The Role of Bioretention Systems: Water and the City

Text and images by Benjamin Loh
Additional diagrams courtesy of National University Singapore and Singapore-Delft Water Alliance

Water plays a vital role in our existence on this planet. Without water there would be no life. Water is now an emerging issue in the contemporary agenda of urbanism. This is probably not such a surprise, as we are constantly reminded of the consequences of climate change, the ongoing intensification of the water cycle (Huntington 2006), urban flooding, rising sea levels, increases in global river runoff (Miller and Russell 1992), the changes in water resource availability, and an amplification of warming through the water vapour feedback. The list of environmental, economical, social, and political issues involving water increases year after year, as the natural forces of water seem to take their revenge on so much of the environmentally insensitive urban planning and development.

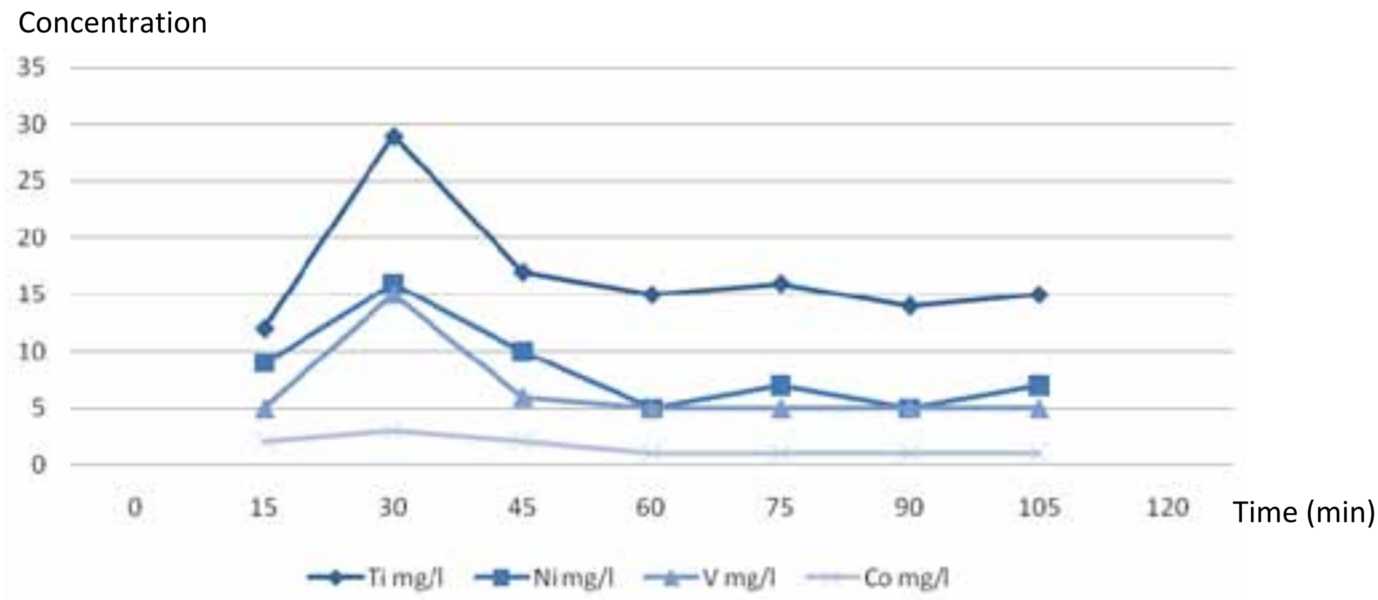
As cities develop, more and more land is laid with impervious surfaces, which do not allow water to infiltrate them. These include shopping malls, vehicular roads, civic squares, parking lots, homes, offices, schools, and pedestrian walkways. Most of this expanding infrastructure is required to maintain 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 water bodies.

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 "storm water superhighway" that conveys storm water and associated pollutants to downstream of the urban water catchment. It is widely recognised that for residential and urban areas, pollutants are mobilised early in an event due to the wash-off pollutants from impermeable surfaces (Duncan 1999; Lee 2007; Chua et al. 2009). Likewise, urbanisation in Singapore has increased the amount of impervious surfaces and storm water runoff (MEWR 2012), while positive correlations were found between peak flow and loading at various locations in the country most impacted by urbanisation and agricultural activities (Chua et al. 2009).

