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Sydney Water

Green infrastructure stormwater retention performance

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CONTENTS

1. Executive summary

Urbanisation increases the frequency, volume and magnitude of urban stormwater flows. Efforts to improve waterway health are broadening to include managing stormwater flow volumes as well as water quality. Simultaneously, flood management practices in Australia are shifting from peak flow rates to storm event volumes. There is also a recognised need for urban areas to achieve a more natural hydrology with water retained within the landscape to both protect downstream waterways and support plants and trees for urban greening.

Green infrastructure practices such as bioretention, green roofs and tree pits can potentially meet these objectives to reduce stormwater volumes discharged to drainage and waterways and retain water within the landscape.

The fundamental principles and processes by which green infrastructure reduce volumes are reasonably well understood. However, there remain significant gaps and uncertainties in our understanding and modelling approaches. Furthermore, there has been limited recent synthesis of learnings and detailed monitoring data from experimental studies of green infrastructure assets and in Australia there is no comprehensive database of such studies. Such a database is a necessary precursor to support the development of improved design methods and tools to design green infrastructure to achieve stormwater volume management objectives for flood mitigation, waterway protection and landscape enhancement.

Intended uses of the data

This study seeks to review relevant data, report evidence on green infrastructure volume performance and mechanisms to inform green infrastructure planning and practice and collate a database of green infrastructure hydrologic data, focussing on increasing Australian content, to inform improved modelling, assumptions and calibration.

It is intended the detailed data obtained will be used for two purposes, model calibration and validation and to inform planning and design of green infrastructure assets:

- *Calibration and validation of models* for green infrastructure assets including bioretention. Once it can be confirmed that a given model can provide a reasonable representation of flow patterns, volume reduction performance and processes for a range of conditions, climates and assets, it can then be applied across a range of conditions and design configurations with greater confidence.
- *Planning and design of green infrastructure assets* may be improved using the data and learnings collected including event and site level performance across many studies. These

provide valuable insight into the likely range of stormwater volume performance for green infrastructure including bioretention and green roofs. While some of outcomes are mixed, several key messages emerge from the literature on factors influencing performance. These are discussed in general terms as well as the specific application of these within the context of Western and Central Sydney. These insights may be used to inform planning and practice for green infrastructure responses to manage stormwater volumes.

Summary findings

The key findings can be briefly summarised as follows:

- Bioretention assets and green roofs are generally effective for reducing stormwater volumes.
- Performance varies widely and depends on climate, soils, design, size and other factors
- Bioretention assets and tree pits are typically small relative to catchment and infiltration is usually the dominant pathway for volume reductions. Where possible, bioretention and tree pits should be unlined to enable infiltration and support waterway baseflows.
- Satisfactory outcomes may still be achieved in slow draining soils or lined assets subject to context, design and potentially larger sizing than required for stormwater quality purposes.
- Green roofs are typically large relative to catchment and evapotranspiration is usually the dominant pathway for volume reductions. Green roofs can substantially reduce stormwater volumes from roofs.
- Current modelling approaches with MUSIC in combination with current guidelines may underestimate performance. Further calibration work is needed to support better guidance on modelling hydrologic performance. There may be opportunities to improve process modelling.
- Within or intra-event processes depend mostly on inflow patterns and inter-event processes on local climate and soil conditions for corresponding evapotranspiration and infiltration. Calibration for intra-event processes can potentially draw on data from many sources while continuous data for a local or similar climate is ideal to support inter-event process simulation.

The range of stormwater volume reduction performance of green infrastructure assets reported in the literature is shown in Table 1-1. Results for bioretention and green roofs respectively are graphed in Figure 1-1 and Figure 1-2 (tree pits were not graphed given the limited number of studies).

Table 1-1 Stormwater volume reduction performance summary

Paper ID	n	Min	Mean	Median	Max
Biofilters	29 assets 1522 events	8%	55%	59%	87%
Green roofs	55 assets 782 months	11%	50%	56%	77%
Tree pits	28 assets (only 2 studies) 18 months	5%	18%	-	44%

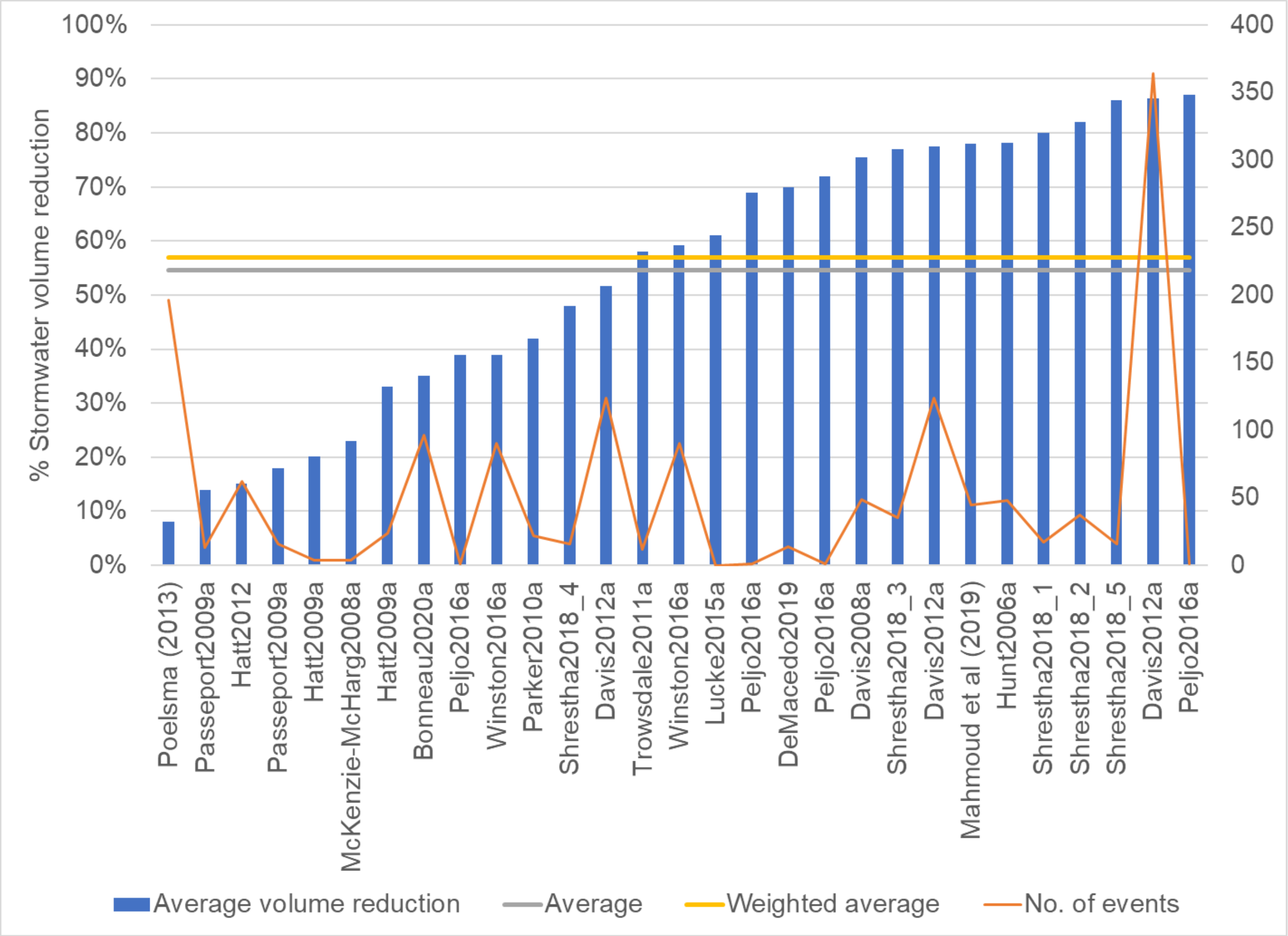


Figure 1-1 Stormwater volume reductions in bioretention

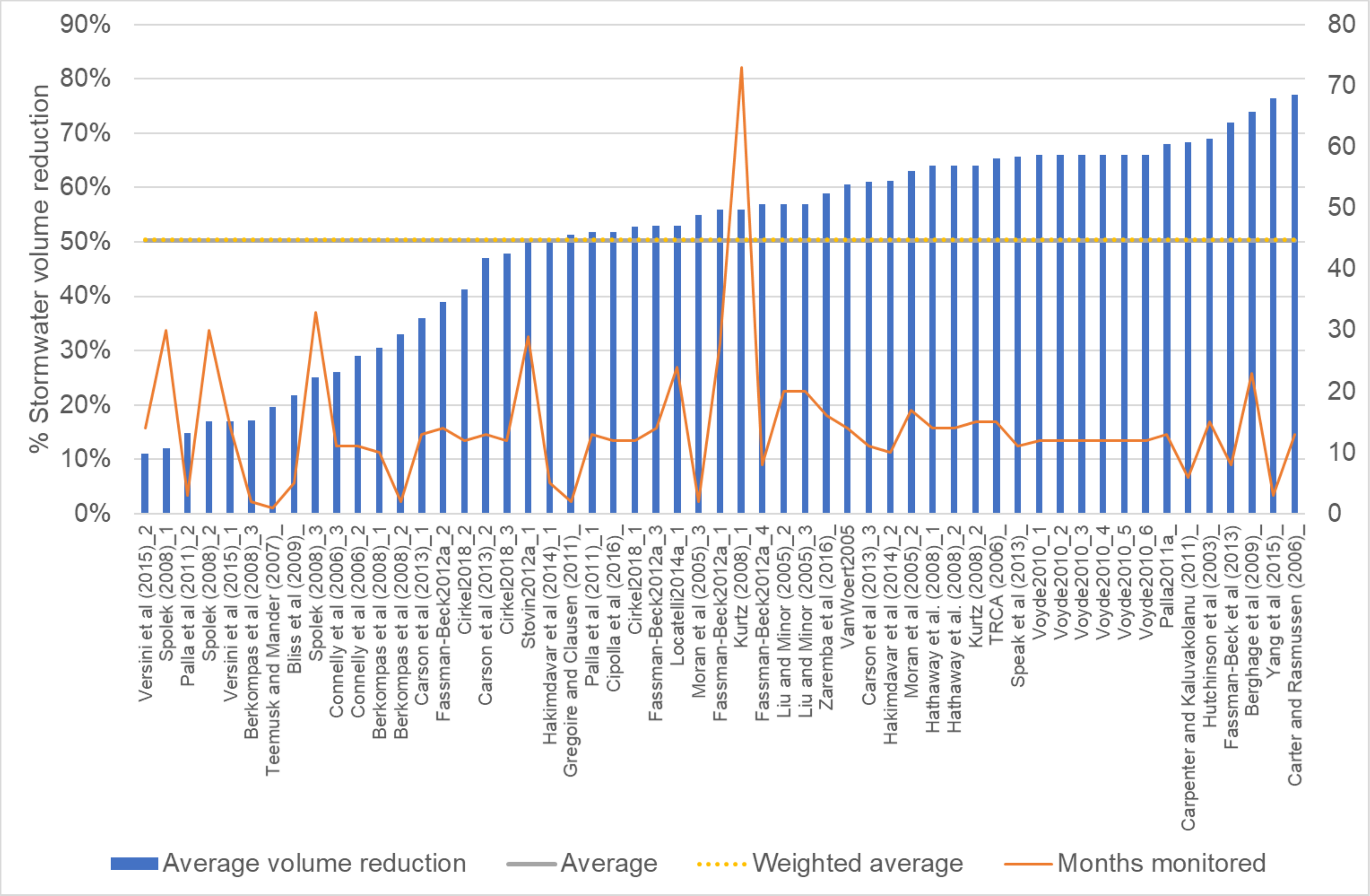


Figure 1-2 Percentage stormwater volume retained for green roof assets from a range of studies

Detailed data sets

Five Australian detailed data sets for bioretention assets were obtained through this study that have previously not been readily or publicly available. Three of these have continuously monitored data and two have event data.

A further six US data sets are publicly available from the US EPA and have previously been used for calibration of the SWMM stormwater model (Developed and maintained by the US EPA). These are mostly event data with 4-5 events per location although continuous data exists and is available for one asset for two periods of three months.

A number of other potential data sets that could not be obtained within the timeframes of the study were identified and may be pursued through future work.

Further discussions with Green Roof Diagnostics to procure data from their monitoring laboratory and follow progress for a new test site in Sydney in collaboration with Western Sydney University and Sydney Water are recommended.

The datasets have significant potential to support model calibration and validation efforts for bioretention in particular and for green roofs.

Recognised gaps

The study was necessarily limited in time and resources and the timing during the COVID-19 pandemic placed some additional constraints on sourcing data, particularly from international sources.

Gaps that can potentially be addressed through contributions from others and further study include:

- Despite the large number of studies identified and ready availability of US data aggregated at the event level (*International Stormwater BMP Database*, 2020), detailed monitoring data (hydrographs not aggregated event or site data) could only be obtained for a relatively small number of assets. There is significant potential for more data to be sourced. It is hoped the creation of a database will motivate interested researchers to come forward and contribute additional data.
- Relatively few studies monitor or measure evapotranspiration and, with a few notable exceptions (Hess, Wadzuk and Welker, 2017), it is commonly modelled or inferred. The relative split of evapotranspiration and infiltration is infrequently reported. More monitoring and standardised protocols for estimating or measuring proportions of evapotranspiration and infiltration specifically for green infrastructure based on available data would be beneficial.
- Few studies with long term (multi-year) monitored data exist and are essential for understanding long term performance. Such studies and sharing of outcomes should be a priority for future work.
- There is significant potential for additional international data to be sourced, primarily from the US and also green roof data from the UK and Europe.

- Focus was placed on bioretention and green roofs due to the much larger volume of information potentially available. Detailed data for tree pits, infiltration trenches and buffers or downspout disconnections are also desired.

Learnings for design and management

Some key outcomes and learnings with respect to design for achieving stormwater volume retention are as follows:

- To maximise stormwater volume retention, designers should seek to encourage infiltration into the adjacent and underlying soils through the use of unlined assets wherever possible. This may be through the inclusion of an *unlined* submerged zone where soil conditions allow. While improving infiltration rates, submerged zones were also found to increase evapotranspiration within an asset.
- Where possible, bioretention assets should be combined with trees within, surrounding and down-slope of the asset to encourage additional evapotranspiration of water infiltrating into the surrounding soils.
- Climate including rainfall and evapotranspiration are highly significant for green roof performance as most of water retention occurs through evapotranspiration.
- Climate factors being equal, the main influence on green roof performance is the water storage capacity.
- Passively irrigated tree pits have been less extensively studied and monitored.
- Initial studies of passively irrigated street trees indicate that:
    - Avoiding water-logging (e.g. through adequate sub-soil infiltration rates or sub-surface relief drainage) is important for tree health and survival.
    - Inlet capacity and sediment clogging are constraints on performance and effective inlet design to maximise inflows while minimising sediment influx is essential
- Outcomes for passively irrigated tree pits are comparable to those observed for Australian studies of bioretention.
- The soil and canopy areas of trees need to be considered as independent variables within modelling.
- Maintenance to manage sediment and minimise clogging is important
- Studies that have evaluated long-term design indicate that well designed and constructed assets with maintenance sustain performance in the long-term with equal or better performance relative to ‘young’ assets (which are the most commonly monitored)

Application for Western and Central Sydney

Soil conditions are a significant consideration in Western Sydney:

- The Sydney region is diverse with soil conditions ranging from heavy clays in Western Sydney through to more favourable conditions such as sandy areas adjacent to the river and coastline.
- A significant proportion of areas of interest in Western Sydney have clay soils. These may have one or more identified issues including:

  - Salinity (moderate to high risk);
  - Low infiltration rates;
  - Reactivity;
  - Dispersivity;
- Given the heterogeneity of soil conditions, actual conditions should be considered to assess potential and appropriate responses involving stormwater infiltration

Generally, infiltration is not recommended in saline landscapes due to the potential to either increase groundwater levels or transport salts resulting in impacts on infrastructure, waterways or vegetation. However, as noted by Hoban et al. (Hoban *et al.*, 2020), *this must be balanced with the greater risk of degradation of waterways posed by urban stormwater runoff*. In the Western Sydney context, reducing urban stormwater runoff is recognised as being essential for the protection of waterways such as South Creek.

The overall objective of stormwater management for volume control is to achieve waterway hydrologic conditions that approximately mimic the natural conditions. Urbanisation reduces evapotranspiration and infiltration and increases stormwater surface runoff. The larger change from urbanisation is reduced evapotranspiration. This can be mitigated through retaining or planting vegetation which is proposed in the aspirations for a parkland city and through providing this vegetation with additional water through active or passive irrigation. Infiltration from green infrastructure assets can help restore the lost infiltration which contributes to both waterway baseflows and recharging groundwater. Rainwater and stormwater reuse will likely be necessary to achieve the balance of reductions in stormwater volume to effectively protect waterways from damaging increases in stormwater volumes.

There are significant opportunities and benefits to be realised in delivering on both a parkland city and healthy waterways and at the same time difficult challenges to be overcome for stormwater practices supporting evapotranspiration to be adopted through the Western Sydney area. These are an important part of efforts to restore the natural hydrology including reducing damaging stormwater surface runoff volumes and maintaining baseflows.. Given the anticipated challenges related to infiltration in Western Sydney soils, the following recommended principles are proposed:

- Infiltration should be pursued to an extent proportional to that which would naturally occur
- Assets should be designed to maximise evapotranspiration. Larger ratios of asset to catchment size designed for stormwater volume management rather than stormwater quality management are preferable to provide broader distribution of water
- Specific soil conditions should be considered and infiltration in areas with known or high salinity risks, reactive soils close to infrastructure and dispersive soil areas shall be generally avoided or minimised
- Infiltration should be combined with vegetation where possible to provide opportunity for water to be used and to increase evapotranspiration to provide both stormwater volume reductions and latent heat fluxes to improve urban micro-climate
- Vegetation loss can contribute to salinity and revegetation and tree planting can help to address this by drawing down water tables. Future development should be complemented

with trees and vegetation to offset historical and development vegetation losses and establish a suitable hydrologic balance.

- The use of trees which can establish canopy beyond the bounds of the asset should be considered for smaller assets and design should encourage tree planting around and particularly downslope of infiltrating assets.
- Higher salinity risks are likely to occur in floodplain areas close to waterways. The use of distributed assets across a catchment is therefore preferred to infiltration in floodplain areas.
- Preference is for infiltration to be distributed and to occur over large areas rather than being highly concentrated. For example, distribution over an entire lawn area would be preferable to concentration into a small raingarden and the use of several smaller assets preferred over a single end of line asset.

