Water sensitive design features: their function and effectiveness over ten years in a botanic garden

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Abstract

Water sensitive design (WSD) is a nature-based solution to urban stormwater problems which involves intercepting rainfall and stormwater from impervious surfaces using a range of devices. These devices rely on soils and plants to slow water flows, reduce water volumes and improve the quality of the water reaching our rivers, streams, lakes and oceans. Common devices used in Auckland, New Zealand are rain gardens and swales. Auckland Botanic Gardens (ABG) has applied a variety of these devices, often in 'treatment trains' and focusing on the use of native New Zealand plants, to solve an on-site environmental problem. ABG additionally supports research, advocates for the selection and effective maintenance of the native New Zealand plants, and educates the public about WSD. Recommendations for plant selection in Auckland for rain gardens and swales are made based on ten years of observations and trials at ABG.

Introduction

Nature-based solutions are a cost-effective way of building environmental resilience in our cities, while providing social and economic benefits (European Commission, Directorate-General for Research and Innovation, 2021). Water sensitive design (WSD) is one such solution to urban stormwater problems created by an increase in impervious surfaces due to urbanisation, densification and loss of vegetation. Broadly, WSD uses infrastructure to intercept rainfall, stormwater and runoff in a way that mimics how water moves through natural ecosystems using engineered devices (Kuller *et al.*, 2012). Specific soils and plants slow the flow of water (reducing peak flows in streams), reduce the volume of stormwater discharged through infiltration and evapotranspiration, and improve water quality from contaminated surfaces. Auckland Botanic Gardens (ABG) has applied WSD and used native New Zealand species to solve environmental problems on site as well as to research and advocate for the selection of native plants for WSD. These solutions have been presented in an engaging way to educate visitors to the garden.

ABG is in south Auckland, New Zealand, and covers 64 ha (158 acres), including 10 ha (25 acres) of native forest. The topography of the site is generally undulating, with

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tributaries of the Puhinui Stream, which flows into the Manukau Harbour, contributing to the character of the landscape. The soil is a combination of Yellow Ultic, Orthic Brown and Orthic Allophanic (Manaaki Whenua Landcare Research, 2023).

Since WSD was implemented at ABG in 2010, there has been a shift in the aspirations of what it can achieve, particularly with regard to the incorporation of better biodiversity outcomes and habitats for threatened species within urban environments. The value of researching and promoting WSD at ABG has been clearly demonstrated. Auckland's mean annual rainfall is 1,198 mm (MetService, 2023). In the first six months of 2023, however, the city experienced more than this annual average (National Institute of Water and Atmospheric Research, 2023), with the airport – which is near ABG – recording its wettest day on record (258 mm) on 27 January 2023. This rain, combined with further intense rainfall on 1 February, resulted in the costliest weather event in New Zealand's history. Floods and slips resulted in four fatalities, and up to 8,000 homes needed damage assessments. The role played by WSD at ABG in the current challenges cities face has never been more relevant. Extreme rainfall events are predicted to increase under climate change and the intensity of short duration events is projected to increase by 14 per cent per degree of warming (Pearce *et al.*, 2020).

Solving an on-site problem

Two amenity ponds with a combined area of approximately 7,250 m^2 were constructed in a small stream valley when ABG was established in the late 1970s. New Zealand has few natural examples of shallow permanent ponds, and amenity ponds in New Zealand's urban areas frequently harbour aquatic weeds and pollution issues. Many of Auckland's stormwater ponds may contribute to the thermal pollution of streams (Young *et al.*, 2013). The ABG ponds provide a habitat for exotic aquatic plants, waterfowl (primarily mallard ducks) and native eels that have colonised the ponds over the past four decades (Fig. 1). The weedy aquatic *Egeria densa* is the primary plant of the lower pond and can cover up to 80 per cent of the pond's surface. The shallow, open nature of the ABG ponds means that the water warms up in summer, resulting in the proliferation of *E. densa*. The original water sources for the ponds were a stream and natural springs, but now most of the water is stormwater piped in from neighbouring roads and suburbs, with the internal roads and extensive nursery of ABG also discharging into the ponds.