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 Storm Water Best Management Practices (BMPs) (Fig. 1), which is almost equivalent to the Active, Beautiful and Clean (ABC) Waters Programme in Singapore. Some examples of the ABC Waters Programme features are vegetated swales, bioretention systems, sedimentation basins, constructed wetland, and cleansing biotopes. In areas where land is scarce, where aesthetics are an important concern of the community, and where safety is a major issue, bioretention systems may prove to be the best ABC Waters Programme feature to install.

System Types	Description	Landscape Surface	
		Vegetated	Non-vegetated
Sockaways	Underground chamber or rock-filled volume where storm water soaks into the ground via the base and sides.		💧
Porous asphalt	A uniformly graded blend of mineral aggregate, filler, and bitumen designed to provide a network of air voids so that water can be percolated vertically within the layer thickness.		💧
Porous paving	An alternative to conventional concrete and asphalt paving materials hat allows for the infiltration of stormwater into a storage area, with void spaces that provide temporary storage. (See pages 34 to 39 by Bruce K. Ferguson.)	💧	💧
Vegetated swale	An open-channel drainageway used to convey storm water runoff.	💧	
Sedimentation basin	A temporary or permanent basin used to collect, trap, and store sediment produced by construction activities, or as a flow detention facility for reducing peak runoff rate.	💧	💧
Infiltration trench	A linear system consisting of a continuously perforated pipe at a minimum slope in a stone-filled trench. It is usually used as part of of a conveyance system.		💧
Bioretention basin (Rain garden)	A landscaped depression basin used to slow and treat onsite storm water runoff. Storm water is directed to the basin and percolates through the system where it is treated by a number of physical, chemical, and biological processes.	💧	
Bioretention swale	A bioretention system that is located within the base of a vegetated swale.	💧	
Retention basin	A "wet pond" that includes a substantial permanent pool for water quality treatment and additional capacity above permanent pool for temporary runoff storage.	💧	💧
Detention basin	A "dry pond" designed to temporararily retain some volume of storm water and to protect against flooding.	💧	💧
Constructed Wetland	A shallow, extensively vegetated water body that uses enhanced sedimentation, fine filtration, and pollutant uptake processes to remove pollutants from storm water.	💧	

1 Descriptions of Different Structural BMPs



2 Trace Metals in a Storm Event (edited from Joshi et al. 2010)

What is a Bioretention System?

It is recognised that in urban areas, pollutants are mobilised early in an event due to the wash-off of pollutants from impervious surfaces (Duncan 1999; Lee 2007; Chua et al. 2009). It is observed that concentrations of Total Suspended Solids (TSS), Total Phosphorus (TP), and Total Nitrogen (TN) are higher during the first flush periods (Chua et al. 2009). Some of the trace elements from urban runoff, such as Cobalt (Co), Nickel (Ni), Titanium (Ti), Vanadium (V), and Zinc (Zn), also exhibited first flush phenomena. Although concentrations of most of the metals and metalloids were below the discharge limit, statistics show that some of the elements exceeded the limit during the first flush periods (Joshi et al. 2010) (Fig. 2).

Recommended by Public Utilities Board Singapore (PUB 2009) and supported by the Expert Panel on "Drainage Design and Flood Protection Measures" (MEWR 2012), a bioretention system is effective in capturing and treating the "first flush" of storm water 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 urban landscapes or even rooftops to treat the runoff prior to discharging to receiving waters. Controlling storm water pollutants at their source has the advantages of reduced hydraulic loading, greater ability to attenuate flows, and reduced pollutant loads to downstream storage facilities, such as reservoirs and ponds.

In particular, a storm water bioretention system (also known as a biofiltration system, biofilter, or rain garden) is an open, vegetated drainage system that aims to improve storm water quality by filtering water through biologically influenced media. 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 the kerb or pipe into the bioretention system, where it is physically filtered through dense vegetation and temporary ponds on the surface of filter media (also a planting media), before slowly infiltrating vertically downwards through the media. Depending on the design, treated water (effluents) is either exfiltrated into the underlying or surrounding soils, or collected in the underdrain system (subsoil perforated drain) for conveyance to downstream waterways or receiving water bodies. 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 verges, parking lot islands, commercial areas, civic squares, and unused lot areas (Fig. 3 - 5).