Next steps

The following next steps are planned:

- Stakeholder engagement
    - Monitoring data and findings to date through a webinar or conference
    - Publish findings and data collected. This may be through a website or journal paper.
    - Summary report on calibration outcomes
    - Webinar on calibration outcomes and any new tools or models
- Model calibration and validation
    - Establish assumptions
    - Data and event selection
    - Model selection and/or development
    - Calibration and validation
- Develop tools for industry to better assess stormwater retention for green infrastructure assets
- Recommend performance outcomes based on data interpretation
- Inform planning decisions

2. Introduction

Urbanisation increases the frequency, volume and magnitude of urban stormwater flows and pollutant loads. Flood management practices are shifting focus from peak flow rates to managing storm event volumes to more effectively reduce flood risks. Waterway improvement efforts are broadening efforts from just improving water quality to reducing stormwater volumes to manage the hydrologic impacts of urbanisation. There is also increased recognition of the need to restore a more natural hydrology with water retained within the landscape to support plants and trees for urban greening. This improves amenity, reduces demands on water for higher performing landscapes and improves urban micro-climate. It is recognised that efforts across the catchment at all scales from lots through to streetscapes and larger regional measures are needed to deliver reduced flood risk, improved waterway health and urban landscapes that provide improved amenity, health, micro-climate and resilience to climate change impacts.

Current policies and requirements for private development drive targeted responses to meet specific objectives but credit is not provided across multiple objectives leading to separate design processes and constructed assets. This is particularly the case for rainwater tanks which typically receive no credit for flood mitigation and on-site detention storages which often provide limited benefits for meeting other objectives. There is potential for multi-functional assets and combinations of assets to be designed that more effectively deliver on and receive credit for meeting a range of objectives. These include flood risk mitigation, reduced stormwater flow volumes to waterways, improved water quality, reduced potable water use and urban landscapes that provide greater amenity, health and micro-climate outcomes while being more resilient.

Sydney Water has recognised the need for improved integrated assessment approaches and has developed a methodology that enables assessment of stormwater detention and retention for assessing flood risk management as well as reduced stormwater flow volumes for waterway protection.

The fundamental principles and processes of green infrastructure influencing ‘volume performance’ of stormwater assets are reasonably well understood. However, there remain significant gaps and uncertainties in our understanding and modelling approaches. There has been limited recent synthesis of learnings and detailed monitoring data from experimental studies of green infrastructure assets and in Australia there is no comprehensive database of such studies. This is a necessary precursor to support the development of robust improved design methods and tools for the design of green infrastructure responses that deliver on objectives to manage stormwater flow volumes more effectively for flood mitigation and waterway protection.

2.1 Purpose

This project proposes to identify, collate and synthesise available monitoring data with the objective of preparing a selected sub-set of detailed data including inflow/outflow hydrographs and other relevant information that can be used to determine the key explanatory variables for volume performance and for the calibration of methods and tools for the design of green infrastructure to achieve stormwater volume related objectives.

The data and learnings collected will also be used to inform planning and practice for green infrastructure responses to manage stormwater volumes.

2.2 Navigating this report

A guide to help readers find relevant information within the report is provided below.

Table 2-1 References to relevant sections

	General	**Biofilters**	**Green roofs**	**Tree pits**
What is green infrastructure? Textbook design and processes	4.1 Green infrastructure processes	3.1 Overview 4.2 Processes	3.2 Overview 4.3 Processes	3.3 Overview 4.4 Processes
What evidence is available? Literature evidence and interpretative comments		5.1.1 Meta studies 5.1.2 Monitoring studies 5.1.3 Infiltration and evapotranspiration 5.1.4 Influencing factors and design 12.2 Evapotranspiration	5.2.1 Meta studies 5.2.2 Monitoring studies 5.2.3 Evapotranspiration and storage 5.2.4 Influencing factors and design 13.1 Paper summary	5.3.1 Meta studies 5.4 Monitoring studies 5.5 Infiltration and evapotranspiration
Show me the data: Volume performance data	Appendix D – Sample data	5.1.2 Monitoring studies	5.2.2 Monitoring studies	5.4 Monitoring studies
Show me the detail: Detailed data	6 Detailed data sets	Table 6-1 Detailed data summary 6.1 Monash car park 6.2 Wicks Reserve 6.3 Hereford Road 6.4 Clifton Hill 6.5 Wakerley 6.6 Graham 6.7 Villanova 6.8 Kfar-Saba	Table 6-2 Detailed data summary 6.9 Hamilton West 6.10 Emergency Operations Centre 6.11 Fire station 10 6.12 Green Roof Diagnostics	Table 6-3 Detailed data summary 6.13 Monash 6.14 Barrow St
Modelling		7.1 Models and calibration	7.2 Models and calibration	7.3 Models and calibration
Implications for Western Sydney	8			

3. Green infrastructure

This study focusses on the most common types of green infrastructure likely to be adopted at the lot scale. Rainwater tanks and on-site detention tanks were not specifically addressed as it is considered these are already well understood. The following green infrastructure asset types were considered:

- Bioretention (raingardens)
- Green roofs
- Tree pits
- Infiltration
- Simple green buffer strips

Focus was subsequently placed on bioretention and green roofs due to the more limited data availability for the remaining asset types while tree pits were also covered to a more limited extent.

This chapter provides:

- Overview of each asset type and configuration
- Outline of general green infrastructure key processes
- Relevant key processes for each asset type

3.1 Bioretention

Bioretention assets (also known as biofilters and raingardens) are vegetated assets that store and filter runoff from a catchment. Stormwater that enters a bioretention asset ponds on the surface (the depth of ponding is often called extended detention depth or EDD) and infiltrates into the filter media. When the ponding depth or EDD reaches the overflow weir, overflow occurs with stormwater bypassing the filter media. Water infiltrating into the media may then either flow out an underdrain, be evapotranspired or infiltrate into surrounding soils.

A bioretention asset typically consists of:

- A surface pond
- A filter media layer
- A transition layer and drainage layer (may also be a submerged zone)

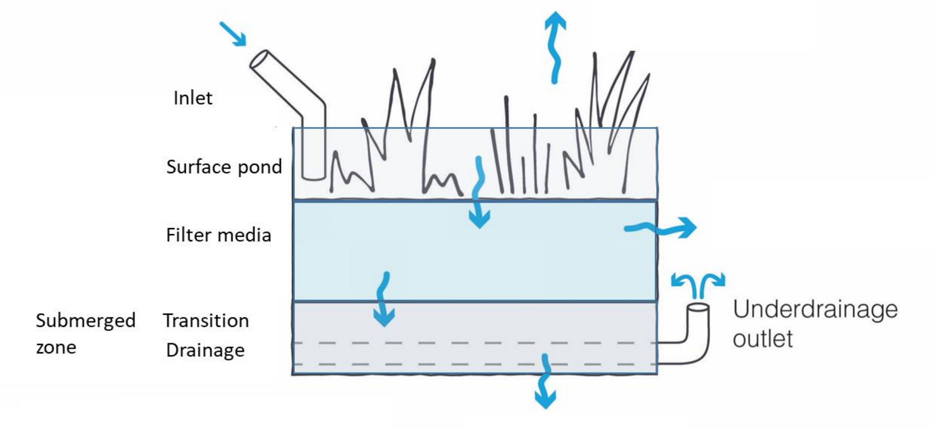


Figure 3-1 Schematic of a typical biofilter or raingarden

The filter media helps to improve the water quality as stormwater passes filters through. The transition media keeps the filter media from washing into the drainage layer, a gravel layer that usually contains underdrainage connected to an outlet pipe. The underdrainage may drain the entire bioretention system or it may up-turn to create a submerged zone within the bottom of the asset. In this case, water will fill the submerged zone (including the drainage layer and transition layer) of the bioretention before draining out through the underdrainage.

Bioretention assets may be lined with an impermeable liner, to prevent the infiltration of water. This is common in harvesting schemes where the treated water is captured as a resource or where infiltration is undesirable due to proximate infrastructure or adverse soil conditions. However, for bioretention systems designed for stormwater retention, an unlined system is desirable where possible as it allows infiltration.

Bioretention assets may be configured in different ways with common variations including:

- Bioretention with no underdrainage and infiltration
- Bioretention with underdrainage and infiltration
- Bioretention with underdrainage and lining
- Bioretention with underdrainage, infiltration and submerged zone
- Bioretention with underdrainage, lining and submerged zone

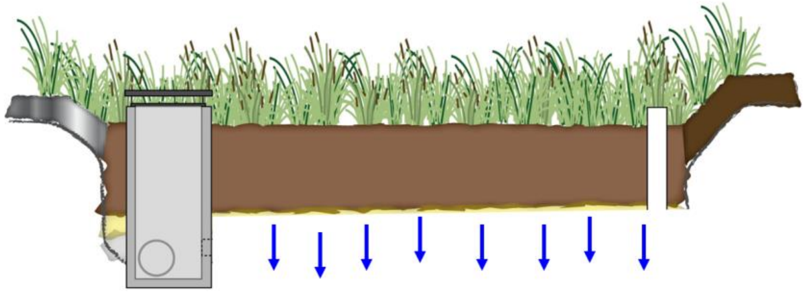


Figure 3-2 Bioretention with no underdrainage and infiltration

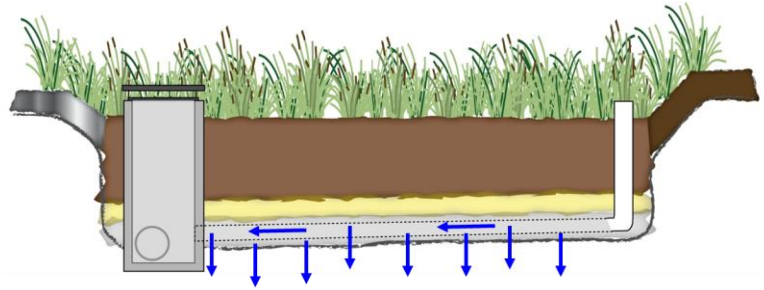


Figure 3-3 Bioretention with underdrainage and infiltration

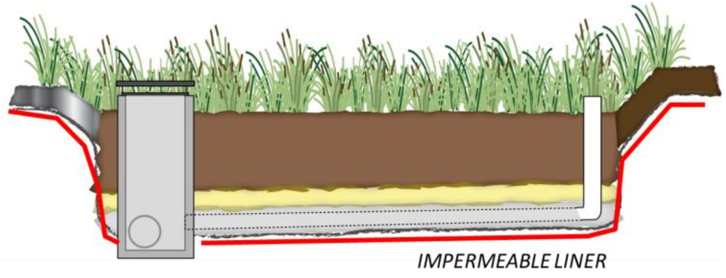


Figure 3-4 Bioretention with underdrainage and lining

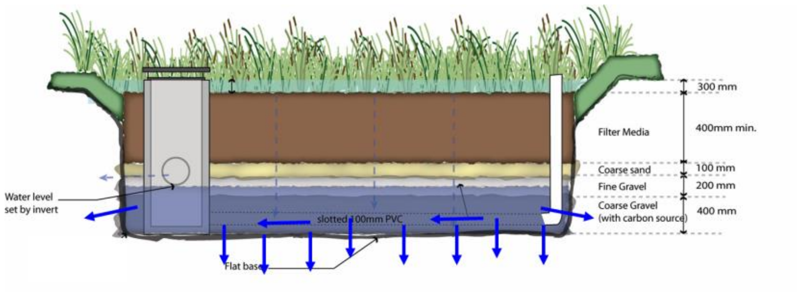


Figure 3-5 Bioretention with underdrainage, infiltration and submerged zone

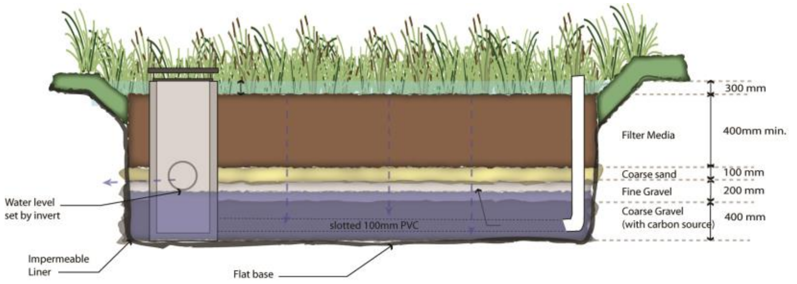


Figure 3-6 Bioretention with underdrainage, lining and submerged zone

3.2 Green roof configuration

Green roofs represent vegetated surfaces constructed on the roof of a building or structure. Generally, green roofs only receive water from the rain that falls directly onto the surface, however in some cases there may be small catchments of impervious roof that drain to a vegetated green roof. Typically, green roofs consist of:

- Vegetation
- A substrate layer
- A drainage layer

Vegetation suitable for green roofs can vary with a range of factors including local climate, green roof depth and expected wind speeds. The substrate layer represents the soil media which infiltrates water. The substrate allows the vegetation to develop roots and stores moisture to support plant growth and evapotranspiration. The drainage layer allows water to drain away from the roof when the substrate layer reaches saturation. This usually includes an overflow system to prevent surface ponding of water.

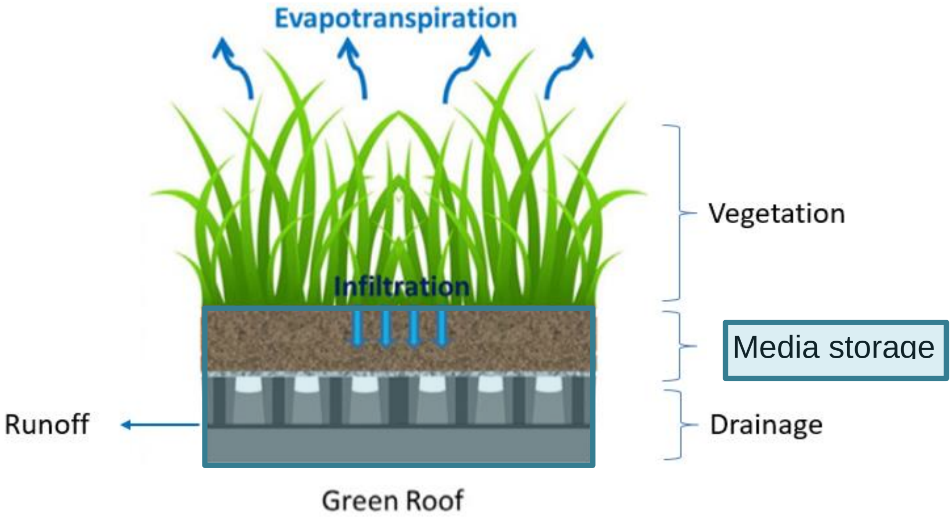


Figure 3-7 Green roof elements and processes adapted from (Ebrahimian, Wadzuk and Traver, 2019)

Green roofs are typically classed as either extensive or intensive and can be defined as follows (Mentens, Raes and Hermy, 2006):

- Extensive green roofs contain a substrate layer of up to 150 mm and typically dry tolerant plants species such as sedum.
- Intensive green roofs contain a substrate layer with a depth of more than 150 mm and typically with vegetation such grasses, perennial herbs and shrubs. The roof slope is usually less than 10% and they may be used as roof gardens.

Extensive roof gardens are more common as they can often be installed on existing rooftops without the need for additional structural considerations. The extra weight of an intensive green roof is often result in impractical to retrofit onto an existing building.

Figure 3-8 - Extensive green roof in Portugal (European Federation of Green Roof Assocations, 2020)

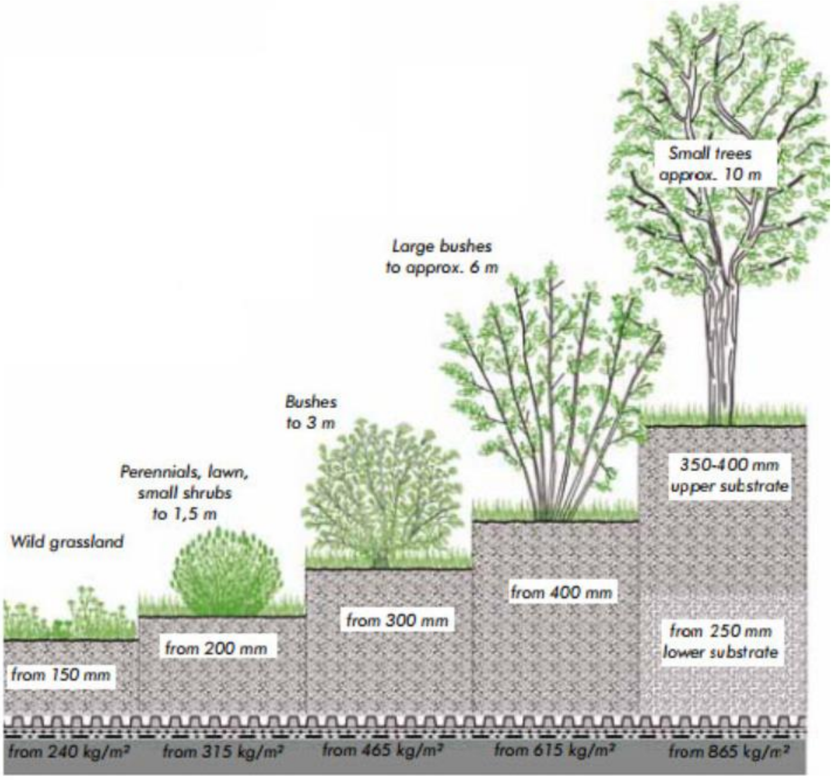


Figure 3-9 - Intensive green roof schematic (Myrroof.com, 2019)

3.3 Passively irrigated tree pits

Tree pits that are passively irrigated with stormwater (passively irrigated tree pits) are similar to bioretention or raingardens but typically contain one or more trees. The differences are not always clear cut. For the purposes of differentiation in this report, passively irrigated tree pits will be classified as any asset where the vegetation predominantly consists of a tree while assets with a mix of vegetation including small trees will be considered bioretention.

Stormwater that enters a passively irrigated tree pit ponds on the surface and infiltrates into the filter media or tree planting soil. If ponding exceeds the extended detention depth then either overflow into a pit or more commonly back-watering of the inlet occurs, which causes flows to bypass down the adjacent gutter.

A passively irrigated tree pit typically consists of:

- The ponding depth or extended detention depth
- A filter media or tree planting soil layer
- A transition layer and drainage layer or zone (may also be a submerged zone)

The filter media helps to improve the water quality as stormwater passes filters through. The transition media keeps the filter media from washing into the drainage layer, a gravel layer that usually contains a collection pipe. This pipe may drain the entire asset or it may up-turn to create a submerged zone within the bottom of the system. In this case, water will fill the submerged zone of the tree pit before draining from the collection pipe.

Tree pits are preferably not lined to allow the tree roots to extend beyond the confines of the pit and access surrounding soil and water. This greatly improves the long-term growth and survival prospects for the tree and reduces the risk of being blown over by wind. Lining of the tree pit may occur in limited situations such as trees on podium or surrounded by other infrastructure. Infiltration may be constrained in some areas due to soil conditions.

Tree pits may be configured in different ways with common variations including:

- Tree pit with open surface and inflow from kerb
- Tree pit with grated lid and inflow from kerb
- Tree with adjacent underground infiltration trench
- Tree with inlet pipe and inflow from kerb

Images of a range of constructed tree pits are shown in Figure 3-11.