In 2000, an internal market research survey of visitors to the garden identified 'duck feeding' as the primary motivator for visiting ABG, followed by 'a place to have lunch and go for a walk'. However, the combination of the shallow, open, warming water, high numbers of bread-fed ducks and urban stormwater contamination culminated in significant algal blooms and dead and rotting vegetation, creating offensive odours. Water-testing revealed faecal coliforms (from waterfowl) that required public health notices warning visitors of the contaminated water. This prompted the dredging of the ponds to remove over 3,700 m^3 of contaminated sediment (Shaver, 2008) and a decade-long programme to improve the water quality of the ponds using WSD.

Creating the WSD devices

With ABG welcoming around 1 million visitors per year, it is an ideal site to profile WSD and monitor its efficacy, as well as to educate the public on the benefits of this

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Fig. 1 The lower pond in 1999 looking towards the original rose garden, today the site of the visitor centre. Photo: ABG.

stormwater management approach. In the late 2000s, when ABG was developing WSD as a solution to the problems described above, it was a novel approach promoted by the environmental regulator Auckland Regional Council. Communication and education were incorporated from the start (Puddephatt, 2008) to engage and educate visitors and practitioners such as landscape gardeners. Education started with campaigns to discourage visitors from feeding the ducks and the installation of information signs. Grain was provided so that what was a popular visitor activity could continue, with ducks being fed with a more natural and less polluting food type. Mown lawns adjacent to the pond were replaced with unmown native sedge buffers to deter ducks from nesting around the ponds.

New stormwater infrastructure was designed for installation in 2009 across the site (Fig. 2) including a swale, sediment forebay and water re-use tank system (Ortheil, 2009). The installation programme was supported by an analysis of the lifecycle costs for the various stormwater devices, and the necessary permissions were obtained, including a Resource Consent to carry out work in a waterway to excavate the forebay. The design of all devices was consistent with regional guidance in Technical Publication 10 (TP10) (Auckland Regional Council, 2003).

Nursery irrigation water re-use

The ABG nursery sits at the nearest high point to the ponds, and all water including irrigation and rain runoff from the nursery used to flow untreated directly into the ponds. This water was nutrient-rich, being derived from the mixes and fertilisers used to cultivate plants. The nursery standout area was redesigned by installing a series of drains that channelled water into a detention

Fig. 2 Map of the WSD devices across the ABG sites, linked by a trail for visitors to self-guide. © ABG.

tank at the nursery's lowest point (Fig. 3). The water collected in the detention tank is recycled and pumped over the plants growing in the nursery, rather than the mains water supply being used. This collecting and pumping system has the dual benefits of reducing the quantity of nutrient-enriched runoff that enters the ponds and streams, and maximising the use of fertilisers applied to the nursery crops.