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 (Duncan 1999). If properly designed, bioretention facilities can improve the quality of storm water runoff to urban waterways. Bioretention systems function as soil- and plant-based filtration devices that mimic the following natural treatment processes:

Physical

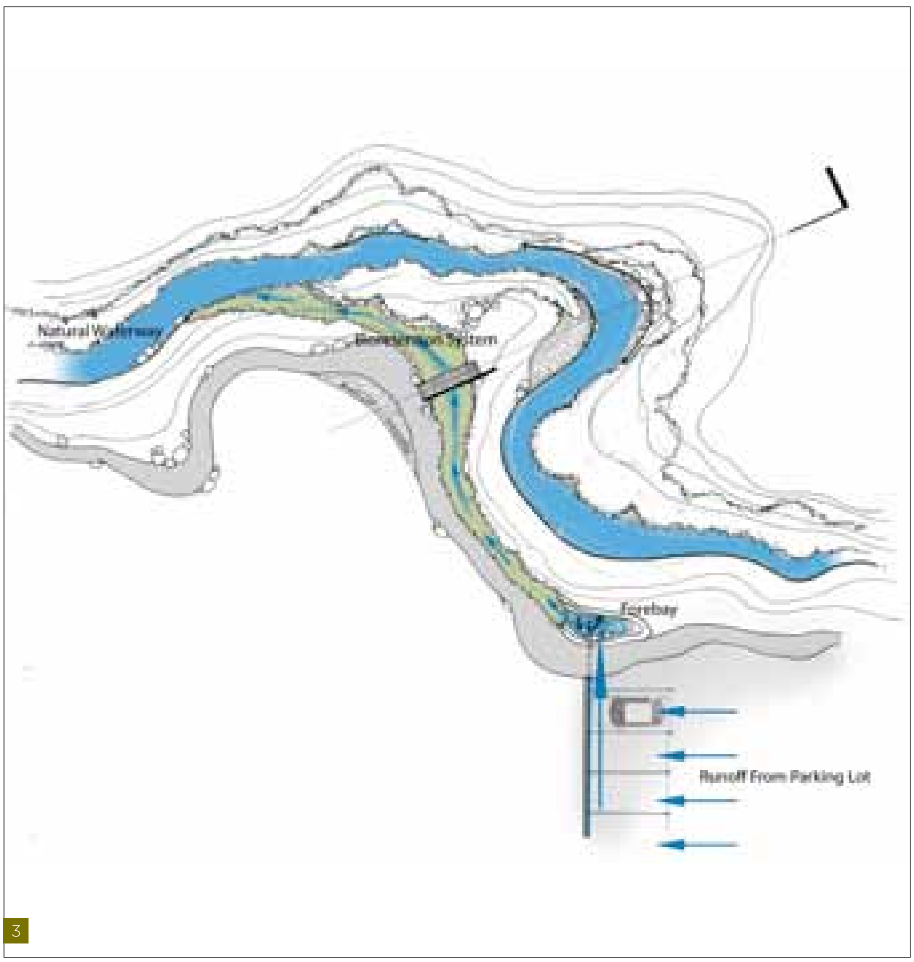
As storm water enters the basin or conveying vegetated swale, the dense vegetation reduces flow velocities, causing the deposition and retention of soil particles and particulates. Furthermore, soil particles are filtered from the water as it infiltrates downwards through the engineered mixtures of highly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