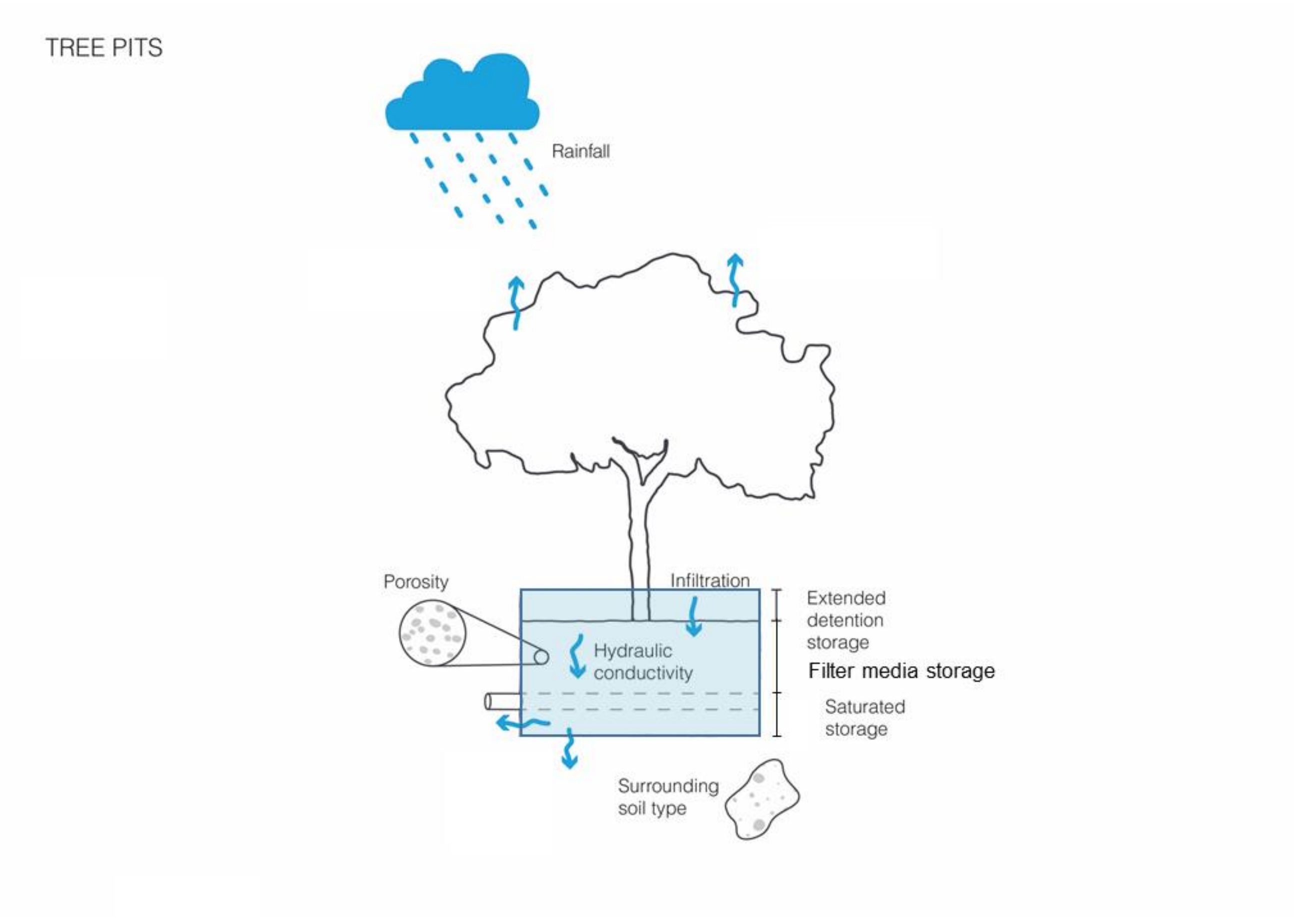


Figure 3-10 – Schematic of a typical tree pit

Figure 3-11 – Examples of tree pits

4. Water retention processes and pathways

4.1 General water retention processes and pathways

The key processes for stormwater runoff volumes to be reduced through green infrastructure assets are generally some or all of the following, see Figure 4-1.

- Storage of water
- Infiltration
- Evapotranspiration

The relationship of these key processes to basic functionality of green infrastructure assets are described briefly below. The key processes with respect to each asset type are discussed within the subsequent sections.

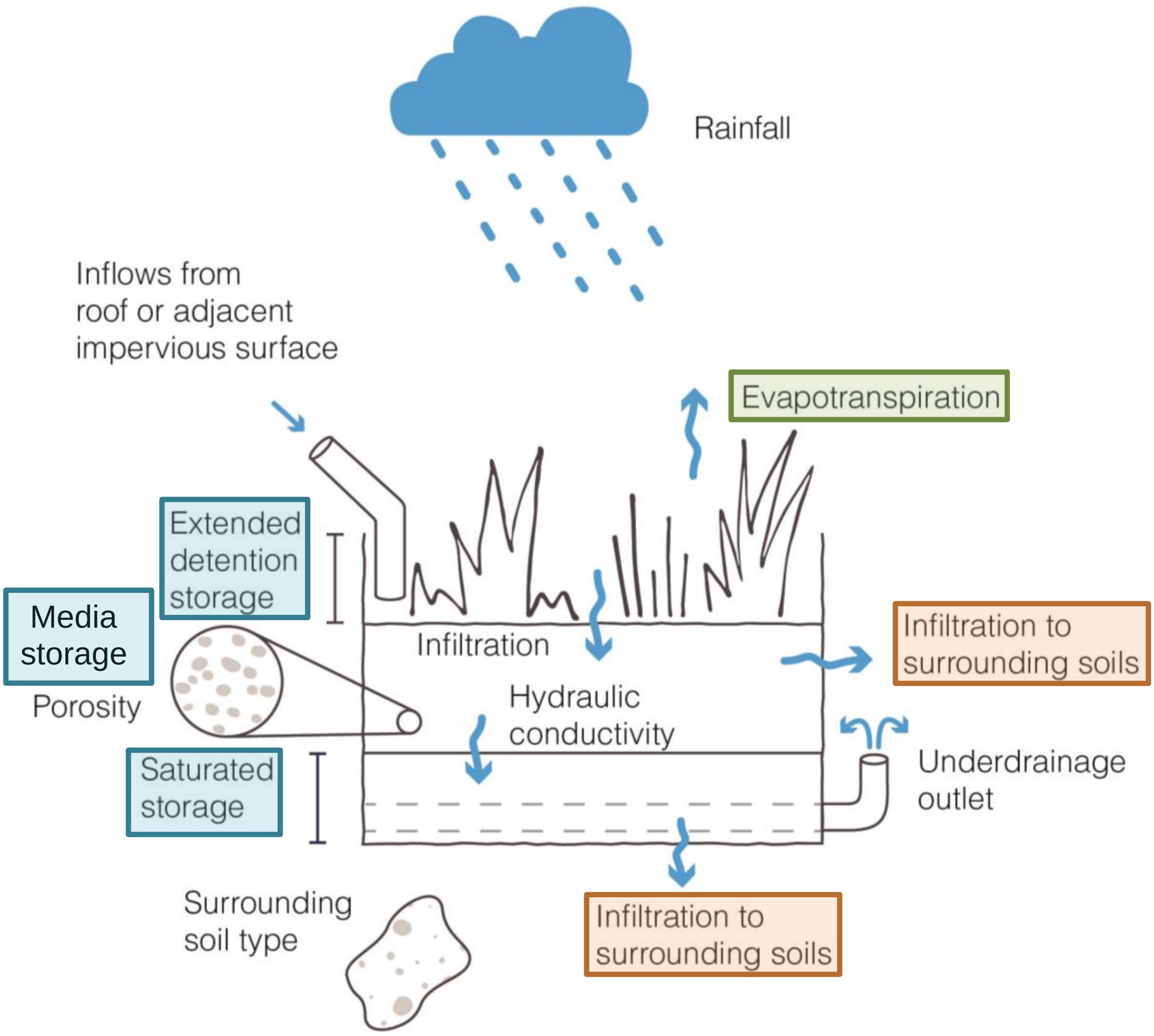


Figure 4-1 Flow processes for a typical green infrastructure asset

4.1.1 Storage of water

Water storage within in an asset generally refers to the capacity to which an asset can detain runoff volume during a storm event, before triggering overflow. The main influencing factors for an asset's water storage include:

- Extended detention depth (EDD). Extended detention depth describes the depth of 'ponding' that can occur on the surface of the asset before overflow occurs. For bioretention, tree pits and infiltration systems there is often an EDD between 0.2-0.4m provided. Green roofs and buffer strips often have no or minimal provision for EDD.
- Soil moisture. The moisture level of the soil before a rain event determines the volume of water than can be 'absorbed' by the asset's soil media. The ability for soil to absorb water also depends on the media characteristics, in particular pore volume. The larger the pore volume,

the more freely water will move through the media (note: media that is too freely draining may be unlikely to support vegetation through dry periods).

- Submerged zone. A submerged zone (also called a saturated zone) is created when the underdrain of an asset is elevated above the base of the asset, creating an area at the base of the asset where water can accumulate. Water may only exit the submerged zone via infiltrating into the surrounding soil, which can be a slow process depending on the is-situ soils or capillary rise to the soils above. This means water content will increase to saturation during events and store additional water in the asset. This additional water can then be accessed by plants through capillary rise to the overlying filter media. A submerged zone that is unlined provides additional storage and time for water to infiltrate to underlying soils.

4.1.2 Infiltration

Infiltration describes the process by which water ‘seeps’ into the in-situ soils surrounding an asset. It can also be used to describe the process by which runoff initially enters through the surface of the asset itself. Infiltration rates are influenced by the hydraulic conductivity of a soil media (how freely water can move through a soil), the head (or pressure) of the water infiltrating and the initial moisture of the soil. Key points for infiltration are as follows:

- Infiltration is usually the key process for reducing runoff volumes in assets with infiltration (e.g. raingardens, infiltration trenches).
- Underlying soil conditions heavily influence infiltration rates.
- Systems located in slow draining soils can still achieve significant levels of infiltration, however storage within the system becomes critical.
- Storage in systems is critical to allow infiltration to occur without triggering overflow.

4.1.3 Evapotranspiration

Evapotranspiration describes the combined process of solar radiation causing evaporation from asset surface area and transpiration from asset vegetation, both serving to remove water from within the asset. Evapotranspiration is a complex process depending on a variety climatic, soil and vegetation characteristics. Key points for evapotranspiration are as follows:

- Evapotranspiration is the only stormwater retention pathway for green roofs and other fully lined assets.
- Evapotranspiration plays an important role in reducing soil moisture content between events – making water storage available within soil media.
- Vegetation can reduce the moisture content of the root zone to wilting point and begin to use water from the submerged zone via wicking and capillary processes.
- Evapotranspiration is influenced by the extent and shape of vegetation and the amount of water it uses. For trees, the canopy area may be used as the indicative evaporative surface.
- Vegetation roots play an important role in maintaining the porosity of the system media, promoting infiltration pathways and combating the ‘clogging’ effect of fine sediments.

4.2 Bioretention water retention processes and pathways

Using the general approach established previously, the key water retention processes and pathways relevant for bioretention systems are shown in Figure 4-2 and outlined below.

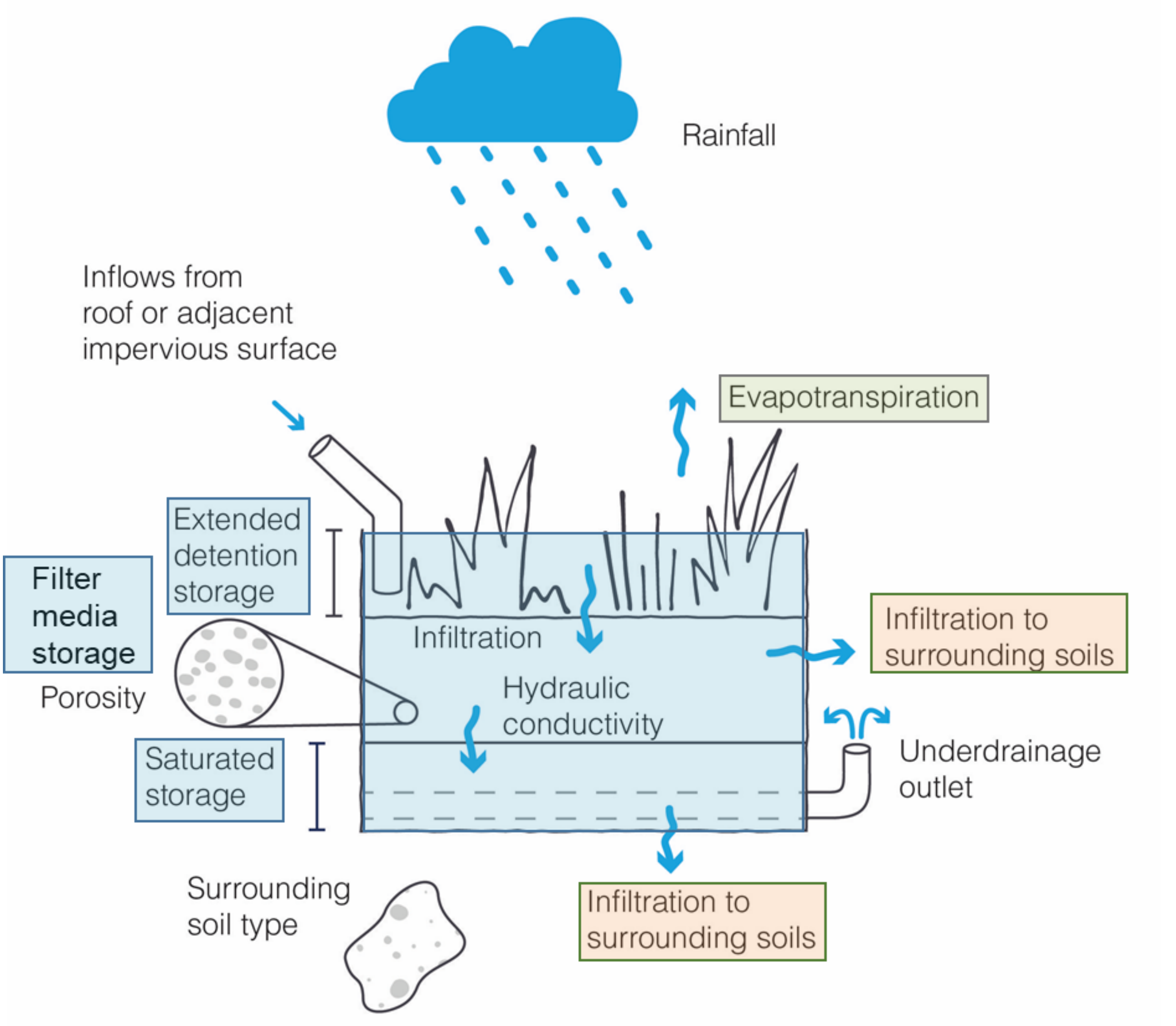


Figure 4-2 Flow processes for a bioretention or raingarden

- **Storage of water**

Storage in a bioretention typically occurs in the extended detention volume, soil media moisture and submerged zone where present. The moisture content of a bioretention media varies between wilting point and saturation. Wilting point represents 'dry' conditions for a certain media type (i.e. vegetation cannot withdraw more moisture from the soils). Saturation represents the situation when pore spaces between the soil are completely filled with water. A bioretention assets below ground storage depends on the temporal availability of its pore space to hold water. A submerged zone (also called a saturated zone or saturated anoxic zone) promotes retention by restricting outflow from the base of a bioretention – in effect a 'below ground extended detention'. Vegetation roots play an important role in maintaining the porosity of the system media, promoting infiltration pathways and combating the 'clogging' effect of fine sediments.

- **Infiltration**

Infiltration is the key process for significantly reducing runoff volumes. Underlying and adjacent soil conditions influence infiltration rates, however systems located in slow draining soils can still achieve significant levels of infiltration. In this case, storage within the system becomes critical, in particular a submerged zone which provides time for infiltration to occur. The presence of a SAZ may also increase infiltration rates into surrounding soils through increased head on the system base and by engaging the sides of the SAZ to increase infiltration surface area.

- **Evapotranspiration**

Evapotranspiration plays an important role of reducing soil moisture content between events – making below ground storage available. Vegetation can reduce the moisture content of the root zone to wilting point and begin to use water from the submerged zone via wicking processes (i.e. drawing water upwards).

4.3 Green roof water retention processes and pathways

Using the general approach established previously, the key water retention processes and pathways relevant for green roofs are:

- Storage of water

Storage in a green roof typically occurs in the substrate soil media. Typically, there is no extended detention depth above the surface of the substrate. Similar to bioretention systems, the moisture content of a green roof varies between wilting point and saturation. Wilting point represents ‘dry’ conditions for a certain media type (i.e. vegetation cannot withdraw more moisture from the soils). Saturation represents the situation when pore spaces between the soil are completely filled with water. A green roof’s storage depends on the temporal availability of its substrate pore space to hold water.

- Evapotranspiration

Evapotranspiration is the only process active in a green roof to remove water from the soil substrate. Unlike bioretention systems, infiltration into surrounding soils is not characteristic of green roofs. Vegetation reduces the moisture content of their root zone to wilting point. Wind can play an important role in the evaporative process in green roofs, as they tend to have higher wind exposure due to their positioning at the top of buildings.

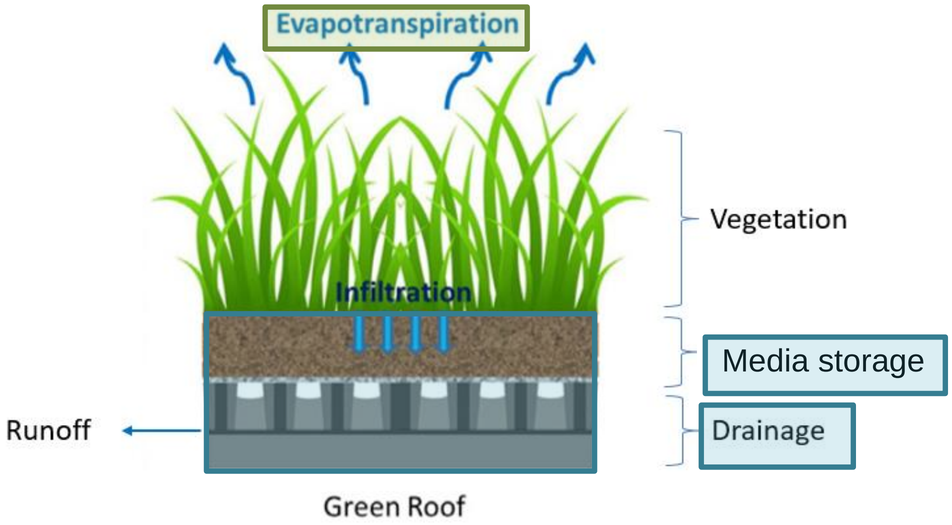


Figure 4-3 Green roof processes adapted from (Ebrahimian, Wadzuk and Traver, 2019)

4.4 Passively irrigation tree pit water retention processes and pathways

Water retention processes and pathways are as outlined for a bioretention in Section 4.2. Established tree-pits with mature trees can also expect to retain rainfall through interception in the canopy. In studies of mature eucalyptus at Melbourne University's Burnley campus, this canopy interception was found to reduce rainfall reaching the ground by 45% (Livesley, Baudinette and Glover, 2014). This is a significant reduction for the canopy area, however for standard tree-pits, the canopy area is a small percentage of the total catchment area. Also, canopy interception is only a significant factor when the tree has a mature canopy.