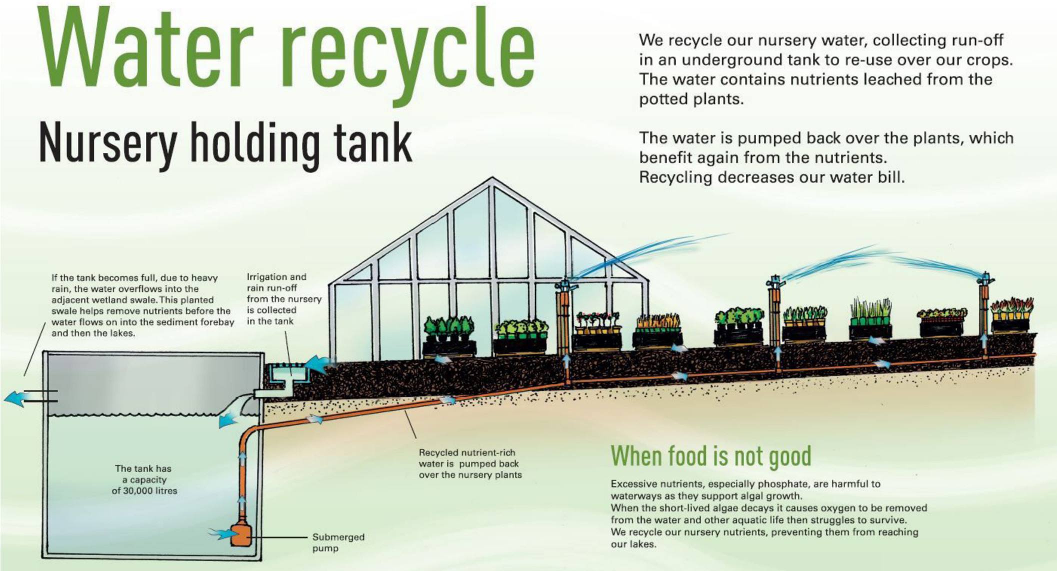

Fig. 3 Illustration of how the water used in the nursery is captured by drains, flows into an underground water tank and is then recycled for further irrigation of nursery plants. The illustration appears on the interpretative signage outside the nursery for visitors to learn about how water is used at ABG. Illustration: © ABG. Designed by Snapper Graphics.

Vegetated swale

A vegetated (unmown) swale was installed in 2009–2010 alongside an internal access road immediately outside the nursery (Fig. 4). The swale was designed to treat stormwater runoff from the 2,900 m^2 nursery, which overflows when the tank is full, and other hard surfaces including the access road before it enters the ponds. Water is channelled into the swale through rock mulch 50 mm in diameter. The rock mulch minimises erosion at the inlet into an engineered ditch 3.3 m wide. The ditch has a flat base 0.9 m in width and sloping sides (3:1 and 4:1). The ditch is 30 cm deep, creating a cross-sectional area that is designed to contain and convey a once-in-a-decade storm in terms of water volume through the device (Auckland Regional Council, 2003). Based on TP10 (Auckland Regional Council, 2003) modelling indicated the swale needed to be a minimum of 43 m long to create an average slope of 1:25 which would provide the filtration treatment required (Fig. 5). The swale provides minimal water retention, as just 100 mm of topsoil overlies a heavily compacted road sub-grade that excludes roots.

It has been important to monitor the plants in the swale (Fig. 6) in order that ABG can provide recommendations to others on the development of WSD devices (Table 1). Based on TP10 (Auckland Regional Council, 2003) and observations made at ABG, plants that are expected to perform well in a swale

- must be suitable for two separate habitats: the sides, or banks, of the swale, and its base. Swale base plants must filter water flow evenly and not block or channel the flow, as both reduce treatment efficiency. They must also tolerate prolonged periods of waterlogging interspersed with occasional drought. Swale sides require plants that tolerate drier conditions with less frequent waterlogging.

- must retain the designed channel roughness coefficient (the friction applied to the flow of water by the channel). In this case a high value of 0.35 was used to reflect the dense growth of native species (which is higher than grass).
- must meet maintenance requirements. In this instance species should require minimal maintenance, with no mowing and only annual trimming, weeding and mulching. Trimming is required because one side of the swale abuts a road, which has to remain clear.

Table 1 List of New Zealand native species that perform well in swales with minimal maintenance and no mowing based on observations at ABG in August 2022.

Name	Family	Swale location/soils
Apodasmia similis	Restionaceae	All locations
Carex tenuiculmis	Cyperaceae	Swale sides, imperfect to well-drained areas
Coprosma 'Taiko'	Rubiaceae	Swale sides, imperfect to well-drained areas
Leptospermum scoparium 'Wairere Falls'	Myrtaceae	Swale sides, imperfect to well-drained areas
Muehlenbeckia complexa	Polygonaceae	In combination with other plants, a gap filler
Phormium 'Green Gem'	Xanthorrhoeaceae	Swale sides, imperfect to well-drained areas

Fig. 4 Construction of the vegetated swale in 2010 at ABG. Photo: ABG.