Chemical

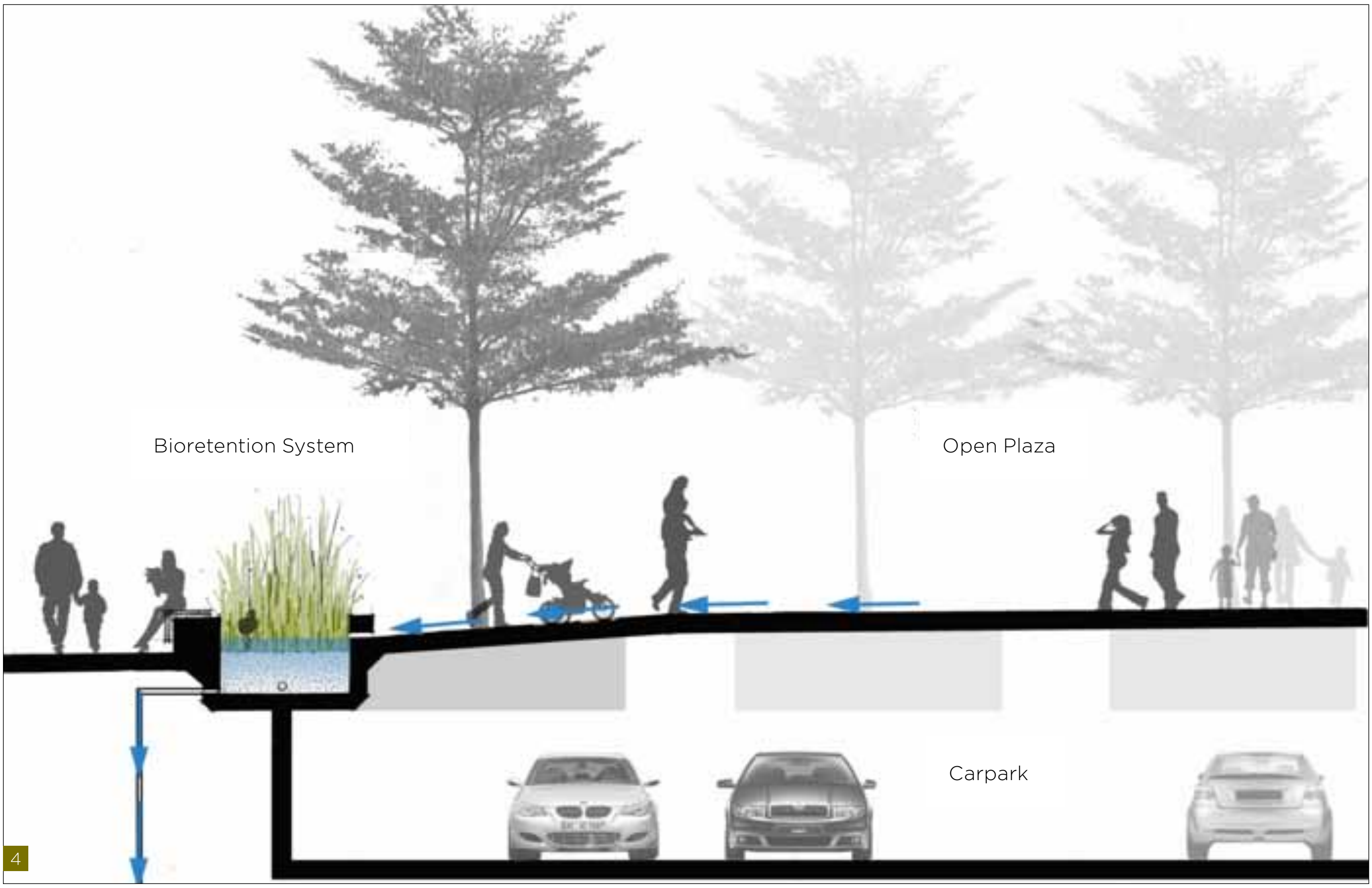
Soil filter media contains minerals and other chemically active compounds that bind soluble and colloidal (fine particles held in suspension) pollutants by sorption (absorption—“into”, and adsorption—“onto”) to clays, organic matter, soil aggregates, and biofilms.

Biological

Plants and the associated rhizosphere microorganisms take up nutrients and some other pollutants as growth components.



3. Runoff from impervious surfaces, such as car park areas, can be diverted into drains and channelled into bioretention systems for treatment before it is discharged into the receiving waterway.