The key difference for tree pits is that the surface area over which evapotranspiration can occur is the canopy area of the tree which is often larger than the surface area of the tree pit. As noted above the size of canopy only gain significance as the tree matures. The area of filter media or dedicated soil may also be larger than the surface area. This may also include structural soils that allow for tree roots to expand beyond the tree pit.

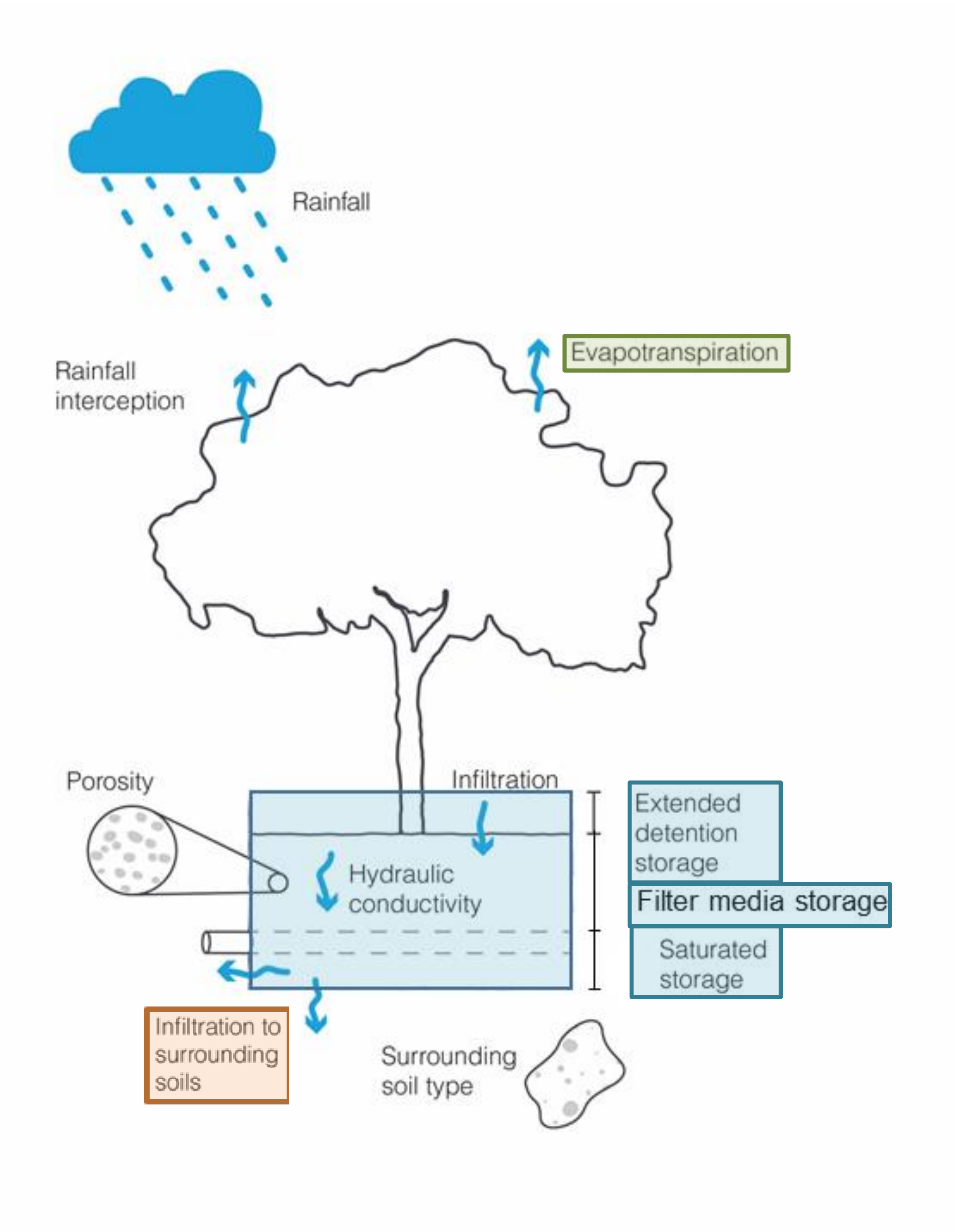


Figure 4-4 – Schematic of a typical tree pit

5. Literature review

A literature review was undertaken to identify studies quantifying performance of green infrastructure and potential sources of detailed data for model calibration and validation. The following green infrastructure asset types were reviewed:

- Bioretention (raingardens)
- Green roofs
- Tree pits
- Infiltration
- Simple green buffer strips

Focus was placed on bioretention and green roofs as these are the most important assets and data availability was more limited for other asset types. Tree pits were also covered to a more limited extent.

This chapter provides:

- Overview of identified meta-studies collating data from a range of studies
  - Bioretention: 5.1.1
  - Green roofs: 5.2.1
  - Tree pits: 5.3.1
- Overview of monitoring studies identified and key performance outcomes
  - Bioretention: 5.2.2
  - Green roofs:
  - Tree pits:
- Discussion of relative contributions to stormwater volume reductions
- Implications for design

5.1 Bioretention

5.1.1 Bioretention meta-studies

There are several meta-studies (the process of compiling and comparing the results of various experimental studies) that explore the effectiveness of bioretention systems for stormwater detention. One of the most substantial studies in Australia to date was undertaken by Hoban and Gambirazio (2018). The meta-study found the weighted average reduction volume bioretention assets achieved was 60%. It is noted that 48 of the 128 events were for the monitoring study with the largest volume reductions and in this study 1 out of 11 runoff events produced a bypass overflow that was not accounted. Nevertheless, the outcomes are generally promising. Results from this meta-study are summarised in Figure 2 7.

The study makes a key observation that current modelling practices in Australia (using MUSIC) appear to significantly underestimate likely stormwater volume reductions from bioretention relative to the observed data. It is unclear to what extent this is due to any issues with the model itself and the extent to which it is due to adoption of guideline recommendations. Typical recommendations for infiltration are highly conservative and to test the model itself, comparison needs to be made between observed data and model results with model parameters selected for the conditions and preferably calibrated.

At present there are very few calibration studies for MUSIC for bioretention. However, it is fair to say that using existing models and guidelines, performance is likely to be underestimated. While this is conservative it should be scientifically based and not adversely ‘rule-out’ options that would be viable with more accurate analysis as argued by Hoban and Gambirazio (2018).

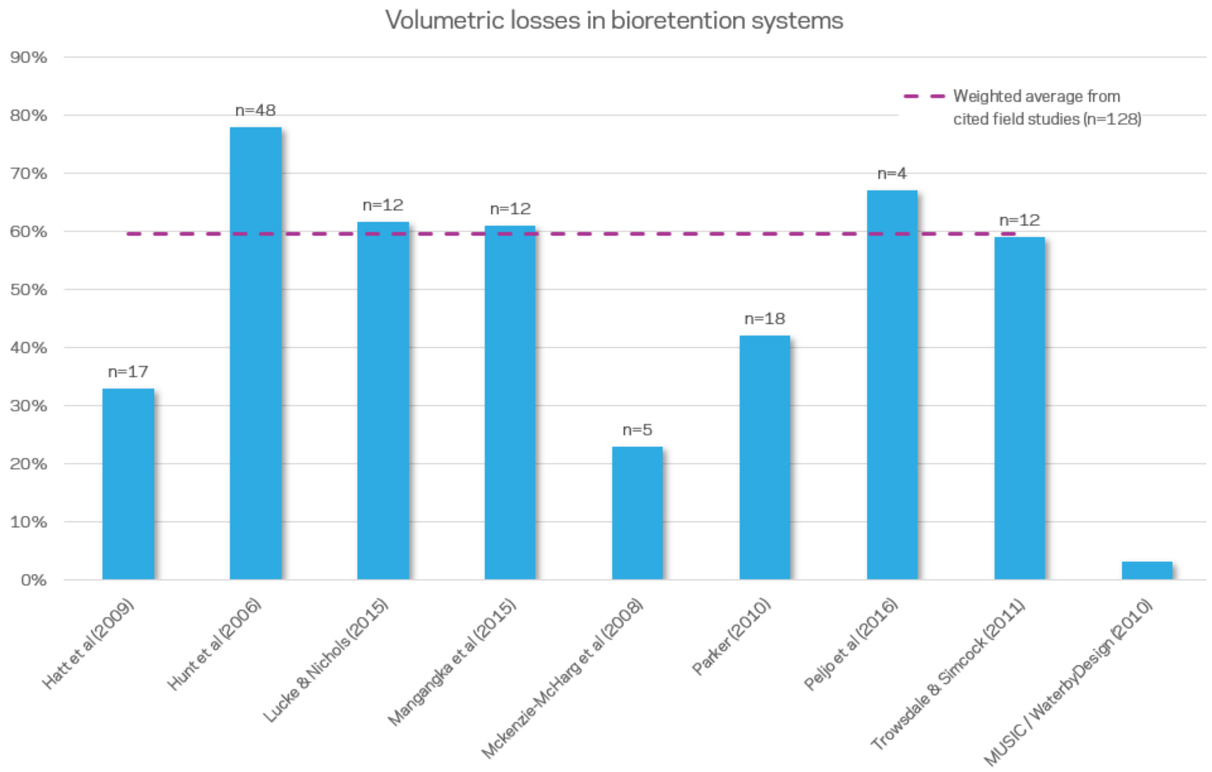


Figure 5-1 Volumetric losses in bioretention (Hoban and Gambirazio, 2018)

In the USA, water sensitive urban design (WSUD) is typically referred to as Low Impact Design (LID) and a corresponding asset is referred to as a ‘Best Management Practice (BMP). Internationally, the BMP database (*International Stormwater BMP Database*, 2020) contains extensive data on a range of BMP’s including bioretention. It focusses on *quality* performance, but much less so on *retention* performance. One study did assess retention performance across a range of assets (Poresky *et al.*, 2012). The International BMP database is maintained through a collaboration supported by EPA, other government stakeholders, the Water Research Foundation (a not for profit organisation dedicated to research and education related to water) and several consultants.

The average stormwater retention performance for studies assessed was 56% for assets with underdrains and 89% for assets with no underdrains. This result clearly shows the importance of considering biofilter configuration in assessing potential performance.

An assessment was made of the potential statistical relationship at a high level between volume reduction and treatment to catchment area ratio. The results were inconclusive, clearly showed that other variables were significant and that treatment to catchment area ratio alone was not sufficient. This is not surprising given evidence within this and other studies (Davis *et al.*, 2012) that design configuration and other factors significantly influence performance. It is apparent that a fairly sophisticated statistical analysis would be needed to develop statistical relationships and this is likely to be further challenged by differences in study approaches, assumptions and limitations. In this study we do not attempt to establish statistical relationships but there is potential for this to be pursued using the data collated.

Davis (Davis *et al.*, 2012) reviewed a selection of assets and performance data in the US and developed a range of equations to estimate volumetric performance for events. They also found that there were wide differences between system performance for different configurations. The configurations considered included bioretention systems with:

- No underdrainage (Figure 3-2)
- Underdrainage (Figure 3-3 and Figure 3-4)
- Underdrainage with (unlined) submerged zone (Figure 3-5)
    - Slow draining soils
    - Quick draining soils

The paper also found that a fairly clear threshold of potential capture emerged. Event inflow volumes reached this threshold before outflow occurred in the majority of events followed by a linear relationship between inflow and outflow, see Figure 5-2.

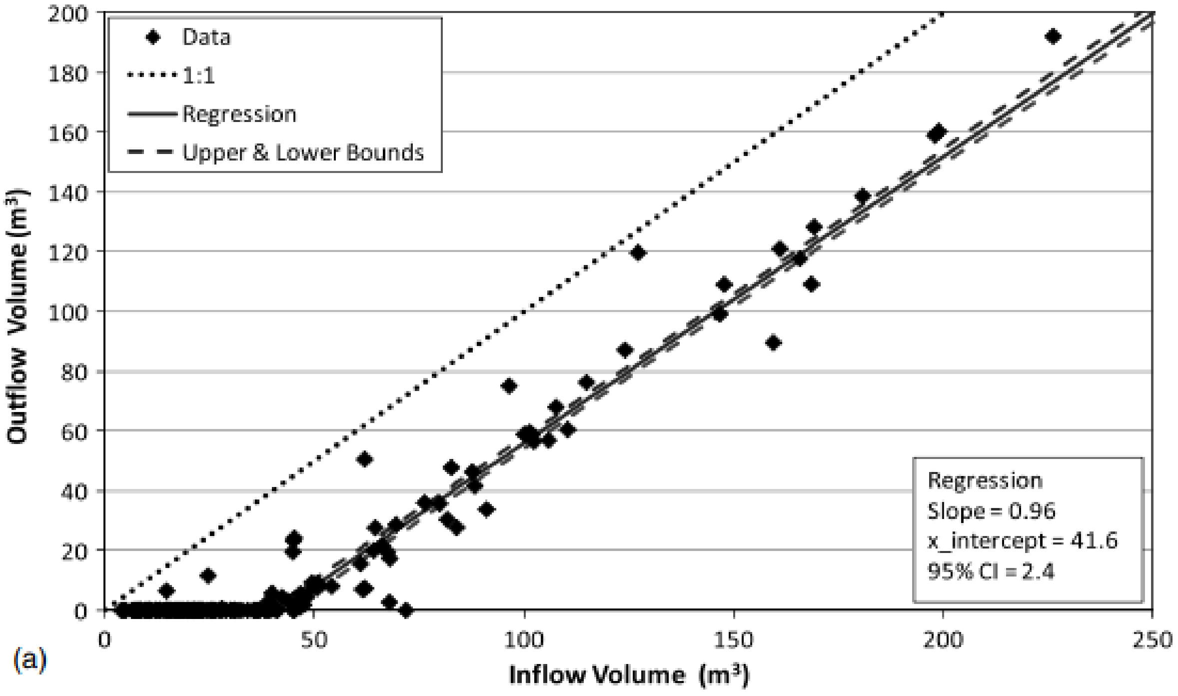


Figure 5-2 Relationship between inflow and outflow (Davis *et al.*, 2012)

5.1.2 Bioretention monitoring studies

This section explores the results for bioretention papers identified that contained experimental results from monitoring campaigns. A tabulated summary of papers is provided in Appendix A – Bioretention Bioretention paper summary

Table 12-1. Briefly, the following were reviewed and outcomes collated:

- 8 monitoring studies
- 43 bioretention assets
- 29 bioretention assets either reported or had data allowing calculation of stormwater retention performance

The stormwater retention performance, calculated as a percentage of monitored inflows, is summarised in Figure 5-3 for the 29 assets for which data was available. This metric was selected as the simplest and most commonly reported metric of performance. It is recognised that other metrics may also be considered and provide further insight into asset performance and behaviour. The results contained significant variations in performance as shown in Table 5-1.

Table 5-1 Bioretention stormwater volume reduction performance summary (% of inflow volume)

Assets	n	Min	Mean	Median	Max
Bioretention	29 assets 1522 events	8%	55%	59%	87%
Bioretention (Australia)	12 assets 412 events	8%	42%	37%	87%
Bioretention (Lined)	10 assets 206 events		58%		

A summary of key parameters and stormwater volume reduction outcomes is provided in Table 5-2.

This table is also available in a spreadsheet in the Supplementary Information to this report, see Figure 5-4 in:

- Spreadsheet: StormwaterVolumeReductionsSummary_20210210Version1.2.xlsx
    - Sheet: AssetSummary
    - Graph output sheet: VolumeReductions

A user may access a summary or expanded information and can filter the table by various parameters using the drop-down arrows to assess stormwater retention performance for subsets of data of interest. For example, data for assets with or without lining or a submerged zone or with certain soil types may be selected to evaluate potential performance for a given configuration of interest.

An indicative graph of the selected subset of data is provided in the sheet ‘VolumeReductions’.

