the maintenance costs associated with weed control

Vegetation Types	Form	Height (mm)	Planting Density (Qty/m2)	Example of Plants
Groundcover	Turf	50 - 150	Sodding	*Paspalum vaginatum*
	Tufted	300 - 1000	6 - 8	*Pennisetum setaceum* 'Rubrum'
	Prostrate	100 - 200	6 - 8	*Dissotis rotundifolia*
Shrub	Shrub	300 - 400	3 - 4	*Osmoxylum lineare*

- Planting zones within large system

  Areas furthest from the inlet may not be ponded during small rain events in a large scale bioretention system. Vegetations selected for these areas may therefore need to be more drought resistant than those nearer to the inlet. On the contrary, plants near the inlet may be frequently inundated, and potentially buffeted by higher flow velocities, and therefore plants selected should be tolerant of these hydrologic impacts.

- Range of species and types

  Planting a bioretention system with a range of species, depending on the size of the planting area, can increase the success of the system as plants are able to "self-select" suitable establishment areas within the vegetated area (i.e. drought tolerant plants will gradually replace those plants that prefer wetter conditions in areas furthest from the inlet).

  From the biodiversity perspective, it is evidenced that bioretention system with higher number of plant species and types has positive impacts on urban biodiversity compared to monoculture lawns. The presence of mid-stratum (bush canopy) provides quality foraging and sheltering habitat for invertebrates that monoculture lawns (low-stratum) can not otherwise provide. Bioretention system with mid-stratum also subject to less indirect impact from high human disturbance either directly through human traffic or through extensive maintenance regimes such as mowing which is applied to lawn-type bioretention system.

  Where the landscape design includes mid-stratum, more shade tolerant species should be chosen for the groundcover layer. Trees and shrubbery should be managed so that the groundcover layer is not out-competed.

- Use of mulch

  The use of an organic mulch such as hardwood chips is generally not recommended for system where there is an overflow pits, due to the risk of clogging. Mulch is susceptible to washout or move to the perimeter of the system during a storm and high flows. Another reason for not recommending organic mulch, such as woody mulches, is nitrogen depletion from the filter media. Microbial decomposition requires a source of carbon (cellulose) and nutrients to proceed. As microbial breakdown of the woody mulch material proceeds, nutrients from the surrounding soils (filter media) is rapidly used, often resulting in the depletion of nitrogen. Microbes will out-compete plants for soil nitrogen, and therefore, the decomposition of woody mulch may have detrimental impacts on plant health.

A stone mulch (10-20mm dia, min. depth 100mm) is preferred where there is a need to protect the soil from erosion or reduce the gradient of the batter slope (for safety reasons), whilst still maintaining the designed ponding volume. Minimum depth of 50-100mm gravel mulch is recommended to effectively prevent weeds from germinating and penetrating through the mulch layer. However, high planting densities should be adopted, to compensate for the reduced spread of plants caused by the stone or gravel mulch.

- Safety consideration

  The standard landscape design principles of public surveillance, exclusion of places of concealment and open visible areas apply to the planting design of bioretention basins. Regular clear sightlines and public safety should be provided between the roadway and footpaths or comply to the requirement of local authority.

- Traffic sightlines

  The standard rules of sightlines geometry apply. Planting designs should allow for visibility at pedestrian crossings, intersections, rest areas, medians and roundabouts.

Studies on Selection of Plants for Bioretention System in the Tropics

The aim of this joint project between NParks and NUS-SDWA is to screen and select plants suitable for application as vegetation in bioretention systems. The research project also aims to investigate the remediation capacity of these selected plants and their associated rhizosphere microbial communities. Of the numerous stormwater pollutants, the phytoremediation study will concentrate on two important plant nutrients, namely nitrogen and phosphorus. The project works towards the goal of generating a list of plant species suitable for cultivation in bioretention systems.