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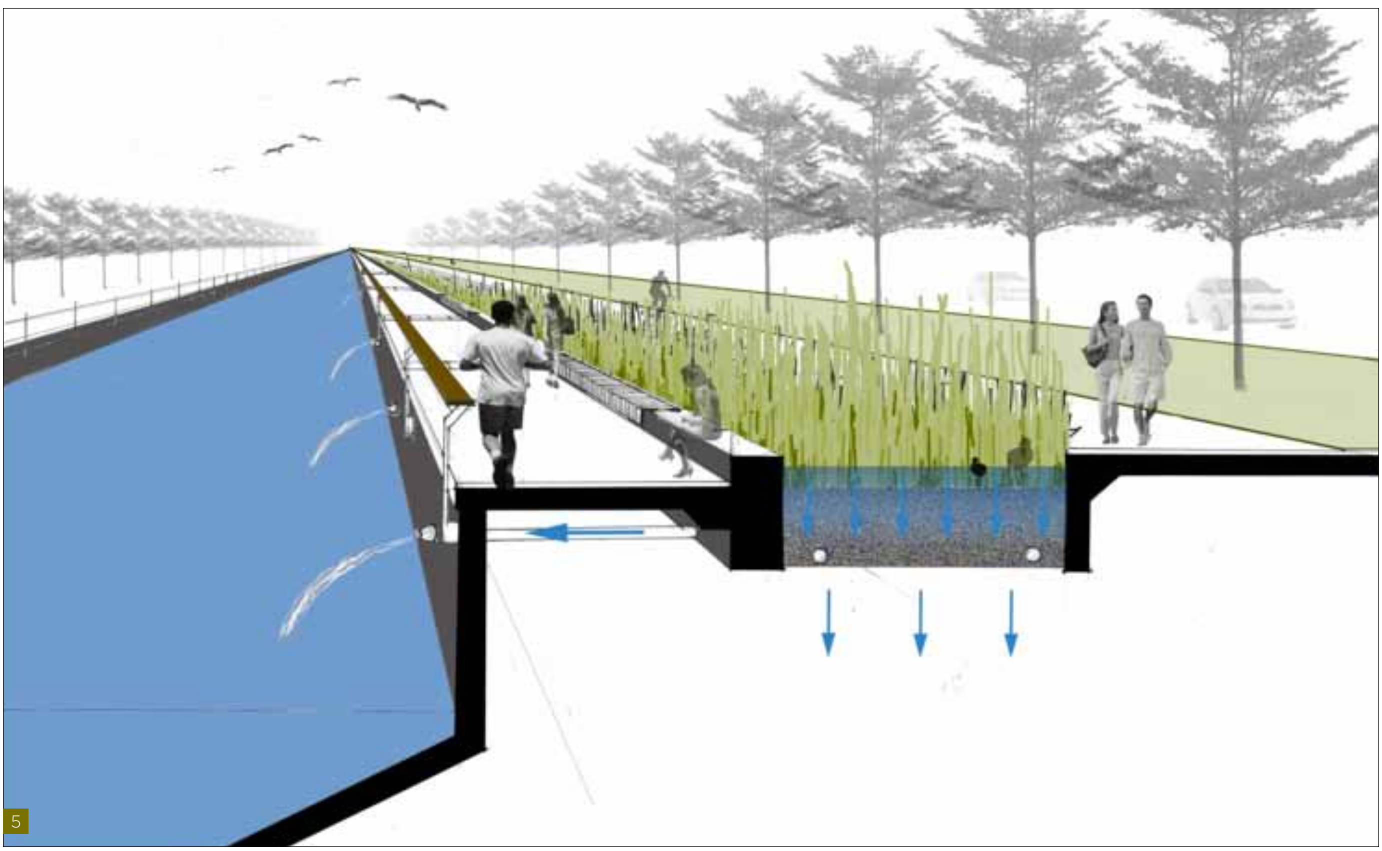

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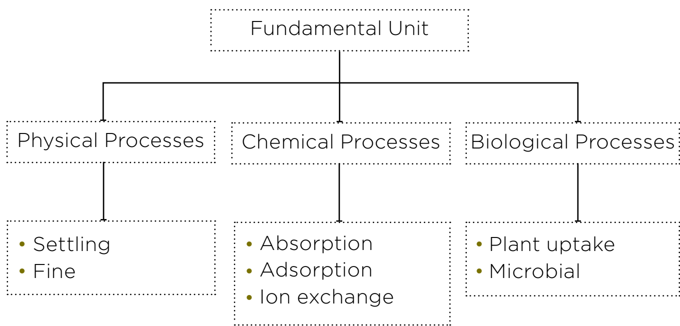