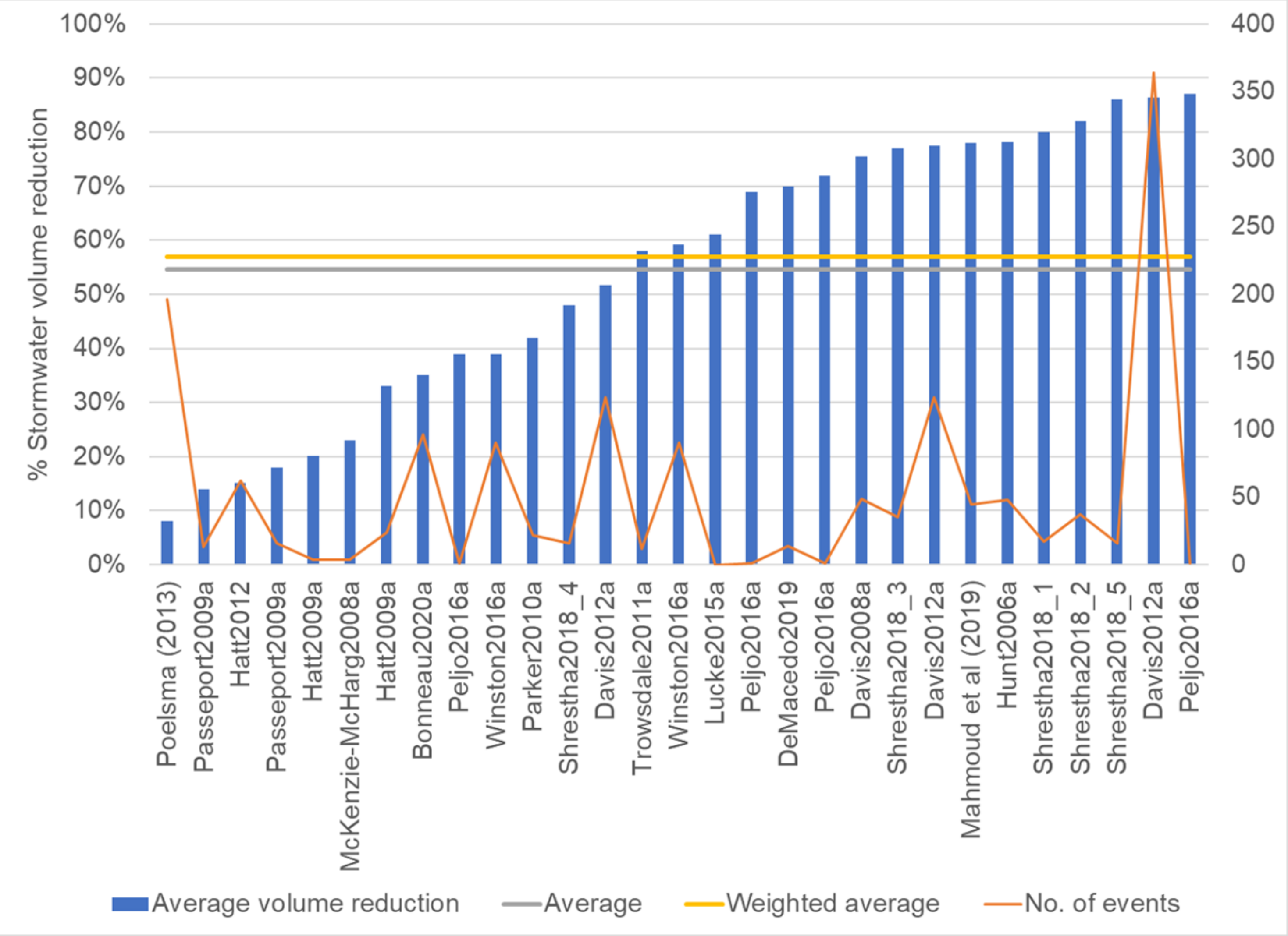


Figure 5-3 Stormwater volume reductions in bioretention

Table 5-2 Bioretention assets with stormwater retention reported

Author	Year	Asset location	Length of monitoring (months)	No. of events monitored	Mean annual rainfall (mm/year)	Catchment area (m^2)	Impervious fraction	Treatment area (m^2)	EDD (m)	Filter media (m)	Transition layer (m)	Drainage layer (m)	Submerged zone (m)	Lined (Y/N)	Underlying soil	Overall retention (%)
Bonneau2020a	2020	Melbourne, VIC	36	96	730	330000	15%	1800	0.35	0.8	0.15	0.35	0.5	N	Heavy clay	35%
Davis2008a	2008	Maryland, US	24	49	1070	2500	100%	52.8		1	-	-	-	N	-	75.5%
Davis2012a	2012	Maryland, US	Began 2007	124	1070	1836	85%	102	0.3	0.9	-	Underdrain	-	N	Clays	77.5%
Davis2012a	2012	North Carolina, US	Began 2008	124	1140	2200	76%	146	0.16	1.1	-	Submerged Zone	0.7	N	Sandy Loam	86.4%
Davis2012a	2012	Villanova, US	Began 2004	124	1040	5261	50%	149	0.25	1.2	-	No underdrain	-	N	Loam (50% sand 20% clay)	51.6%
de Macedo2019	2019	San Carlos, Brazil	36**	14	1361.6	23,000	25%	60.6		0.5	0.7	2 No underdrain	2.7	N	NR	70%
Hatt2009a	2009	McDowall, Qld	N/A	4	1140	1000	100%	20	0.2	0.4	0.1	0.2	-	Y	-	20.1%
Hatt2009a	2009	Monash University, Vic	6	17	680	4500	100%	45	0.25	0.5	-	0.2	-	Y	N/A	33.0%
Hatt2012	2012	Melbourne, VIC	9	62	650	73000	40%	200	0.175	0.4	0.1	0.15	-	Y		15%
Hunt2006a	2006	NC, USA	12	11	1096	2000	-	100	-	1.2	0	0	-	N	Clay Loam	78.2%
Lucke2015a	2015	Sunshine Coast, QLD	N/A	4	1140	58	-	9	0.1	0.9	0.1	0.2	-	Y		62%
Mahmoud2019a	2019	McAllen, Texas	13	45	526.5	1619	100%	55	0.3	0.76	-	0.15	-	Y*	-	78%
McKenzie-McHarg2008a	2008	McDowall, QLD	N/A	4	1140	-	-	20	-	-	-	-	-	-	-	23%
Parker2010a	2010	Coomera Waters, Qld		22	1320	6530	52%	250	0.1	0.8	0.2	0	-	N	Silts	42%
Passeport2009a	2009	North Carolina, US	12	16	1140	3450	40%	102	0.23	0.6	-	0.15	0.45	N	Loamy clay	18%
Passeport2009a	2009	North Carolina, US	12	13	1140	3450	40%	102	0.23	0.9	-	0.15	0.75	N	Sandy Loam	14%
Peljo2016a	2016	Caloundra, Qld	N/A	1	1686	1550	NR	10.9	0.2	0.6	0.1	0.2	-	N	Sand/sandy loam	69%
Peljo2016a	2016	Caloundra, Qld	N/A	1	1686	320	NR	14.5	0.2	0.6	0.1	0.2	-	N	Sand/sandy loam	39%
Peljo2016a	2016	Caloundra, Qld	N/A	1	1686	1210	NR	13.5	0.2	0.6	0.1	0.2	-	N	Sand/sandy loam	72%
Peljo2016a	2016	Caloundra, Qld	N/A	1	1686	290	NR	15.8	0.2	0.6	0.1	0.2	-	N	Sand/sandy loam	87%
Poelsma2013	2013	Melbourne, Vic	9	196	997	9,800	100%	100	0.3	0.4	0.2	0.4	0.9	N	Heavy clay	8%
Shrestha_1	2018	Burlington, US	15	17	934	40	100%	3.72	0.15	0.61	0.08	0.23		Y	-	80%
Shrestha_2	2018	Burlington, US	15	37	934	33	100%	3.72	0.15	0.61	0.08	0.23	-	Y	-	82%
Shrestha_3	2018	Burlington, US	15	35	934	120	100%	3.72	0.15	0.61	0.08	0.23	-	Y	-	77%
Shrestha_4	2018	Burlington, US	15	16	934	64	100%	3.72	0.15	0.61	0.08	0.23	-	Y	-	48%
Shrestha_5	2018	Burlington, US	15	16	934	63	100%	3.72	0.15	0.61	0.08	0.23	-	Y	-	86%
Trowsdale2011a	2011	Auckland, NZ		12		18,000	86%	200						Y		58%
Winston2016a	2016	Ohio, USA	13	90	1010	4600	58%	136	0.39	0.84	0.15	0.3	0.38	N	-	39%
Winston2016a	2016	Ohio, USA	7	90	1010	3600	77%	182	0.3	0.6	0.15	0.3	0.6	N	-	59%

*Reported as lined on three sides and no infiltration, not clear if still potential for infiltration through base or remaining side

**Monitoring during dry season of this period only

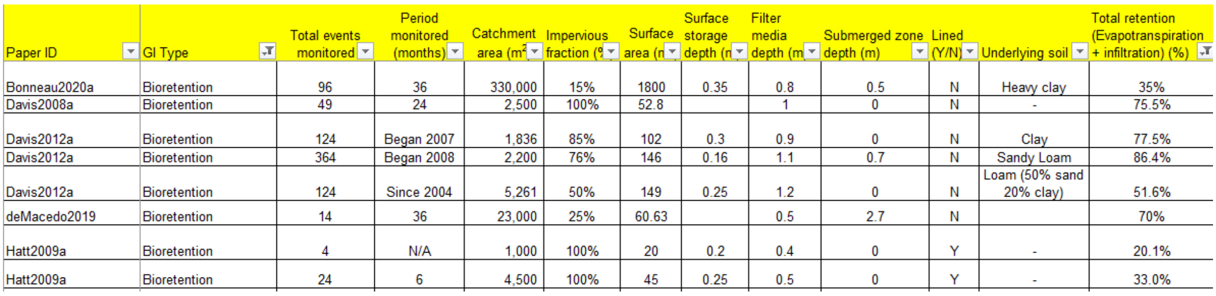
NR – Not reported

A number of Australian studies were identified within the literature such as (Hatt, Fletcher and Deletic, 2009)(Lucke and Nichols, 2015; Bonneau *et al.*, 2020)(Parker, 2010)(Peljo, Dubowski and Dalrymple, 2016)(Mckenzie-mcharg, Smith and Hatt, no date)(Poelsma, Fletcher and Burns, 2013a)(Hatt *et al.*, 2012)(Mangangka *et al.*, 2015)(Roberts *et al.*, 2012)(Hamel *et al.*, 2011). Further studies from abroad (the majority from the US) were also identified.

Analysis varied in scope and breadth across the studies, however several limitations to comparison should be considered:

- Bioretention configurations monitored vary across the studies. As explained in the previous section, the hydraulic response of bioretention systems depends on choices made during the design and construction process. The size of the asset compared to catchment, drainage arrangement, presence of a submerged zone, media choice and extended detention depth are key characteristics that influence the detention performance of a bioretention system, and these elements all vary across the analysed studies.
- Climate and soils vary with location and can influence outcomes. For example, the higher latitudes in the US have a modified hydrology, where a large portion of the annual runoff can occur as a single pulse during spring snow melt.
- Averaging only Australian studies resulted in lower apparent overall stormwater reduction percentages compared with all worldwide results, see Table 5-1. However, further exploration of relevant factors is needed to understand the reasons for this.
- It may reasonably be expected that outcomes for Western Sydney with clay soils may be below average and that larger asset sizing may be needed to compensate for this.
- Bypass and outflow are often not accounted and studies may be more indicative of average or typical performance than for very infrequent storm events. This is due to practical issues of measuring high-flow rates and flow paths as well as the duration of studies.
- Given the wide range of researchers, differences in approaches to data monitoring, analysis and results makes it difficult to make direct comparisons across studies. Researchers focus on different aspects including peak flows, flow volumes and water quality and not all focus or even report results of annual stormwater retention performance. Infiltration rates were sometimes a key subject of monitoring campaigns, leading to variation in the type of captured data. Monitoring periods vary with some studies focussing only on events and others pursuing a long-term monitoring period.

While these factors help to explain the variations in retention performance results from the examined monitoring studies, there is potential for further investigation to better understand the reasons for variations affecting performance.



Paper ID	GI Type	Total events monitored	Period monitored (months)	Catchment area (m^2	Impervious fraction (	Surface area (	Surface storage depth (	Filter media depth (m	Submerged zone depth (m)	Lined (Y/N)	Underlying soil	Total retention (Evapotranspiration + infiltration) (%)
Bonneau2020a	Bioretention	96	36	330,000	15%	1800	0.35	0.8	0.5	N	Heavy clay	35%
Davis2008a	Bioretention	49	24	2,500	100%	52.8		1	0	N	-	75.5%
Davis2012a	Bioretention	124	Began 2007	1,836	85%	102	0.3	0.9	0	N	Clay	77.5%
Davis2012a	Bioretention	364	Began 2008	2,200	76%	146	0.16	1.1	0.7	N	Sandy Loam	86.4%
Davis2012a	Bioretention	124	Since 2004	5,261	50%	149	0.25	1.2	0	N	Loam (50% sand 20% clay)	51.6%
deMacedo2019	Bioretention	14	36	23,000	25%	60.63		0.5	2.7	N		70%
Hatt2009a	Bioretention	4	N/A	1,000	100%	20	0.2	0.4	0	Y	-	20.1%
Hatt2009a	Bioretention	24	6	4,500	100%	45	0.25	0.5	0	Y	-	33.0%

Figure 5-4 Interactive summary table of stormwater retention performance

The broader site and event data may be assessed statistically to better understand the various factors and drivers that influence performance. It is recognised that this is complex and previous efforts have found it difficult to establish clear-cut relationships across multi-site data as shown by some studies (Barrett, 2008; Poresky *et al.*, 2012). Useful information can still be gleaned as demonstrated through the work of Davis (Hunt, Davis and Traver, 2012) and others. Rather than seek to resolve the recognised challenges in this approach, this project sets up the data required for testing, calibrating and validating physically based models for green infrastructure. The data may also be later assessed to further explore statistical relationships and sensitive factors and parameters in future work.

5.1.3 Contribution of infiltration and evapotranspiration to stormwater volume reductions

Three studies in particular highlighted the contribution of infiltration and evapotranspiration pathways in bioretention systems.

The Wicks Reserve Bioretention asset was monitored for a long period of 3 years (Bonneau *et al.*, 2020). The results indicated an average stormwater retention of 35%. The study found that infiltration was by far the dominant process (see Figure 5-5), with ~31% of inflow infiltrated while ~5% was evapo-transpired.

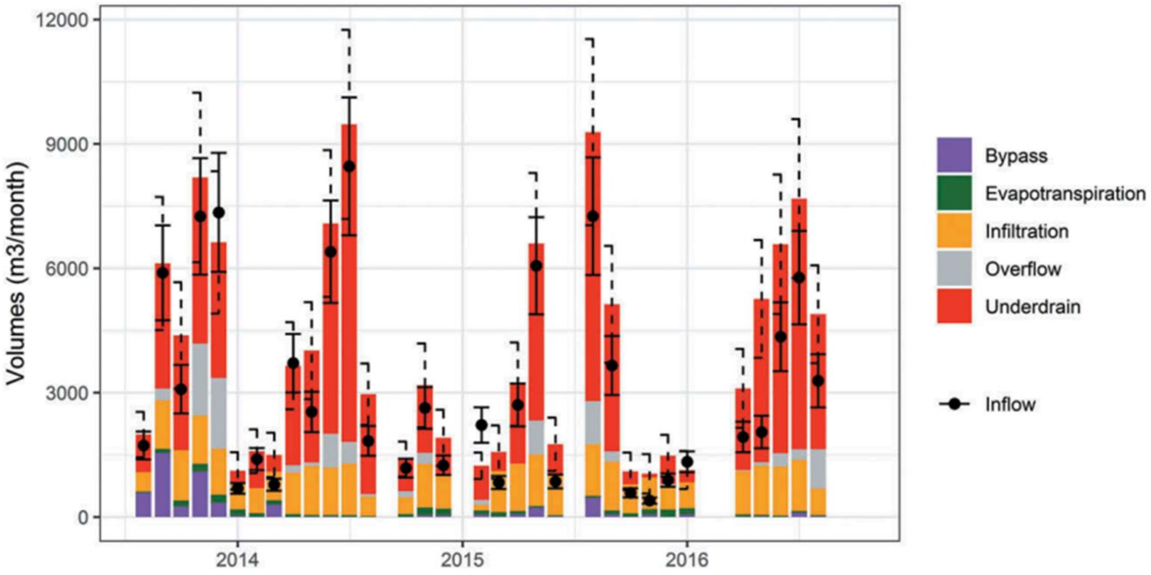


Figure 5-5 Stormwater pathways for a range of events

Another study of a bio-infiltration trench in Mt Evelyn, Melbourne (Hamel, 2013) also found the water balance was dominated by infiltration rather than evapotranspiration. It was estimated infiltration represented 98% of the annual water balance with a monthly range of 90-99% while evapotranspiration represented less than 3% annually.

Winston (Winston, Dorsey and Hunt, 2016) expected low infiltration rates for the soils underlying the bioretention assets monitored at Holden Arboretum and Ursuline College. However, they still delivered significant volume reductions. In their study the bioretention asset was quite new and given the immature state of the vegetation they found it difficult to register a clear beneficial effect of evapotranspiration. Results suggested that exfiltration accounted for between 36 and 59% of total losses, a number which suggests that evapotranspiration was still significant for these assets.

5.1.4 Summary and implications for biofilter design

Key outcomes include:

- Stormwater retention performance may vary considerably due to a combination of design and environmental factors (results ranging from 8-87% with a mean of 55% and median of 60%).
- For biofilters, the main pathways for stormwater to be retained are through infiltration and evapotranspiration. This is largely a function of their typical small size relative to catchment.
- There is considerable evidence to show infiltration is usually the dominant pathway for overall retention performance even in areas of slow-infiltrating surrounding soils.
- To maximise stormwater volume retention, designers should seek to encourage infiltration. This may be through the inclusion of an *unlined* submerged zone where soil conditions allow. While improving infiltration rates, submerged zones were also found to increase evapotranspiration within an asset.

5.2 Green roofs

5.2.1 Green roof meta-studies

A number of meta-studies and reviews on hydraulic performance of green roofs have been identified as part of the literature review. A study from 2019 brought together and summarised performance of a large range of monitored systems from different studies around the world (Ebrahimian, Wadzuk and Traver, 2019). Ebrahimian et. al. summarises, ‘A review of the hydrologic performance of 44 full-scale green roofs in the US, Canada, New Zealand, China, and Europe indicate that the annual volume retention in green roofs can range from 11% to 77% of the total rainfall volume with a median of 57% depending on meteorological conditions and green roof design characteristics. These retention values are based on sample of studies with a median monitoring duration of one year of green roofs with a median substrate depth of 100 mm.

A German study explored the factors influencing the retention performance of green roofs, assembling a statistical analysis from 18 monitoring studies and 628 events from sites within Germany (Mentens, Raes and Hermy, 2006). The study found the number and depth of the substrate layers, climatic conditions and mean annual rainfall were the primary factors influencing retention performance.

This study reported annual retention performance with a median ranging from 45% for extensive green roofs (median substrate depth: 100mm) to 75% for intensive green roofs (median substrate depth: 150mm) (averages of 50% and 75% respectively). The study also reported a significant reduction in performance during winter, attributed to the seasonal reduction in potential evapotranspiration and change in rainfall distribution in the German climate. The impact of seasonality on evapotranspiration processes may be less pronounced in some Australian conditions.

The results also emphasise the importance of green roof depth as a factor for retention performance. Figure 5-6 shows the increase in retention performance of green roofs with increased depth of substrates layers.

The green roof data from the latter study has only been reported at an aggregate level with most of the original sources being in German. Therefore, these have not been incorporated into the current study, but the results can be compared.

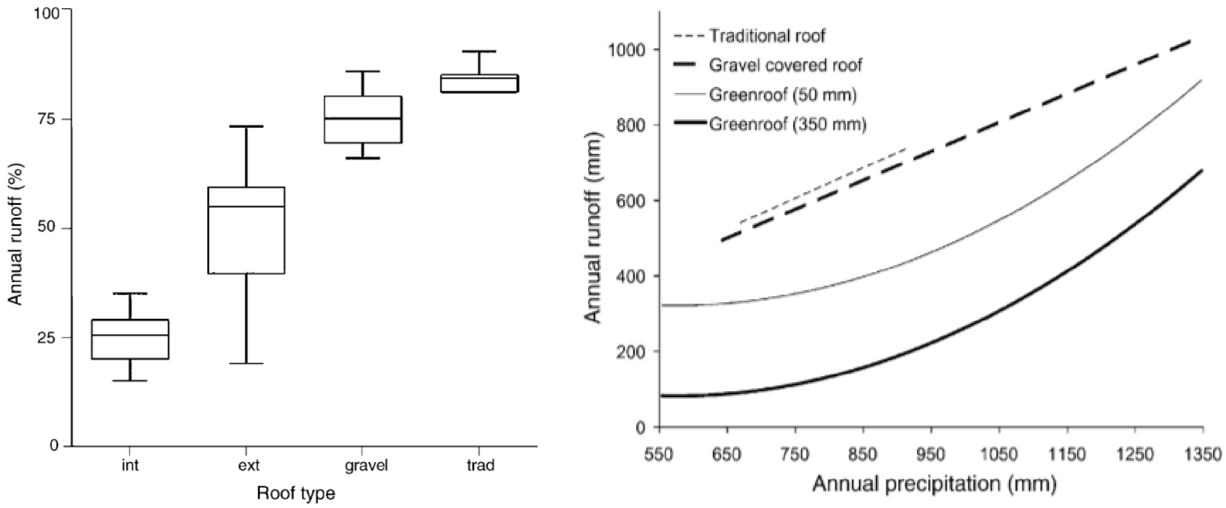


Figure 5-6 - Runoff from different types of green roofs as a percentage of total annual rainfall for intensive green roofs (int, n=11), extensive green roofs (ext, n=121), gravel roofs (gravel, n=8) and non-greened roofs (trad, n=5). Box plots show range of data after removal of outliers including 25%, 50% and 75% (Mentens, Raes and Hermy, 2006). Performance increases with substrate depth and reduces with higher annual precipitation as shown in the second graph.