Experimental setups were designed closely to the working specifications of bioretention systems according to PUB, 2009. The columns, measuring 50 cm length by 50 cm width by 115 cm height, was fabricated using opaque polyvinyl chloride (PVC) and the inner walls sandpapered to minimise preferential water flow (Figure 7). The outer walls were double coated in black paint to render the setup light impermeable except at the 10 cm-wide viewing window in front of the column. Each column was constructed with 5 ports, along with attached PVC valves, at varying depths to facilitate the collection of effluent grab samples. Ponding at a prospective height of 20 cm was made possible by a sixth outlet placed at the top corner of the column. To allow for visual examination in the investigation of plant root development, 10 experimental setups were without black coating and fitted with detachable light impermeable PVC sheets. Similar removable sheets were used to cover the viewing windows of the columns at will. The bioretention system comprised of three distinct layers: filtration layer, transition layer, and drainage layer. The top filter media is composed of 50% available soil moisture (ASM) and 50%

medium to coarse sand, while the transition media is made of coarse sand and the bottom drainage media of fine gravel (Table 2). The filter media had a hydraulic conductivity of ca. 136 mm h-1, which was compliant with the 50 – 200 mm h-1 range proposed in the bioretention design guidelines (PUB, 2009).

Table 2 Components of the substrate layers in the bioretention setup.

	Layer	Substrate	Particle Size (mm)	Depth (mm)
1	Filter Media	mixture of 50% ASM and 50% medium-coarse sand	Varied	600
2	Transition Layer	Coarse sand	0.7 - 1.0	100
3	Drainage Layer	Fine gravel	1.0 - 5.0	200

More than thirty plant species were chosen across a range of angiosperm families, including monocots and dicots, and herbaceous and woody plants. All plants were obtained through commercial nurseries and carefully re-potted into each bioretention set-up. Depending on plant size, 2 to 9 of each species were uniformly placed in each set-up with the exception of the experimental control which was left unplanted.

The experiments were conducted from September 2010 through June 2011 at the Pasir Panjang nursery, Singapore. An average day time temperature of 32±1.87°C and night time temperature of 25±1.28°C was recorded during the period of study. A total of 70 bioretention setups were placed outdoors under a two-sided slope tent with a transparent top cover that allowed full natural sunlight, but prevented rainfall and side rain shields that averted rain splatter (Figure 7)