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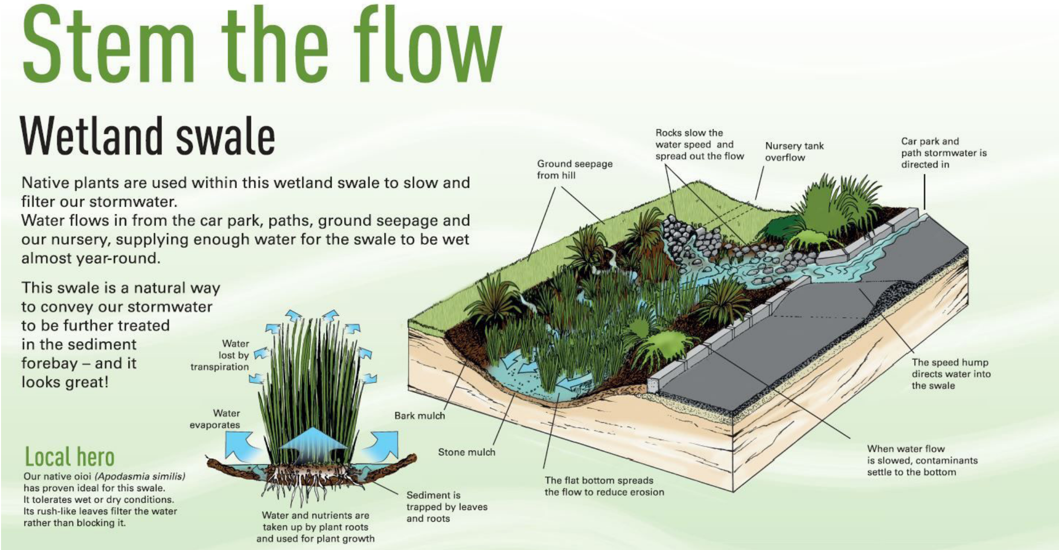

Fig. 5 Illustration of the vegetated swale with the flow of water through the WSD device displayed on interpretative signage for visitors. Illustration: ABG. © ABG. Designed by Snapper Graphics.

Fig. 6 In 2023, 13 years after construction (shown in Fig. 4), the plantings of the vegetated swale at ABG are well established and the swale channel can no longer be seen. Photo: Emma Simpkins.

Sediment forebay

An underground stormwater pipe from the neighbouring suburb discharges near the top of the headwater stream. A sediment forebay was excavated in the streambed (Fig. 7) in March 2010 and is designed to slow the force of stormwater and allow sediment to drop out of the water, reducing mobilisation into the ponds. Access for an excavator has been provided so that sediment can be removed from the forebay when required.

Riparian planting

The banks for the headwater stream were planted with New Zealand native riparian plants using published guidance on riparian planting from Auckland Regional Council (2001) and now form a key demonstration site for this guide. In addition, all pond edges that were previously lawn were vegetated with over 6,000 native plants (Fig. 8). This riparian planting helps filter stormwater running from adjacent lawns (containing grass clippings resulting from using a mower without a catcher) and from plant beds (containing sediment and nutrients). A pair of the threatened New Zealand dabchick or weweia (*Poliocephalus rufopectus*) has subsequently nested in this vegetation, usually raising two or three chicks per year (R. Stanley, pers. obs.). The planting includes a range of species that stabilise banks alongside species that filter stormwater and provide protective vegetation cover including *Apodasmia similis*, *Carex secta*, *Cordyline australis*, *Coprosma robusta*, *Coprosma virescens* and *Phormium tenax.*

Living roofs

A new toilet block and a new entry shelter were constructed in 2010 in the Children's

Fig. 7 Construction of a sediment forebay in 2010, with a channel dug into the streambed to capture stormwater from the neighbouring suburb before it flows into the ponds at ABG. Photo: Jack Hobbs.

Fig. 8 Native riparian planting around the lower pond at ABG, 2023. Photo: Emma Simpkins.

Garden, providing the opportunity for two living roofs to be created. The entry shelter roof was planted with a range of exotic plants to evoke a quirky feel aligned to the Children's Garden, while the toilet block roof was planted with native plants (Fig. 9). A list of the best-performing native and exotic plants for living roofs in Auckland was evaluated from these roofs (Bodley *et al.*, 2022). The roofs do not contribute to pond health but function as an amenity feature and are used as a plant trial bed, for living roof research (Fassman-Beck & Simcock, 2013) and as an educational tool. They include 'drip chains' where water can slowly drip down into the surrounding swales and wetland, demonstrating how WSD is ideally constructed as a series of interconnected devices.