5.2.2 Green roof monitoring studies

A total of 40 studies containing the results of green roof monitoring campaigns were analysed. From the studies, a total of 67 individual assets were identified. Of these, 55 assets with reported retention results were collated. The retention performance is summarised in Figure 5-7.

See Appendix B – Green roofs: Table 5-3 Green roof asset data for a summary of key parameters for each of the assets for which retention performance was available.

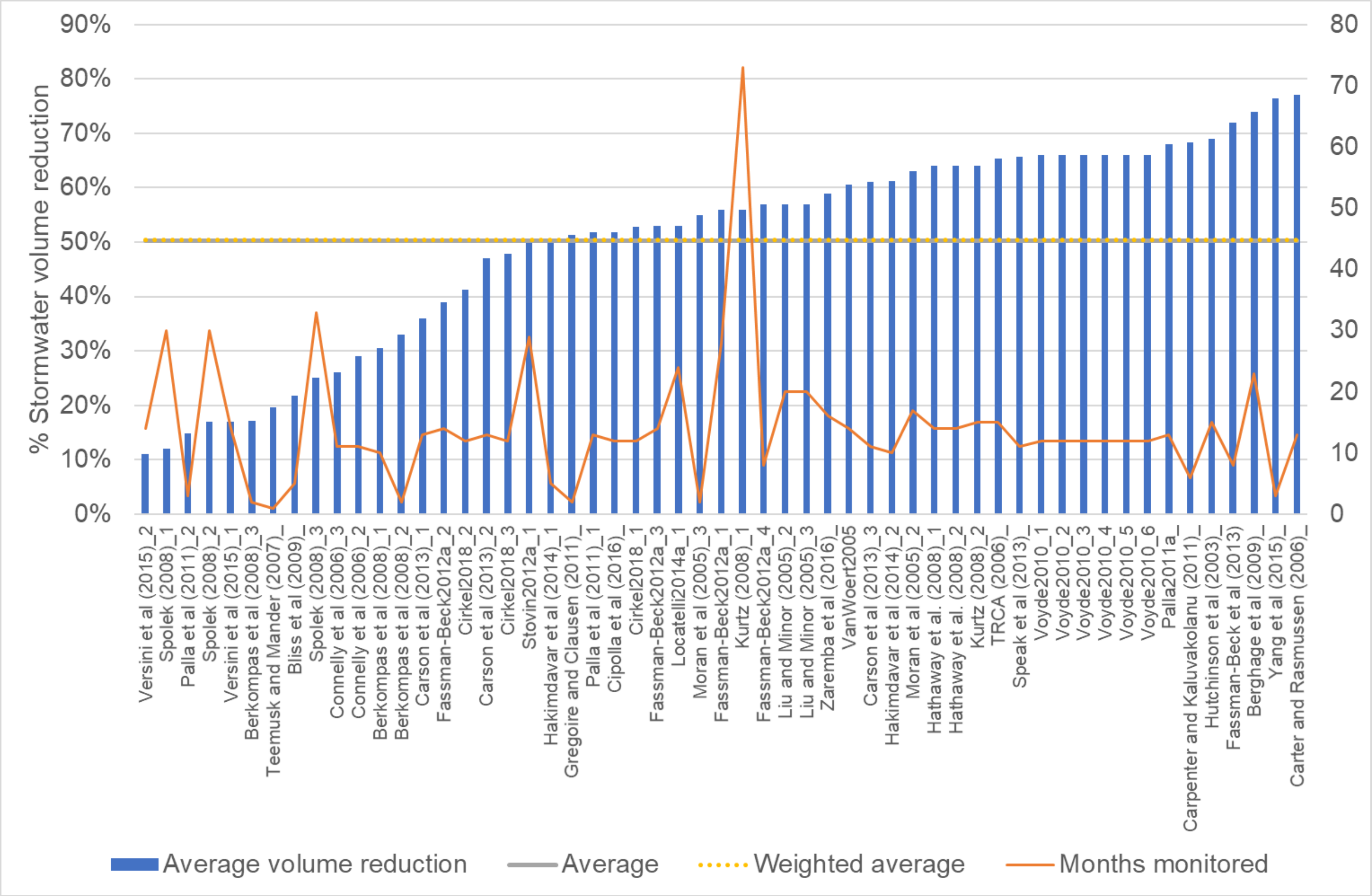


Figure 5-7 Percentage stormwater volume retained for green roof assets from a range of studies

Table 5-3 Green roof asset data

Paper ID	Period monitored (months)	Study location	Surface area (m^2)	Overall thickness (m)	Mean annual rainfall (mm/year)	Overall retention
Berghage et al (2009)	23	Chicago, US	7000	0.076	937*	74%
Berkompas et al (2008)	10	Seattle, US	743	0.15	952*	31%
Berkompas et al (2008)	2	Seattle, US	1860	0.113	952*	33%
Berkompas et al (2008)	2	Seattle, US	80	0.15	952*	17%
Bliss et al (2009)	5	Pittsburgh, US	330	0.14	965*	22%
Carpenter and Kaluvakolanu (2011)	6	Southfield, US	325	0.102	864*	68%
Carson et al (2013)	12	New York, US	310	0.032	1143*	36%
Carson et al (2013)	24	New York, US	390	0.15	1143*	47%
Carson et al (2013)	36	New York, US	940	0.1	1143*	61%
Carter and Rasmussen (2006)	13	Athens, US	21.3	0.076	397*	77%
Cipolla et al (2016)	12	Bologna, Italy	58	0.1	774*	52%
Cirkel (2018a)	12	Amsterdam, NL	18.1476	0.11	852	53%
Cirkel (2018a)	12	Amsterdam, NL	18.1476	0.04	852	41%
Cirkel (2018a)	12	Amsterdam, NL	18.1476	0.07	852	48%
Connelly et al (2006)	11	Vancouver, Canada	33	0.075	1283*	29%
Connelly et al (2006)	11	Vancouver, Canada	33	0.15	1283*	26%
Fassman (2012)	14	Auckland, NZ	16	0.1	1281	39%
Fassman (2012)	14	Auckland, NZ	16	0.15	1281	53%
Fassman (2012)	8	Auckland, NZ	500	0.1	1120	57%
Fassman (2012)	28	Auckland, NZ	235	0.06	1027	56%
Fassman-Beck et al (2013)	8	Auckland, NZ	171	0.1	1284*	72%
Gregoire and Clausen (2011)	2	Storrs, US	307	0.102	1270*	51%
Hakimdavar et al (2014)	5	New York, US	310	0.032	1143*	51%
Hakimdavar et al (2014)	10	New York, US	99	0.032	1143*	61%

Paper ID	Period monitored (months)	Study location	Surface area (m^2)	Overall thickness (m)	Mean annual rainfall (mm/year)	Overall retention
Hathaway et al. (2008)	14	Goldsboro, US	35	0.075	1219*	64%
Hathaway et al. (2008)	14	Kinston, US	27	0.1	1270*	64%
Hutchinson et al (2003)	15	Portland, US	240	0.113	1092*	69%
Kurtz (2008)	73	Portland, US	246	0.125	1092*	56%
Kurtz (2008)	15	Portland, US	465	0.075	1092*	64%
Liu and Minor (2005)	20	Toronto, Canada	200	0.075	785*	57%
Liu and Minor (2005)	20	Toronto, Canada	200	0.1	785*	57%
Locatelli (2014a)	24	Copenhagen, DK	9	0.08	650	53%
Moran et al (2005)	17	Goldsboro, US	35	0.075	1219*	63%
Moran et al (2005)	2	Raleigh, US	65	0.1	1168*	55%
Palla (2011a)	13	Genova, Italy	1000	0.035	1096	68%
Palla et al (2011)	13	Genova, Italy	170	0.2	1086*	52%
Palla et al (2011)	3	Genova, Italy	170	0.2	1086*	15%
Speak et al (2013)	11	Manchester, UK	408	0.17	867*	66%
Spolek (2008)	30	Portland, US	290	0.125	1092*	12%
Spolek (2008)	30	Portland, US	280	0.125	1092*	17%
Spolek (2008)	33	Portland, US	500	0.15	1092*	25%
Stovin (2012)	29	Sheffield, UK	3	0.08	844	50%
Teemusk and Mander (2007)	1	Tartu, Estonia	120	0.1	670*	20%
TRCA (2006)	15	Toronto, Canada	240	0.14	785*	65%
Versini et al (2015)	14	Paris, France	35	0.03	624*	17%
Versini et al (2015)	14	Paris, France	35	0.15	624*	11%
Voyde et al (2010a)	12	Auckland, NZ	41	0.05	1284*	66%
Voyde et al (2010a)	12	Auckland, NZ	13	0.05	1284*	66%
Voyde et al (2010a)	12	Auckland, NZ	46	0.07	1284*	66%
Voyde et al (2010a)	12	Auckland, NZ	45	0.07	1284*	66%
Voyde et al (2010a)	12	Auckland, NZ	12	0.07	1284*	66%
Voyde et al (2010a)	12	Auckland, NZ	38	0.05	1284*	66%
Yang et al (2015)	3	Beijing, China	120	0.15	610*	76%

Paper ID	Period monitored (months)	Study location	Surface area (m^2)	Overall thickness (m)	Mean annual rainfall (mm/year)	Overall retention
Zaremba et al (2016)	16	Villanova, US	54	0.1	1219*	59%

*Values in orange are mean annual for the location, not specifically for the testing period.

5.2.3 Contribution of evapotranspiration and water storage capacity to stormwater volume reductions

Several studies explore the impact the key processes of evapotranspiration and water storage capacity on green roof retention performance. The following is a summary and discussion of key observations and learnings from monitoring studies.

Fassman-Beck (Fassman-Beck *et al.*, 2013) and Locatelli (Locatelli *et al.*, 2014) both found that substrate water holding capacity had the most significant impact on runoff retention performance. Locatelli states: ‘It can be seen that increasing the retention capacity reduces the annual runoff and the relation between the two is not linear. Even a few mm of storage can result in significant reductions in annual runoff’ (Locatelli *et al.*, 2014). Figure 5-8 shows the variation of the mean annual runoff as a function of the total green roof retention capacity for different crop coefficients.

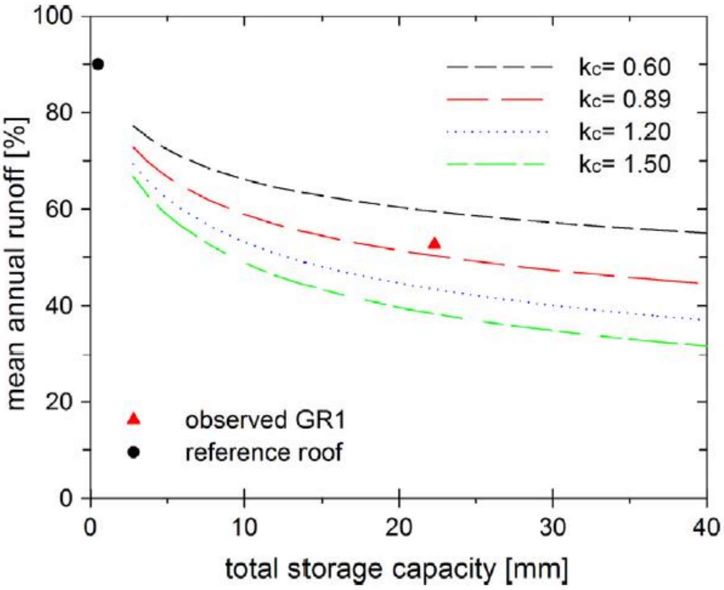


Figure 5-8 - Green roof mean annual runoff as a function of total (surface and subsurface) storage capacity (Locatelli, 2014)

Stovin (Stovin, Vesuviano and Kasmin, 2012) explored the relative impact of evapotranspiration and water storage capacity as key influences on green roof retention performance. They defined water storage capacity as the difference between soil saturation and permanent wilting point. The study suggested that green roof substrate with a depth of 80mm had a maximum water holding capacity of

20mm (i.e. 25% of substrate soil volume is available to store water). Cirkel (Cirkel *et al.*, 2018) found that providing a sub-soil storage and capillary irrigation system can significantly improve potential evapotranspiration losses.

5.2.4 Summary of influencing factors for green roof retention performance

For green roofs, the only pathway available for stormwater retention is evapotranspiration. Water storage usually comprises of water absorbed by the substrate media. From the literature, the key factors influencing retention performance in green roofs are:

- Climatic factors such as mean annual rainfall, temperature and seasonal variation
- Soil structure; wilting point and water storage capacity
- Soil depth

Climatic factors such as mean annual rainfall, temperature and seasonal variation

Without extended detention depth to ‘buffer’ larger rain events, the retention of green roofs is less resilient to larger rain events of higher intensity. Evapotranspiration rates are highly dependent on local climate conditions including temperature, solar availability and wind. Seasonal variation of rainfall and potential evapotranspiration can cause variability of green roof retention performance throughout the year.

Soil structure; wilting point and water storage capacity

Since the soil substrate is the only means a green roof has of storing water, the characteristics of the soil become a critical factor. The substrate media needs to balance several objectives including adequate infiltration rates and moisture availability to support vegetation, while maximising water storage capacity.

Soil depth

The depth of the soil substrate directly influences the water storage available in the green roof. Extensive green roofs (substrate <150mm) are effective at retaining short duration storms. Intensive green roofs (substrate >150mm) can retain larger events, improving the overall retention performance of the asset. Adequate soil depth is also important to support vegetation on a green roof.

5.3 Passively irrigated tree pits

5.3.1 Passively irrigated tree pit meta-studies

A US study (Kuehler, Hathaway and Tirpak, 2017) provides a summary of studies that explore the retention performance of street trees, breaking down interception, transpiration and infiltration. No specific retention percentages were presented. However, the paper makes several important points regarding the importance of non-compacted soil for tree health and promotion of infiltration and the different performance of tree species.

5.4 Passively irrigated tree pit monitoring papers

A number of monitoring studies have been undertaken in Australia (Grey, Stephen J. Livesley, *et al.*, 2018; Sapdhare *et al.*, 2019; Szota *et al.*, 2019a; Thom *et al.*, 2020).

One study focussed on experimental tree pits in Barrow Street in the City of Moreland, Melbourne, Victoria (Grey, Stephen J. Livesley, *et al.*, 2018). Key points include:

- 5 tree pits with different inlet and soil designs, including a control with no inlet.
- Monitoring period of 18 months,
- Stormwater can significantly improve tree growth if waterlogged soils are avoided via an underdrain. No results reported of stormwater reductions.

The study used a number of different designs with small sizes relative to catchment. The tree pits did not have under-drainage and this resulted in poor performance or the tree dying for some pits due to over-saturation while others had adequate infiltration despite the clay surrounding soils. Given the design issues experienced, this study may be a lower priority for modelling and calibration.

Another study monitored tree pits in Oakleigh and Glen Waverley, Melbourne, Vic (Szota *et al.*, 2019b; Thom *et al.*, 2020). Key points include:

- 9 tree pits spread across 2 residential streets in Oakleigh and Glen Waverley, Melbourne, representing different combinations of soil type, tree species and inlet type.
- 6-minute rainfall data from gauges 3km away from each site. Monitoring period of 18 months, with approx. 140 rainfall events captured.
- Suggests an average runoff reduction of 18% even in an area with relatively low permeability of in-situ soils (average of 0.3 mmh^{-1}). The best performing system retained 44% of runoff while systems with reduced performance were impacted by blocked inlets.
- The study highlights that variations were primarily due to inlet design and tendency for blockage due to sediment loading and emphasised the importance of good inlet design and regular maintenance.

Of the Australian tree pit studies considered, this is likely the most suitable for modelling and calibration.

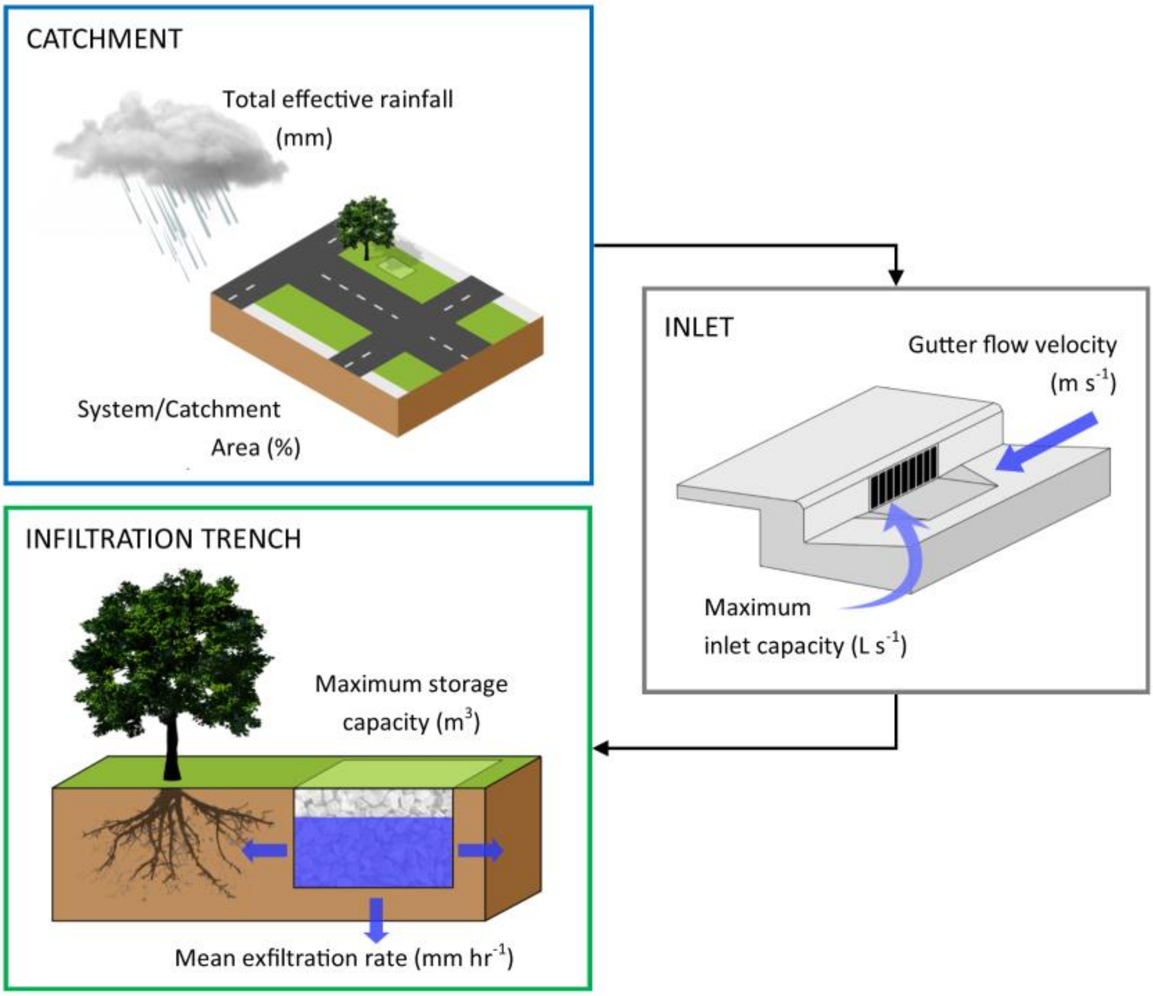


Fig. 3. Conceptual diagram of the six potential drivers of runoff retention by infiltration trenches.