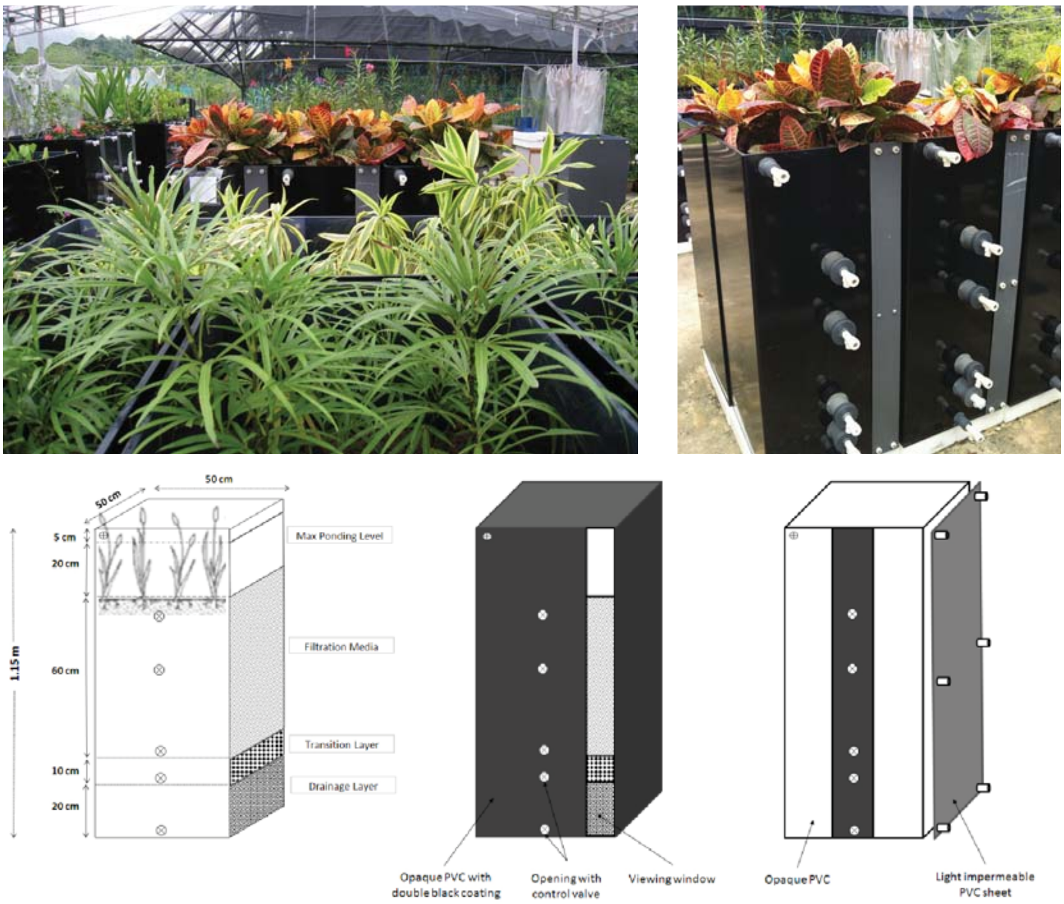


Figure 7 Photo on the top left shows the experimental setups under a transparent pitched roof structure at Pasir Panjang Nursery in 2010. Photo on the top right shows the typical bioretention columns with trial plant species growing in them. Schematic diagram of bioretention columns indicating dimension details and substrate layer configurations.

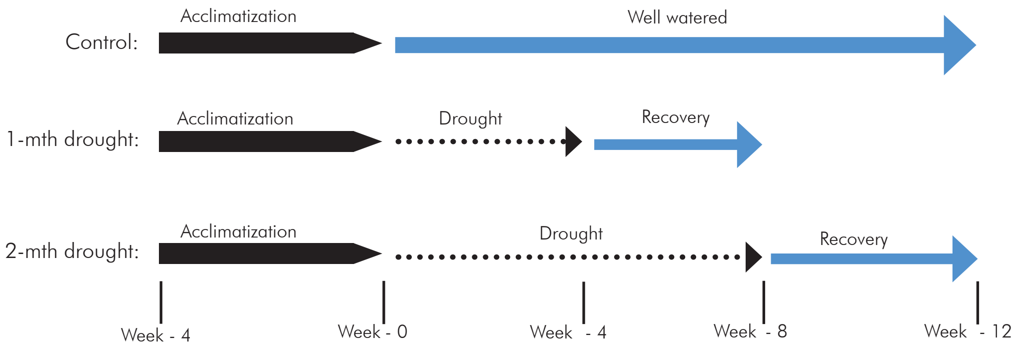


Figure 8 Experimental design used to determine the effect of progressive drought and subsequent recovery

Plants were grown in the bioretention setups and watered with tap water at a twice-weekly dosing regime of 10 L per column. The plants were allowed to establish for 4 weeks before the implementation of drought treatment. Drought stress was imposed by withholding irrigation for 4 or 8 weeks. The drought cycle was determined based on the frequency of dry days in Singapore over a past 10-year duration, which recorded a longest dry period of no more than 2 months. At the end of each drought interval, the plants were rewatered with the same dosing regime for another 4 weeks (Figure 8).

To study the remediation potential of the bioretention systems, the well watered setups were treated with synthetic pollutants at the end of 12 weeks. Effluent samples were collected 12 hours after irrigation with water chemically spiked with 10 mg L-1 nitrate (potassium nitrate, KNO3) and 2 mg L-1 phosphate (potassium dihydrogen phosphate, KH2PO4). Three 10 ml water samples were taken from the outflow of each column: one after 1 L and another 2 after every 3 L discharge. The outflow sampling regime was designed to capture the mean concentration of the outflow, including a mixture of both the resident water (i.e. water which remained in the filter media from a prior dosing event) and the recent filtrate.

In order to test the remediation capabilities of the plants for nutrients, irrigation water was chemically spiked to give a final concentration of 10 mg L-1 nitrate and 2 mg L-1 phosphate. The nutrient concentrations were above the levels commonly detected in urban stormwater runoffs, particularly in Singapore (Chua et al. 2009). In the control setup without vegetation, a higher level (15 mg L-1) than the spiked concentration of nitrate was found in the effluent, indicating leaching from the bioretention substrate. Of the plant species studied, 24 species showed more than 60% nitrate removal, of which 11 plant species were highly efficient in nitrate uptake, removing more than 85% (Figure 9). Arundo donax var. versicolor and Bougainvillea 'Sakura Variegata' were the best performing plant species, showing nitrate removal rates of up to 95% while barely 2% of the nitrate was removed by Pisonia grandis R. Br.(or Pisonia alba) and Rhodomyrtus tomentosa.