Rain gardens

A rain garden is a special type of garden that is sunken to allow low edge maintenance and/or is relatively wide rather than forming a small pocket. Not only is careful plant selection required to minimise maintenance requirements, but plants must also be able to tolerate cyclical flooding and changes in soil moisture (Yuan & Dunnett, 2018). Rain garden infiltration rates are moderate – water is only observed ponding for short periods (less than a day). All ABG rain garden media have moderate to high organic levels (4 to 10 per cent total carbon by weight) thanks to a compost component which provides sufficient short-term nutrition. Initial maintenance of these rain gardens was carried out using organic mulch and hand-weeding until canopy

Fig. 9 Toilet block green roof planted with native species in July 2022. Photo: Emma Simpkins.

closure. Herbicides were not used, so plants that are vulnerable to herbicide are not disadvantaged, unlike in many roadside rain gardens.

The car parks at ABG have six rain gardens installed as primary devices to treat stormwater. They treat the runoff from 3,500 m^2 (the top car park) and 5,000 m^2 (the overflow car park). One was retrofitted in 2012 by blocking all drains, thereby diverting runoff into the rain garden (Figs 10 & 11). The other five were part of a newer development constructed in 2018, with water fed into them from landscaping and swales (Fig. 12).

In order for ABG to provide recommendations to organisations that develop WSD devices, such as Auckland Transport (2021), it has been essential to monitor the plants in the rain gardens.

Plant recommendations are based on the horticultural and ecological experience of ABG staff and collaborating researchers. Plants that are expected to perform well in a rain garden exhibit the following features and behaviours:

- They can tolerate inundation and waterlogging for periods of up to 24 hours but are more tolerant of extended periods of drought. Tolerance to drought is due to deep root zones of between 0.60 and 1.0 m of soils and sands in rain gardens.
- They will maintain a total evergreen plant cover over the rain garden surface that suppresses weed establishment and protects the soil surface from compaction and erosion (and so helps maintain infiltration). New Zealand rain gardens

Fig. 10 Rain garden established in 2012 in the main car park at ABG. Photo: Rebecca Stanley.

Fig. 11 The now well-established rain garden in 2023 in the main car park at ABG. Photo: Emma Simpkins.

Fig. 12 Flourishing rain garden plantings in the overflow car park. Photo: Emma Simpkins.

are only mulched at planting to enable establishment, with short-term organic mulches preferred (Simcock & Dando, 2013).

- They can establish and maintain cover over the surface area of the rain garden without supplementary fertilisers and with minimal plant maintenance.

Table 2 lists New Zealand native species that have performed well in ABG rain gardens for four to ten years with no irrigation or fertilisation. Table 2 includes two native trees suited to medium-sized rain gardens as they are evergreen but form open (*Sophora*) or very small (*Pseudopanax*) canopies. Deciduous trees are not recommended for New Zealand rain gardens because the mass drop of leaves in autumn can smother the evergreen groundcover and risks blocking rain garden inlets, therefore adding to maintenance requirements. Leaves from an oak tree adjacent to the rain garden suppressed the growth of lower groundcover. The relatively large area and/or setting of rain gardens within adjacent landscaping or below retaining walls around 1 m high means that larger plant species can be used, such as *Astelia*, *Leptospermum* and other small trees. These are often excluded from rain gardens that are small or sandwiched between paths and roads, which require edges to be clear of leaves

Table 2 List of New Zealand native species that perform well in a rain garden, based on observations at ABG in August 2022. Recommendations reported in other Auckland-based publications include [a] Lewis *et al.* (2010), [b] Auckland Regional Council (2003) and [c] Auckland Transport (2021).