Another study was undertaken in Kingswood, Adelaide in South Australia (Sapdhare *et al.*, 2019). Infiltration testing was undertaken on the trees, however they were not monitored over an extended period. There is some limited potential that the infiltration test data from this site could be used for model calibration. However, in the absence of natural event or continuous monitoring it will likely be a lower priority.

Another US study (Van Stan, Levia and Jenkins, 2015) explored interception of deciduous trees, finding that rainfall under canopy was reduced by approx. 30% and suggests the different species' canopy can greatly influence the ability for trees to intercept rainfall. These outcomes suggest that the effects of interception should be further considered and explored for assets where the tree canopy is a significant portion of the catchment draining to the tree pit. This also has implications for the survival and effectiveness of trees planted without passive irrigation.

5.5 Contribution of interception, infiltration and evapotranspiration to stormwater volume reductions

Specific research on the proportions of infiltration and evapotranspiration were not researched due to time constraints. However, tree pits may be expected to have similar behaviour to bioretention with the following differences:

- The tree canopy may be larger than the treatment area at ground level and provide greater evapotranspiration volumes
- Tree canopy may also contribute to interception losses

6. Detailed data sets

This chapter identifies and summarises the assets for which detailed hydrographic data sets were sourced that may potentially be used for model calibration. These include some or all of the following: Rainfall, inflows, outflows, overflows, water level, soil moisture and groundwater levels.

The assets and links to the data are summarised in Table 6-1, Table 6-2 and Table 6-3 . This includes assets for which data was obtained and selected assets for which data may potentially become available. Where available, links to original document and data sources are provided or in some cases filenames for sources in the same location as the report.

A number of opportunities for collaboration and leads were identified with potential data as summarised in Table 6-4. Contact will be maintained with these leads and data that becomes available may potentially be added in future.

Table 6-1 Bioretention detailed data set summary

Paper ID	Asset type	Asset name	Location	Events	Status	Links to data and reports
Hatt 2009a	Biofilter	Monash carpark biofilter (3 cells)	Clayton VIC	Continuous	Received	https://doi.org/10.2166/wst.2009.173 Monash Carpark Biofilter_All_Events.xlsx FlowData_Database_DB20201022_v2.xlsx
Bonneau 2020a	Biofilter	Wicks Reserve biofilter	Melbourne, VIC	96	Received	The hydrologic, water quality and flow regime performance of a bioretention basin in Melbourne, Australia WicksCombinedHydrographs.xlsx
Poelsma 2013	Biofilter	Hereford Road biofilter	Melbourne, VIC	Continuous	Received	Restoring natural flow regimes: the importance of multiple scales Poelsma2013_HerefordRdInAndOutFlowsCleaned2011-12.xlsx
Hatt 2012	Biofilter	Walker Street biofilters (2 cells)	Clifton Hill, VIC	Continuous	Received	Hatt2012CliftonHillBiofiltersReportFinal.pdf Hatt2012_WalkerStCliftonHillBiofilter_SummaryOfAllEventFlowData.xlsx
Roberts 2012a	Biofilter	Wakerley biofilter (3 cells)	Brisbane QLD	4 (Continuous also exists)	Received	Bioretention saturated zones: Do they work at the large-scale? WakerleyDataSummaryDB20201217.xlsx
EPA 2020a	Biofilter	Graham H.S. parking lot	Graham, NC, USA	4	Public	FlowData_Database_DB20201022_v2.xlsx Grahammas20180821docx.docx grahamsub.xlsx
EPA 2020b	Biofilter	Villanova Traffic Island biofilter	Villanova, PA, USA	4	Public	FlowData_Database_DB20201022_v2.xlsx Villanova BTI Bioretention Reportmas20180821.docx btisub.xlsx
Tim Fletcher	Biofilter	Rangeview Road biofilter	Melbourne VIC	-	Not available at this time	-
Zinger	Biofilter	Kfar-Saba amphitheatre bioretention	Tel Aviv, Israel	-	Waiting	-

*Significant events with temporal data

US EPA Testing Appendices: https://edg.epa.gov/metadata/catalog/search/resource/details.page?uuid=%7B04561E97-088A-4612-9B0E-F04CB4799A8D%7D

License for US EPA data: https://pasteur.epa.gov/license/sciencehub-license.html

Table 6-2 Green roofs detailed data set summary

Paper ID	Asset type	Asset name	Location	Events	Status	Links to data and reports
EPA 2020e	Green roof	Hamilton Ecoroof East and West	Portland, OR, USA	4	Public	FlowData_Database_DB20201022_v2.xlsx Hamilton Ecoroofmas20180821docx.docx hamiltonsub.xlsx
EPA 2020f	Green roof	Emergency Operations Centre green roof	Seattle, WA, USA	4	Public	FlowData_Database_DB20201022_v2.xlsx eocmas20180821.docx eocsub.xlsx
EPA 2020g	Green roof	Fire Station 10 green roof	Seattle, WA, USA	4	Public	FlowData_Database_DB20201022_v2.xlsx f10mas20180821.docx FS10sub.xlsx
Green roof diagnostics (Brad Garner)	Green roof	Green roof diagnostics laboratory	Stevensburg, Virginia, USA	1 year	Further discussion	-
Stovin 2012a (Virginia Stovin)	Green roof	Sheffield green roof	Sheffield, UK	19*	Not available at this time	-
Stovin 2012a	Green roof	Hadfield green roof	Hadfield, UK	-	Not available at this time	-
Fassman-Beck2012a (Emily Afoa nee Voyde)	Green roof	Auckland green roofs (4)	Auckland, NZ	-	Not available at this time	-
Monash/PUB	Various	Various	Singapore		Waiting	-

*Significant events with temporal data

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Table 6-3 Other green infrastructure detailed data set summary

Paper ID	Asset type	Asset name	Location	Events	Status	Links to data and reports
EPA 2020c	Infiltration trench	Villanova infiltration trench	Villanova, PA, USA	4	Public	villanovatrenchmas20180821.docx villanovainfiltrenchsub.xlsx
Monash/PUB	Various	Various	Singapore		Waiting	-

*Significant events with temporal data

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Table 6-4 Leads for potential data sets

Institution	Contact	Asset type	Location
Melbourne University WERG	Jasmine Thom	Tree pit	Barrow St, Moreland, VIC Monash, VIC
Green Roof Diagnostics	Brad Garner	Green roof	Green Roof Laboratory, Stevensburg University of Western Sydney trial
Center for Water Sensitive Cities in Israel	Yaron Zinger	Biofilter	Kfar-Saba, Tel Aviv, Israel
Monash and PUB	Harsha Fowdar Neo Teck Heng	Various	Singapore
Sheffield University	Virginia Stovin	Green roof	Sheffield UK Hadfield, UK
University of Auckland/Tektus consultants	Emily Afoa nee Voyde	Green roof	Auckland

A summary of each of the assets and associated monitoring and data is provided below. A sample of event hydrographs from selected assets is provided in Appendix D – Sample data.

6.1 Monash University carpark bioretention

6.1.1 Site

The asset is located at the Clayton campus of Monash University and constructed in 2006 to treat runoff from the top level of a 4,500m^2 multilevel car park.

6.1.2 Climate conditions

Monash University's Clayton campus receives around 680mm of precipitation per year, with average maximum summer temperatures of 26 degrees, while the winter average minimums is 6 degrees.

6.1.3 Asset

The bioretention system has a surface area of 45m^2 with a depth profile of 500mm filter media, 100mm transitional sand and 100m fine gravel. The asset is split into 3 cells that tested the performance of different soil -based filter media. Cell 1: sandy loam (media currently recommended by design guidelines); •Cell 2: sandy loam mixed with 10% vermiculite and 10% perlite (by volume); and •Cell 3: sandy loam mixed with 10% compost and 10% light mulch (by volume). Each cell was planted with the same mix of native rushes and sedges.

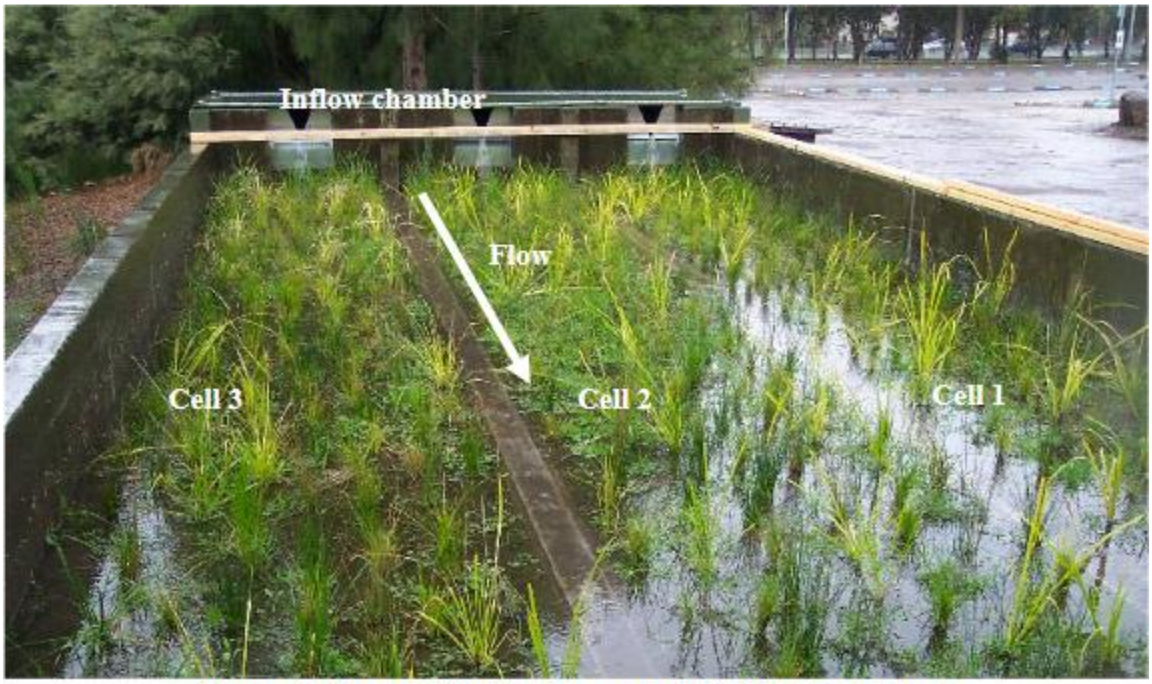


Figure 8. Monash University carpark biofiltration system

Figure 6-1 Monash University carpark biofiltration system (Unknown)

6.1.4 Monitoring setup

The system is fully equipped for monitoring both flow and water quality. Three V-notch weirs installed in the covered inflow chamber are used to monitor inflow into the biofilters. The outflow from each cell is monitored by three small separate V-notch weirs. Autosamplers collect water quality samples at both the inflow and outflow. The system also allows for easy testing with spiked inflows. Water quality samples were analysed for TSS, TP, FRP, TN, NH4þ, NOx, DON, PON, Cd, Cu, Pb and Zn; for three runoff events, all water quality samples were analysed individually, however flow-weighted composite samples were analysed for all other runoff event.

Figure 6-2 Monitoring equipment (Unknown)

6.1.5 Data available

Seventeen natural runoff events were monitored from January 2007 to November 2007. This represents a climatic period of late summer to spring. Inflow and outflow data is present, measured at a 1 minute time step.

The system has experienced issues with leakages, when the asset was reset cracks in the concrete base were found. Analysis of results found that this leakage likely impacted the results of the monitoring study. This should be considered when using this data in the future.

The Monash biofilter is well suited for analysis of a system with a relatively low level of infiltration (Being lined but leaky). A good level of continuous data is available.

6.2 Wicks Reserve biofilter

6.2.1 Site

The site (Wicks Reserve, Boronia) includes a densely vegetated 1800m^2 biofiltration system that is receiving runoff from a 33-ha peri-urban catchment and discharging into Dobsons Creek. The 33-ha catchment was estimated at 15% impervious surfaces (approx. 5-ha).

Runoff from impervious areas of the urban catchment is delivered to the basin via two stormwater pipes which combine in a junction pit, diverting flows up to 200 L s−1 to a gross pollutant trap (GPT). Flows greater than 200 L s−1 bypass the GPT and thus the basin via a narrow crested rectangular weir and are conveyed directly to the local stream. The GPT intercepts large particles such as litter, gravel and some coarse sediment. Further treatment of coarse particles (target particle size >125 μm) is provided by a sedimentation pond located immediately downstream of the GPT. Outflows from the pond spill evenly across the basin filter media. The basin is located in heavy clay soil (hydraulic conductivities was measured between 5e−8 m s−1 and 5e−7 m s−1 [0.005 m day−1 to 0.05 m day−1] (Bonneau *et al.*, 2020).

6.2.2 Climate conditions

Average annual rainfall in the catchment is 730mm, evenly distributed throughout the year with a slight winter-spring bias. Average annual areal potential evapotranspiration is 1050mm, displaying strong seasonality.

6.2.3 Asset

The 1,800m^2 surface area of the asset represents 4% of the catchment size. This is larger than the size of assets focusing only on water quality in the region, a purposeful design choice to increase depleted stream baseflow. The asset is densely vegetated with grasses and rushes and on average 0.8m deep. The top 0.35m layer consists of loamy sand, while the bottom 0.3m being scoria. Three 0.05m transition layers ranging separate these layers. There is a slotted underdrain at the base of the basin which discharges through an elevated orifice in a discharge pit. The orifice is elevated by 0.5 m from the bottom of the basin, meaning that the bottom 0.5 m is a submerged zone.

The basin is not lined along the base and three sides, the southern side is lined to prevent intrusion of upslope groundwater into the basin. The asset contains an extended detention depth of 0.5m before discharging into an overflow pit.

In winter, the surface of the bioretention basin is covered by water for extended periods of time, up to a couple of weeks. In summer, the surface of the basin is covered with water for a few hours after a rainfall event or a few days in the case of a large event (Bonneau *et al.*, 2020)

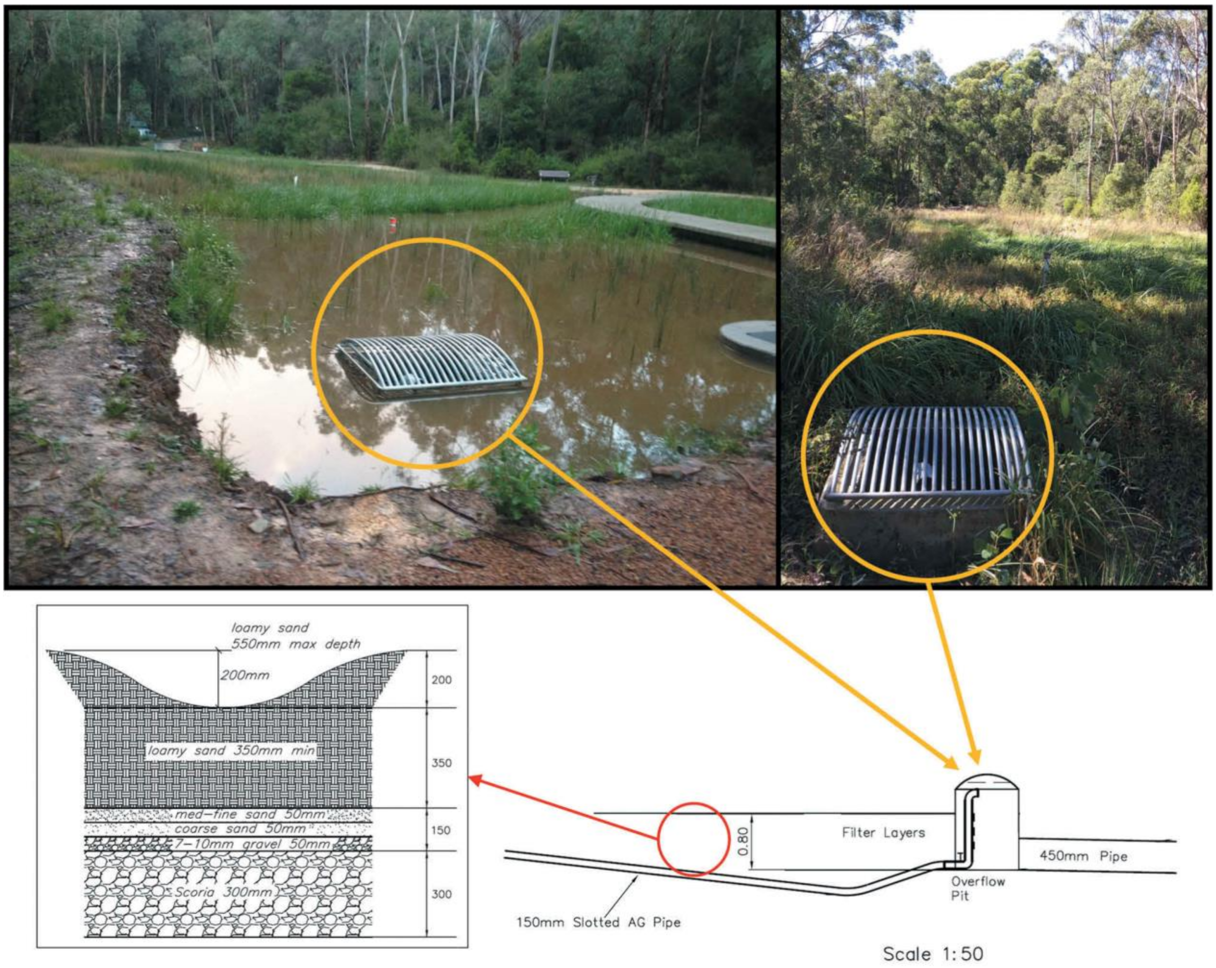


Figure 6-3 Photographs and cross-sections of the asset (top left just after construction in 2012, top right a dry period in 2018) (Bonneau *et al.*, 2020)

6.2.4 Monitoring setup

Monitoring consisted of upstream, downstream and bypass flow gauges, three water level probes in the biofiltration system and a rain gauge on site. Flow Data was collected between September 2013 and September 2016. Sedimentation impacted flow data collection for certain periods, these periods were infilled using a linear regression from the 96 usable rainfall events captured. Water level data begun in March 2013 and was ongoing in December 2019. Two autosamplers were installed at the inlet and at the outlet of the basin to monitor water quality treatment performance.