6 Fundamental Unit Processes of a Bioretention System

Advantages of Using a Bioretention System

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

There are numerous successful implementations of bioretention 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 systems have been found to be viable and sustainable as a water treatment device. In addition to reducing the peak flow generated by impervious surfaces and improving water quality, a bioretention system:

- Has positive impacts on the local micro-climate because perviousness (bare soil fraction from the URB simulation) is able to mimic the evapotranspiration from the vegetation observed in a study (Demuzere and Coutts 2012)

- Provides habitat and increases urban biodiversity (Kazemi et al. 2009)

- Has an acceptably small footprint in relation to its catchment area (three to five percent in Singapore)

- Can be integrated with the local urban design

- Has higher level of amenity than the conventional concrete drainage system

- Serves as a tool to reconnect communities with the natural water cycle

- Is a self-irrigating (and fertilising) garden

4. Bioretention systems can also be designed and constructed above grade level. In this case, bioretention systems were designed above a car park to treat storm water as well as to create a buffer between the open space and main pedestrian circulation path.

5. Bioretention systems can be designed to provide visual as well as ecological connectivity within a strategic open space network.

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Studies on Bioretention Systems in the Tropics

A joint project between National Parks Board (NParks) and National University Singapore and Singapore-Delft Water Alliance (NUS-SDWA) was initiated in 2010 to screen and select plants suitable for application as vegetation in bioretention systems. The research project also aimed to investigate the remediation capacity of these selected tropical plants and their associated rhizosphere microbial communities. Of the numerous storm water pollutants, the phytoremediation study focused on two important plant nutrients, nitrogen and phosphorus.

More than 30 plant species were chosen across a range of angiosperm families, including monocots and dicots, and herbaceous and woody plants (Fig. 7 - 8). All plants were obtained through commercial nurseries and carefully re-potted into each bioretention setup. Depending on the plant size, two to nine of each species were uniformly placed in each setup, with the exception of the experimental control, which was left unplanted.

Of the plant species studied, 24 species showed more than a 60-percent rate of nitrate removal, of which 11 plant species were highly efficient in nitrate uptake, removing more than 85 percent (Fig. 9). *Arundo donax* var. *versicolor* and *Bougainvillea 'Sakura Variegata'* were the best performing plant species, showing nitrate removal rates of up to 95 percent while barely two percent of the nitrate was removed by *Pisonia grandis R. Br.* (or *Pisonia alba*) and *Rhodomyrtus tomentosa.*

More importantly, the bioretention setups exhibited 100-percent efficiency in removing phosphate (Fig. 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.

Maintenance Requirements for Bioretention Systems

Like any landscape feature, bioretention systems must be maintained to prolong their 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 for its overall performance. For large bioretention basins, it is essential that maintenance access points to the inlet, outflow pit, and planting bed are designed for and maintained in the basins. A reinforced concrete ramp or platform for truck or machinery access may be required for a 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 needed. Monitoring should be given particularly 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 speci-


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fied and documented in the maintenance agreements. Maintenance contractors or park managers will use this documented plan to ensure the bioretention system continues to function as designed. An example of a maintenance inspection form is included in *CUGE RTN 04-2012* which can be downloaded from the Centre for Urban Greenery and Ecology (CUGE) website. This form must be customised for each bioretention facility, since maintenance tasks will differ depending on the scale and configuration of the bioretention system and the type of mulch used for surface cover.