Name	Family	Notes
Apodasmia similis [c]	Restionaceae	
Astelia grandis [a c]	Asteliaceae	Up to 2 m tall, slower to establish – accent only
Carex dissita [c]	Cyperaceae	
Carex flagellifera [a b c]	Cyperaceae	
Carex lambertiana [c]	Cyperaceae	
Carex testacea [b c]	Cyperaceae	
Coprosma acerosa [b c]	Rubiaceae	
Coprosma repens [c]	Rubiaceae	
Coprosma x *kirkii* [c]	Rubiaceae	
Cyperus ustulatus [a]	Cyperaceae	
Leptospermum scoparium 'Wairere Falls' [a b c]	Myrtaceae	Only on the edges of a rain garden
Muehlenbeckia astonii [c]	Polygonaceae	
Muehlenbeckia australis [c]	Polygonaceae	Dominant in medium to long term – can smother other plants
Phormium cookianum [b c]	Xanthorrhoeaceae	
Pseudopanax ferox	Araliaceae	Accent only as provides minimal cover
Sophora fulvida	Fabaceae	Tree – accent
Sophora microphylla	Fabaceae	Tree – accent
Sophora molloyi 'Dragon's Gold'	Fabaceae	Shrub

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and plant heights that allow sight lines to be maintained.

A specific trial focusing on *Apodasmia similis* (oioi) was initiated when this plant was identified as one that is successful in swales and rain gardens but requires maintenance when planted within approximately 50 cm of the edge of the WSD device adjacent to paths, roads and car parks. *A. similis* can grow up to 1 m and naturally forms an arch, creating a trip hazard and potentially obscuring sightlines. ABG undertook a trial of selected forms of *A. similis* from wild areas and gardens that, being shorter and more compact, showed potential to remain upright (Fig. 13). Several forms were identified in a garden trial as displaying this desirable quality and are currently undergoing further trials in a rain garden to test their effectiveness in this environment and to ensure they can be propagated to stay true to their form.

Lewis *et al.* (2010) recommended forty-five native species for Auckland rain gardens, including five species under 200 mm tall, especially suitable for edges. None of these shorter species has been trialled in ABG rain gardens, as experience has shown such short plants require intensive maintenance to prevent smothering by exotic wind-dispersed herb and pasture species, such as legumes, grasses, flatweeds and groundsels. Differences also reflect changes in media specifications which have resulted in better-drained soils with higher aeration and only short periods of waterlogging (Auckland Transport, 2021).

Tree pit

An urban green biofilter, more commonly known as a tree pit, was installed to demonstrate a WSD device that is increasingly used where permeable space is extremely limited (such as industrial areas, car parks and town centres) (Fig. 14). The

Fig. 13 A bed of *Apodasmia similis* (oioi) was planted in the trial garden to compare habit and form. From this trial those that passed the selection criteria were moved to a rain garden for further observations of form and function. Photo: Emma Simpkins.

Fig. 14 Tree pit alongside access road with a *Metrosideros excelsa* (pōhutukawa) specimen tree outside the Children's Garden at ABG. Photo: Jack Hobbs.

device uses high through-flow planted media and an adjacent filter chamber to enable an exceedingly small footprint, approximately 1 m^2. Treated water discharges to an adjacent conventional stormwater pipe. *Metrosideros excelsa* (pōhutukawa) was planted in the tree pit in 2023, replacing the original pōhutukawa which was not appropriately watered during a summer drought. In the medium term, the tree is likely to outgrow the device and will have to be removed and replaced. Smaller trees with less aggressive root systems are now more commonly used. Trees can be underplanted with rain garden species or maintained by removing annual weeds and these replaced with non-floating mulch.

Self-guided 'stormwater' trail

A self-guided visitor trail connects many of the WSD devices into an educational and recreational experience (Fig. 1). Technical information at each device is interpreted through 12 signs, making the engineering information easy to digest and using illustrated cross-sections to explain key features. The interpretation explains how the devices work both individually and together as 'treatment trains' supported by a plan of stations modelled on an underground railway map (Fig. 15). The trail has an accompanying brochure (Fig. 16), with more detailed information on the devices available on the ABG website (ABG, 2023). The trail is also useful as a focus for professional training, with ABG used as a location for courses for stormwater engineers, and for commercial trade days. Interaction with other professions and commercial interests facilitates access to contemporary information for ABG staff, enabling them to increase their knowledge and external networks to ensure ABG remains up to date on new research and advice relating to WSD.