More importantly, the bioretention setups exhibited 100% efficiency in removing phosphate (Figure 10). However, phosphate was also completely removed in the unplanted control, indicating that the remediation of phosphate was primarily attributable to the bioretention substrate and not the presence of vegetation.

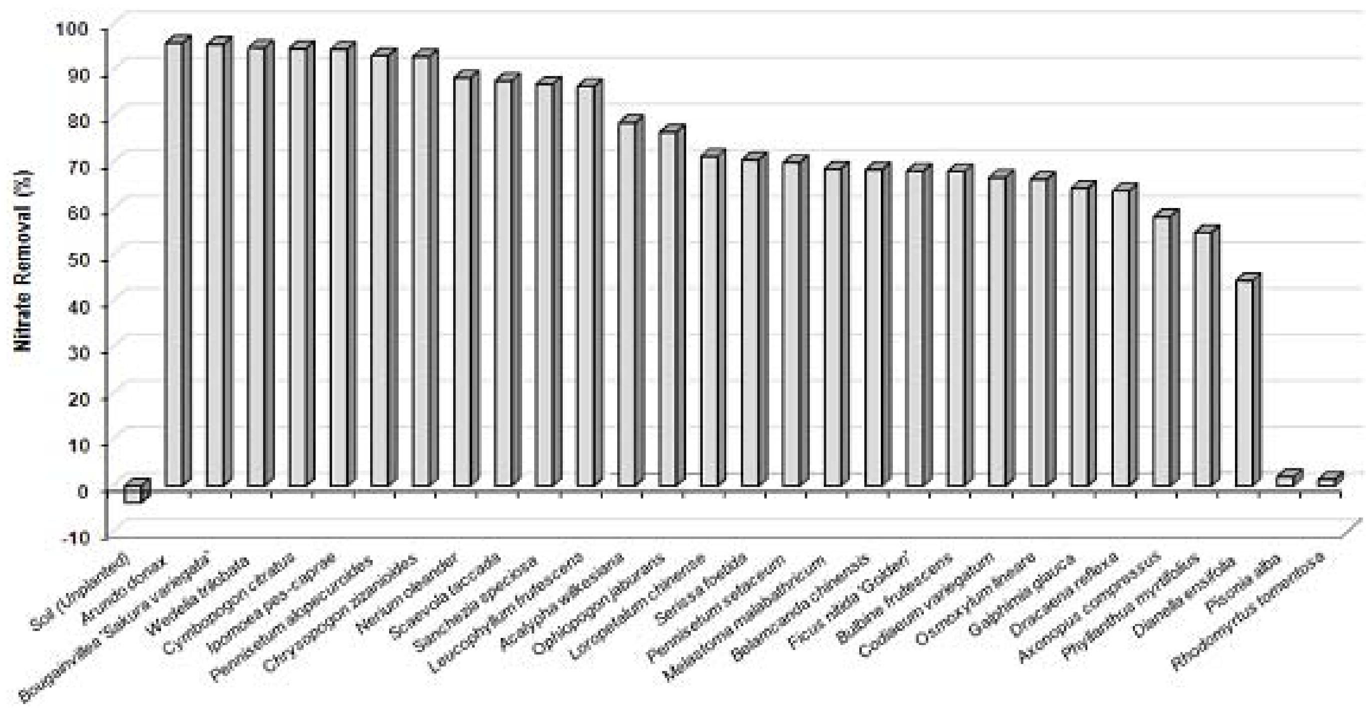


Figure 9 Nitrate removal efficiency of better performaing plant species. Plants were exposed to 10 mg/L nitrate. An experimental control without plants was carried out with same nutrient concentration, Values represent the mean three replicates.