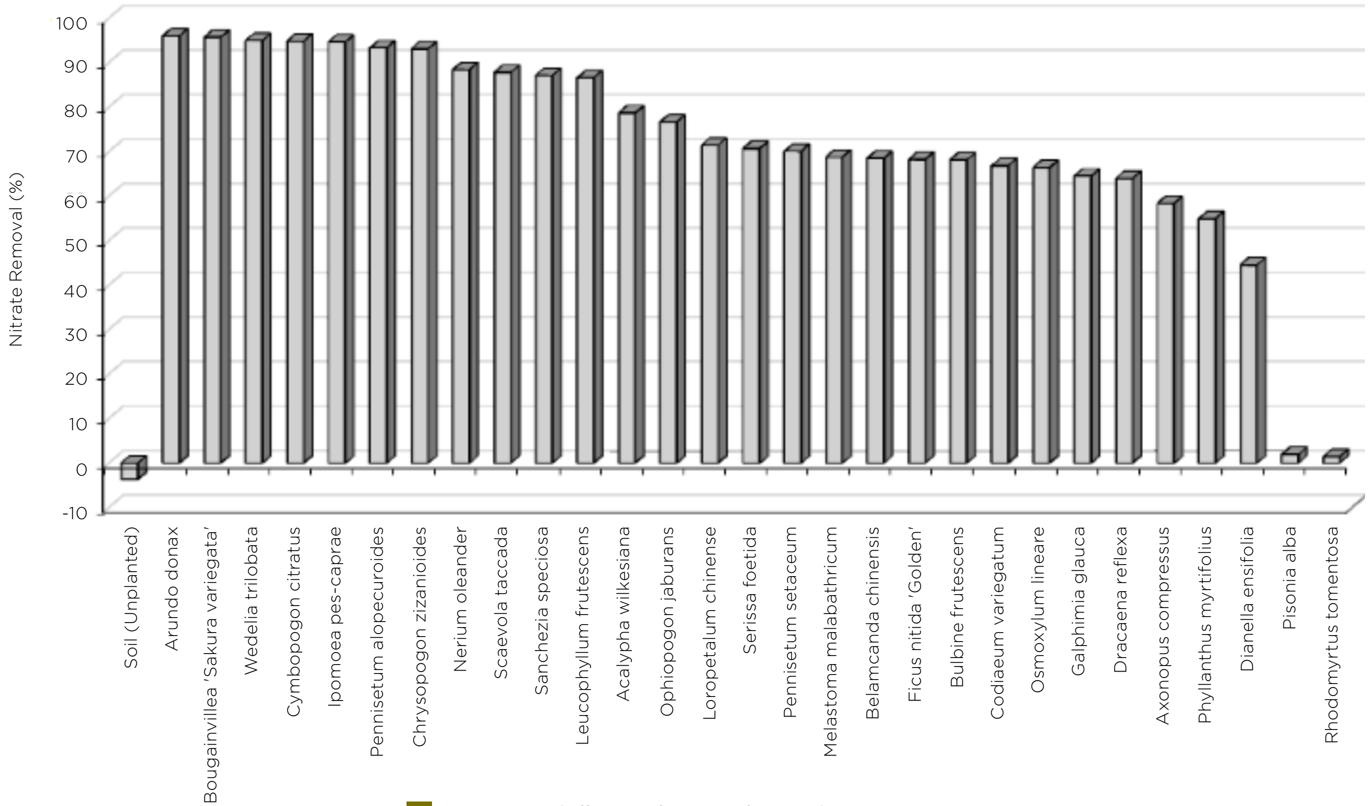
Integrating Trees and Bioretention Systems

Successfully integrating trees and bioretention systems in a dense city like Singapore for creating high-value urban landscapes is a challenge. Retrofitting bioretention systems among large trees, and particularly along the planting verge at roadsides, is desirable from the eco-hydrological standpoint. However, it is challenging as the belowground physical space available to roots for growth and anchorage is limited. There is limited research conducted on tree stability in bioretention systems.