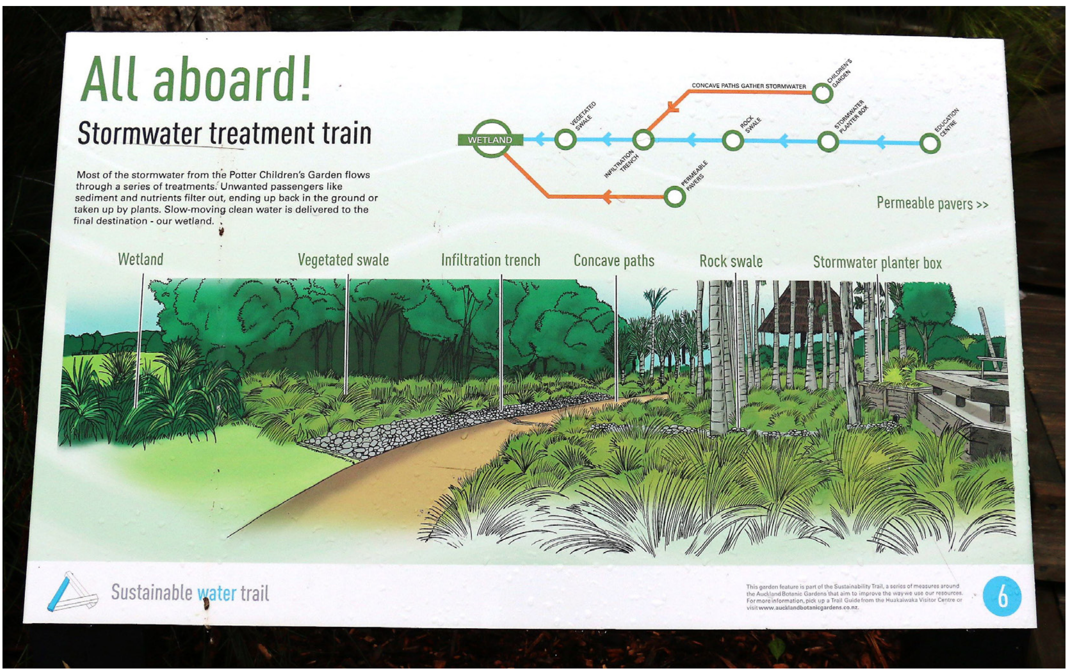

Fig. 15 Interpretative signage for the treatment train at the Children's Garden. Photo: Rebecca Stanley.

Fig. 16 Visitors can pick up a brochure at the visitor centre and guide themselves around the Sustainable Water Trail. Photo: Rebecca Stanley.

Education

The S.O.S. (Save our Streams) programme, run at ABG for students aged 9–13, encourages students to consider the impacts on waterways of expanding urban areas. The programme involves students investigating ways to reduce these impacts as well as exploring the original pond pollution that started the WSD journey at ABG. Students observe the devices and connect the treatment of stormwater to plants and soils. They then go on to construct a mini rain garden using soil and sand to demonstrate how natural materials can filter water. The Children's Garden also has a prominent rainwater tank that demonstrates rainwater capture as stormwater mitigation and ways to save potable water (for example, by using rainwater for irrigation). Bioretention devices and treatment trains have also been used to train stormwater designers (engineers and landscape architects) and bioretention maintenance contractors.

Conclusions

The WSD journey at ABG started by addressing a pollution problem and evolved into a multidisciplinary solution that incorporated stormwater engineering, horticulture, biodiversity and climate change mitigation as well as education for visitors and school-aged children. ABG provides technical advice to professionals on the creation and maintenance of WSD, while developing best practice guidelines. Data collected from both the swales and the rain gardens have contributed to research on mulches (such as Simcock & Dando (2013)) appropriate for these devices. ABG has created and maintained a unique public asset that shows a near-complete range of nature-based solutions with the streams they are designed to protect. All are readily accessible and safe to view, and feature interpretive material. The value of this outstanding asset would be enhanced by adding new devices that use the most recent rain garden media and allow testing of more native plant species, including ABG-developed cultivars.

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