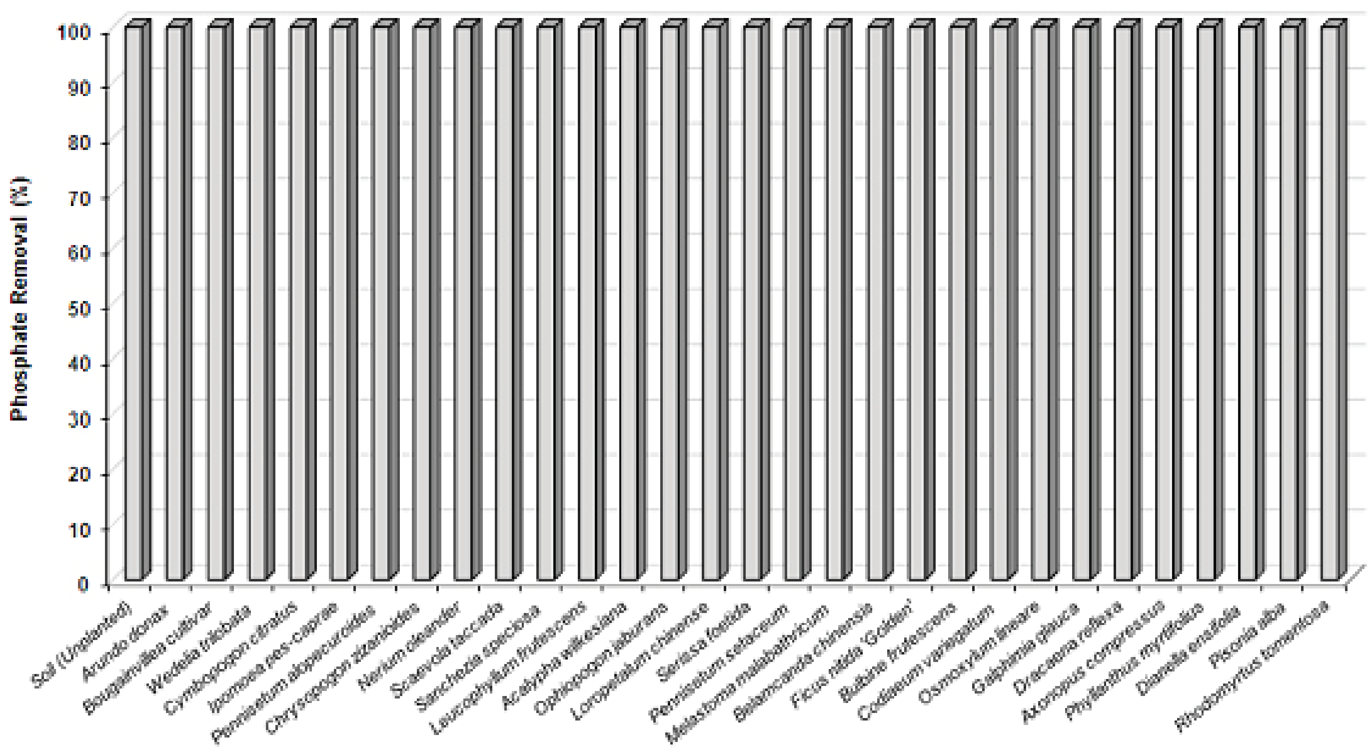


Figure 10 Phosphate removal efficiency of all plant species. Plants were exposed to 2 mg/L phosphate. An experimental control without plants was carried out with the same nutrient concentration. Values represent the mean of three replicates.

Maintenance Requirements for Bioretention System

Like any landscape feature, bioretention systems must be maintained to prolong it's performance. Because vegetation plays a vital role in maintaining the hydraulic conductivity (porosity) of the filter media of a bioretention system, a healthy growth of vegetation is critical to its overall performance. For large bioretention basins, it is essential that maintenance access points to inlet, outflow pit and planting bed are designed for and maintained in the bioretention basin. A reinforced concrete ramp or platform for truck or machinery access may be required for large and complex system.

The most intensive period of maintenance is during the plant establishment period (first year) when weed removal and replanting may be required (Appendix – Examples of Issues Requiring Maintenance). Monitoring should be particularly given to the inlet points as these inlets are usually prone to scour and soil erosion due to the energy of the concentrated inflow.

All recommended maintenance tasks and a copy of an inspection checklist must be specified and documented in the maintenance agreements. Maintenance contractors or park managers will use this documented plan to ensure the bioretention system continue to function as designed. An example of maintenance inspection form is included in this publication (Appendix). This form must be customized for each bioretention facility, since the maintenance tasks will differ depending on the scale, configuration of the bioretention system and type of mulch used for surface cover.