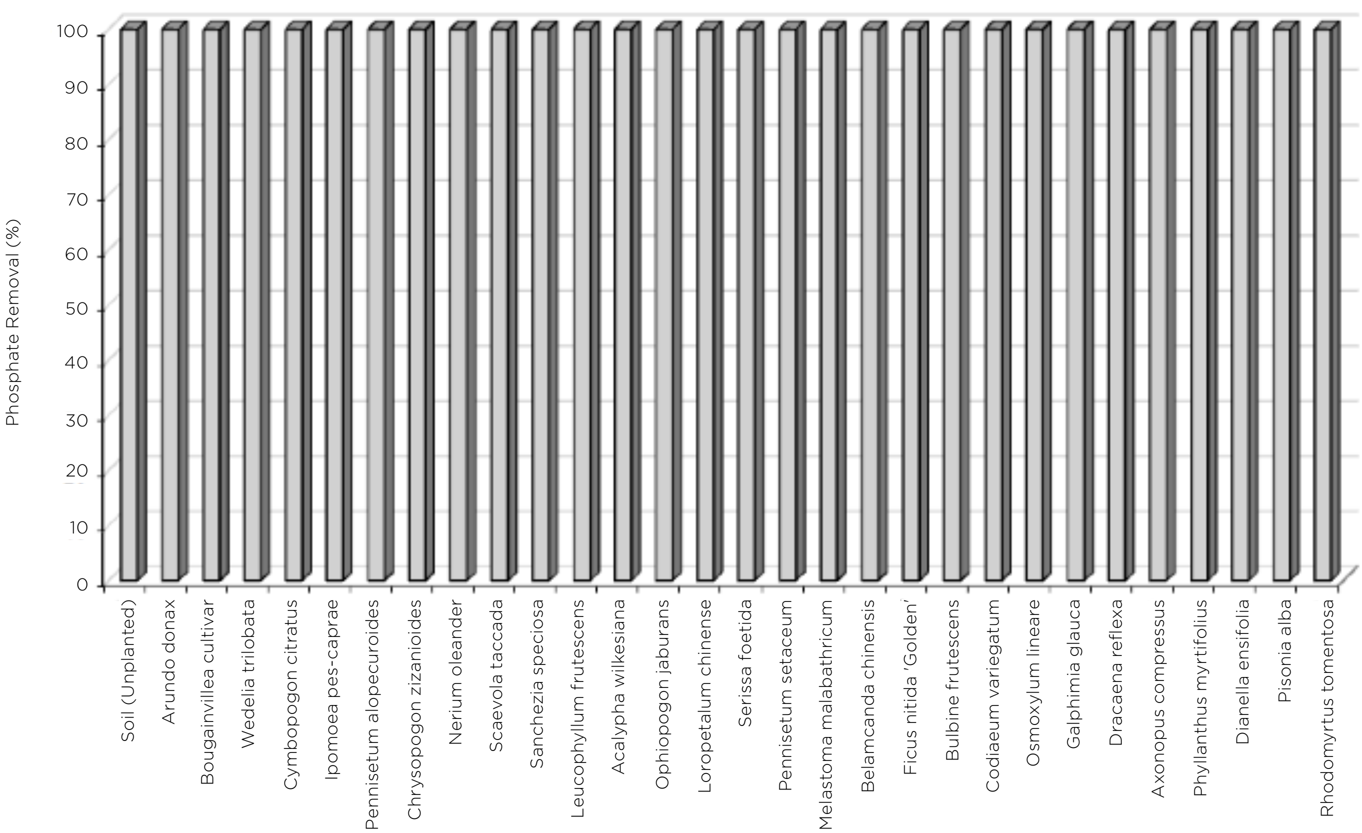
It is well understood that the higher soil water content of nonskeletal soils decreases the soil's shear strength. Tensile strength and other soil physical properties are closely associated with soil moisture (Greacen and Sands 1980), and soil cohesion in particular has been shown to heavily influence the theoretical stability of trees to wind forces (Rahardjo et al. 2009). One would expect that trees in water-saturated soil would tolerate less destabilisation force than those in drier soil conditions due to moisture effects on root slippage and soil shearing. However, the results of a three-year study in North Carolina, USA, on tree stability in both skeletal and non-skeletal soil mixes did not support this hypothesis (Bartens et al. 2010). Further trial tests in field scale is essential to understand the implication of tree planting in bioretention systems. CG

7. The experimental setups under a transparent pitched roof structure at Pasir Panjang Nursery in 2010.

8. Typical bioretention columns with trial plant species growing in them.



9 Nitrate Removal Efficiency of Better Performing Plant Species



10 Phosphate Removal Efficiency of All Plant Species

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9. Plants were exposed to 10 mg/L nitrate. An experimental control without plants was carried out with the same nutrient concentration. Values represent the mean three replicates (Diagram courtesy of NUS-SDWA).

10. 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 (Diagram courtesy of NUS-SDWA).