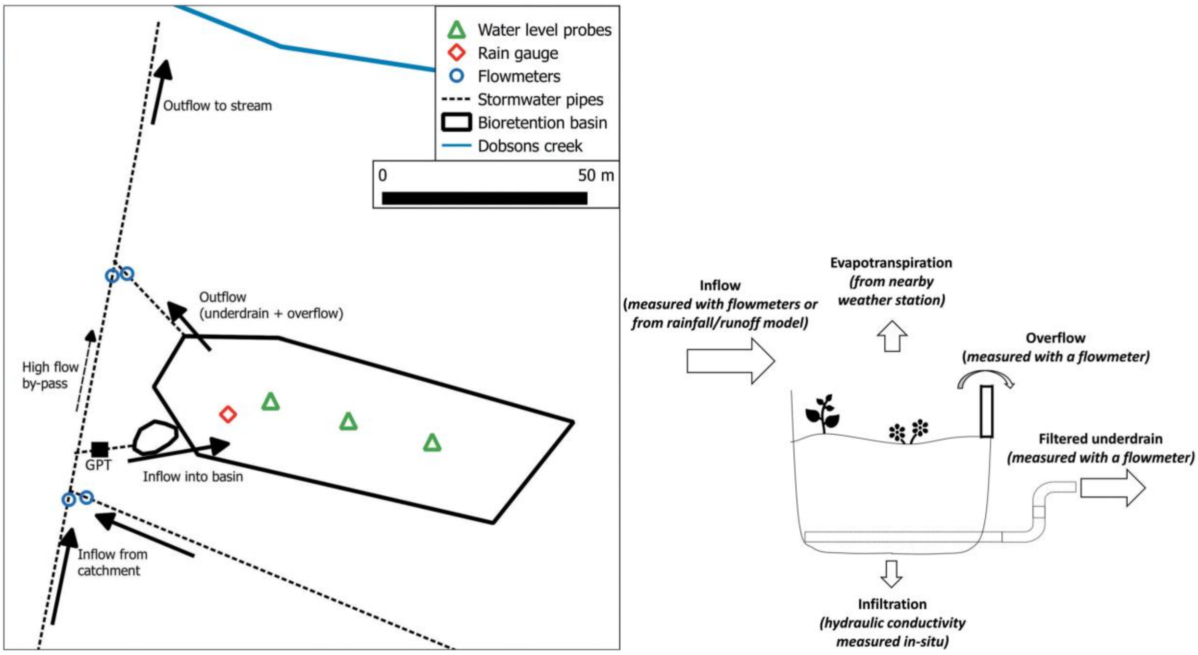


Figure 6-4 Summary of monitoring setup and installed equipment (Bonneau *et al.*, 2020)

6.2.5 Data available

96 natural events monitored over a period of three years. Inflow and outflow data available at a -minute timestep. Water level data for the bioretention system available at 1minute timesteps for a continuous 6-year period.

Wicks Reserve is a large and complex system but has an excellent and large data set available making it an attractive option for calibration and validation.

6.3 Hereford Road biofilter

6.3.1 Site

The biofiltration system treats runoff from a 9,800m^2 impervious catchment comprising of roads (6,170 m^2), roofs (3,050 m^2) and some other paved areas (580 m^2). The system has a surface area of 100m^2, equalling 1% of the catchment area. It is vegetated with indigenous sedges and shrubs. The system is not lined, allowing exfiltration of water into surrounding soils. Extended detention depth is 300mm while below the surface there is 400mm of filter media (loamy sand), a 200mm transition layer (sand and fine gravel) and 400mm of coarse aggregate (scoria) at the base. Riser pipes control filtered flow from the bottom of the system, allowing water to drain to 100mm below the surface, to prevent long ponding periods (Figure 2). Point infiltration rates of the surrounding soil are approximately 3.8 mm/hr in the upper 300 mm, increasing to around 15 mm/hr in the lower depths

6.3.2 Climate conditions

Closest BOM station of Montrose records an annual rainfall of 1,027 mm annually. Maximum average temperatures of 26 degrees in February and a minimum average temperature of 13 degrees in July. Average precipitation is higher in winter, but there is significant rainfall all year round.

6.3.3 Asset

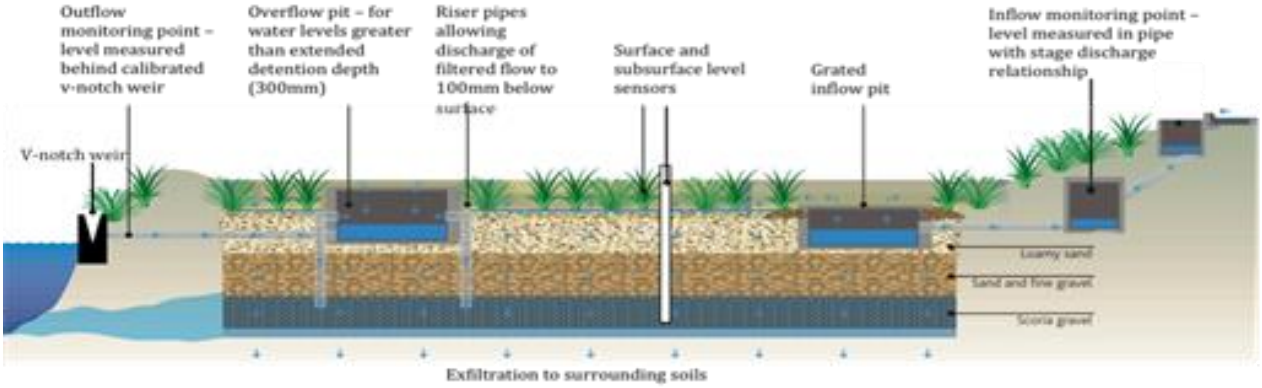


Figure 6-5 Hereford Road biofilter, after (Poelsma, Fletcher and Burns, 2013b)

6.3.4 Monitoring setup

At the bioinfiltration system, inflow and outflow were measured, as well as water level above and below the vegetated surface. The inflow was calculated from measured water level in the inlet pipe and a stage discharge relationship developed from manual discharge measurements. These manual discharges were volumetrically calibrated during the monitoring period, while the water level in the inlet pipe was continuously measured using an ultrasonic level sensor (Microsonic pico100WKI). High flow rates beyond our stage discharge curve were extrapolated using both modelled flows and theoretical flow estimates as a guide. The outflow was calculated using a compound v-notch weir in the outlet pipe (Figure 2). This weir had been calibrated in the laboratory and the water level in the outflow pipe was measured with an ultrasonic level sensor (Microsonic mic35IUTC), just upstream of the weir. The water levels above and below the infiltration basin were measured and recorded by Odyssey water capacitance probes (Figure 2). All data was collected at 1-minute intervals.

6.3.5 Data available

Available data from the monitoring period includes rainfall data, PET, inflow and outflow rates. There is 9 months of data available with the flow-rates collected at the 1-minute time interval. This site is well suited for calibration and validation given the length of continuous data available.

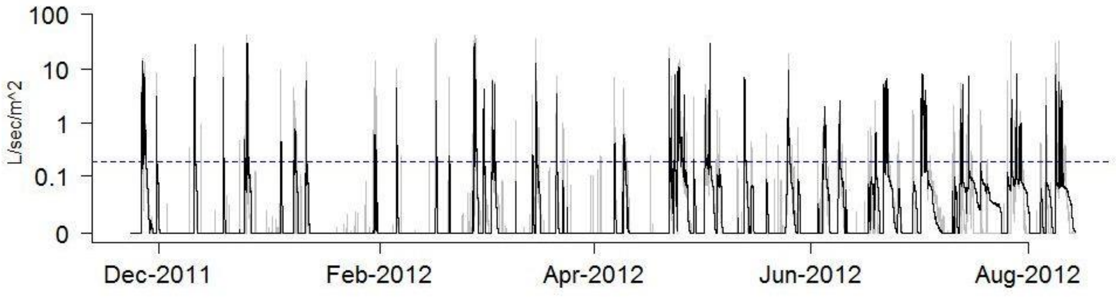


Figure 6-6 Hereford Road long-term hydrograph at outlet (Poelsma, Fletcher and Burns, 2013a)

6.4 Clifton Hill Biofilters

6.4.1 Site

The biofiltration system treats runoff from a 7.3ha residential catchment, is located at the end of Walker St in Clifton Hill, Victoria and drains into Merri Creek. The system is part of an extended treatment train that contains a sediment trap upstream of the bioretention systems and a downstream pond designed to provide frog habitat before discharge to Merri Creek. The system was constructed in 2007

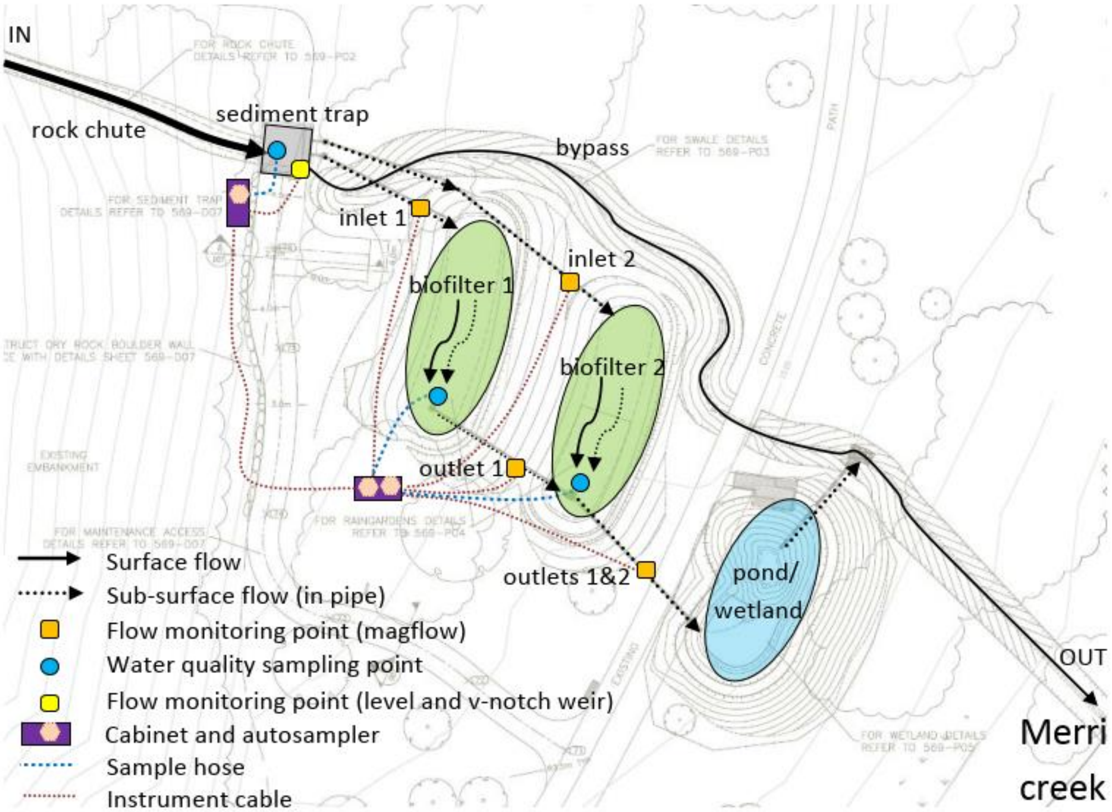


Figure 6-7 Overview of the extended treatment train system and monitoring stations (Hatt *et al.*, 2012)

6.4.2 Climate conditions

Clifton hill experiences annual rainfall of approximately 650mm with average summer and winter temperatures of 14 and 7 degrees respectively.

6.4.3 Asset

The system consists of two parallel bioretention systems, each with a surface area of 100m^2, equalling 0.3% of the catchment area. It is vegetated with indigenous sedges and shrubs. The biofilters have a depth of 750mm are comprised of a 100 mm topsoil layer, a 400 mm filter layer, a 100 mm sand transition layer and a 150 mm gravel drainage layer. There is an extended detention depth of 175mm. The filter bases are lined and the systems are planted with native shrubs.

6.4.4 Monitoring setup

Flow rates into and out of each bioretention system were monitored using a Siemens Mag8000 flow meter. Flow rates were recorded at a one-minute interval. High flows were also recorded at the overflow point within the primary sediment trap. This was recorded via bubbler sensor that took measurements of water height over the weir with an interval of 10 minutes. Rainfall data was collected at CERES Community Environment Park, located 3.4km east of the monitoring site. The monitoring campaign was in place from late September 2009 until the end of July 2010.

6.4.5 Data available

The monitoring campaign suffered from issues that compromised some parts of the data set. During the monitoring period, there were 83 rainfall events, however only 62 of these events were reliably captured at all four monitoring points. For these 62 events, there is flow data on a minute time interval for the inlets of both bioretention system, the outlet of one bioretention and then the combined outlet of both systems (the second bioretention's independent outflow can be calculated by subtracting the first outflow from the combined outflow). This was due to a lack of access to the second bioretention outlet pipe before joining the outlet pipe from the first bioretention.

A good long term data set with numerous events is available although care should be taken in selecting events with reliable monitoring data. Information is available to assist this. The system has experienced issues with the first bioretention system leaching into the second, which compromises the integrity of the monitoring data. This should be considered when using the data in the future. It may be best to model both assets in parallel with an assumed level of infiltration from biofilter 1 reaching biofilter 2.

data quality												
good	ok/ needed manipulation		no good/ absent									

date	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10	May-10	Jun-10	Jul-10
rainfall					4th to 25th							
bypass				from 17th	3rd to 25th							
inlet 1		from 15th		★	★★★		★★	★		★★★ ★★		★★
inlet 2		from 15th									4th to 24th	
outlet 1		from 23rd			dec 31st to jan 21st			mar 10th to apr 9th				
outlet 2												

reasons	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10	May-10	Jun-10	Jul-10
rainfall					logger failed							
bypass	gas regulator no good until Thiess finally replaced it				debris?							
inlet 1	litter affecting readings in											
inlet 2	event peaks until litter trap built										damaged cable	
outlet 1	cable connection to sensor damaged				cable vandalised			water in repaired join in cable				
outlet 2												

★ monitored event

Figure 6-8 Timeline indicating periods of good, adequate and poor quality flow data

6.5 Wakerley Bioretention (Roberts *et al.*, 2012)

6.5.1 Site

The studied bioretention system is located in Wakerley, Queensland and treats stormwater runoff from a primarily low-density residential catchment (87ha). This system consists of a sediment pond (995 m^2) feeding a bioretention basin with a total treatment area of 2,865 m^2. The bioretention basin consists of three bioretention cells (955 m^2 per cell) that are separated by vegetated bunds. All dry weather base flows leaving the sediment pond are diverted into cell 3 to mitigate the risk of the submerged zone within the drainage layer of this cell drying out.

A maximum ponding depth of 0.3m is provided to increase the volume of runoff infiltrated through the system. When the maximum ponding depth is exceeded overflow pits allow for the egress of stormwater. In the event that design flood flows are exceeded (3.7m3/s, >100yr ARI) a high flow bypass is activated and runoff from the sedimentation pond is diverted away from the bioretention basin in order to protect vegetation from scour.

In each cell the same filter media is used (saturated hydraulic conductivity of 100mm/hr) but the transition and drainage layers vary in terms of depth and material. Cells 1 and 2 have a drainage layer that consists of a 100mm thick layer of gravel (5mm) placed around subsurface drainage pipes followed by a 100mm thick upper ‘transition layer’ of clean coarse sand (1-2mm, minimum saturated hydraulic conductivity of 4000+mm/hr). The drainage layer of cell 3 was designed to incorporate an additional submerged zone and includes a 900mm layer of pre-mixed material consisting of rock, woodchips and bio-solids (Table 1). The bio-solids seed the system with denitrifying bacteria while the wood chips act as a source of organic carbon to fuel microbial denitrification. The transition layer in cell 3 consists of a 150mm thick layer of 5mm gravel beneath a 150mm thick layer of clean coarse sand (1-2mm).

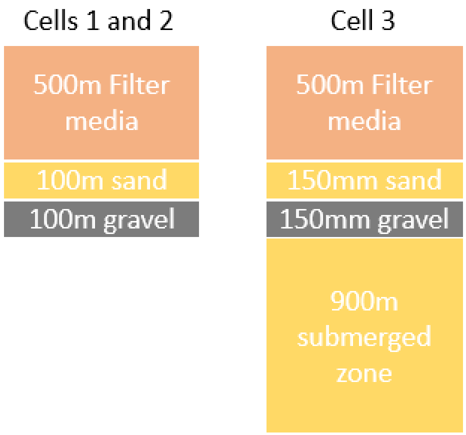
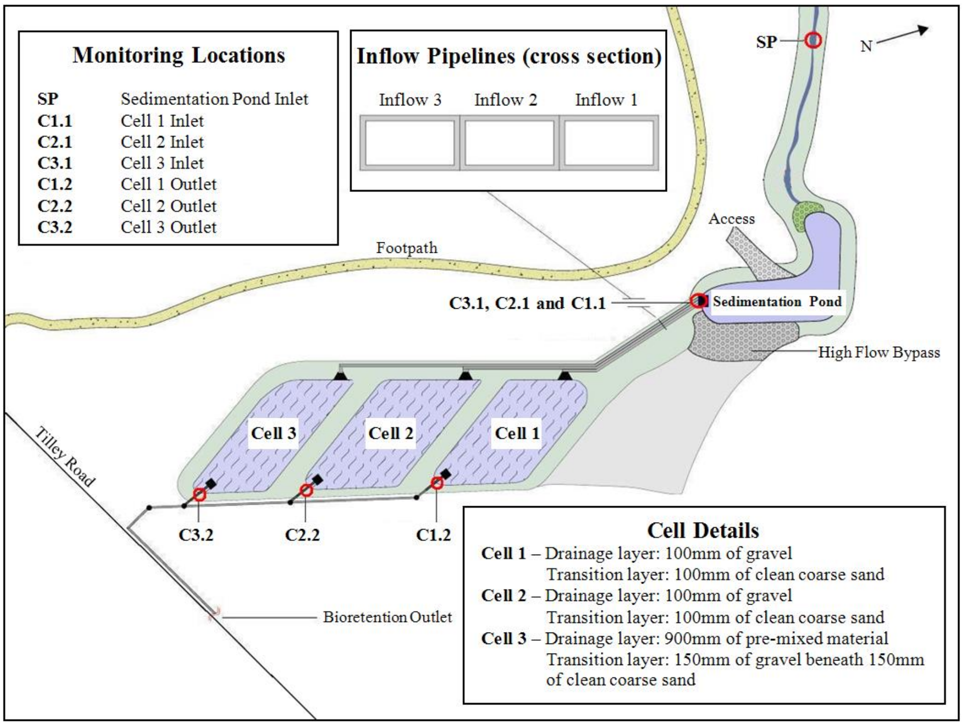


Figure 6-9 Visual representation of different cells

6.5.2 Climate conditions

Brisbane receives an average of 1,149 mm of precipitation per year with the relatively local BoM Capalapa Water Treatment Plant rainfall gauge 40458 receiving 1,270 mm during the monitoring period of April 2009 to March 2010.

6.5.3 Asset



Monitoring Locations

SP	Sedimentation Pond Inlet
C1.1	Cell 1 Inlet
C2.1	Cell 2 Inlet
C3.1	Cell 3 Inlet
C1.2	Cell 1 Outlet
C2.2	Cell 2 Outlet
C3.2	Cell 3 Outlet

Cell Details

Cell 1 – Drainage layer: 100mm of gravel
Transition layer: 100mm of clean coarse sand
Cell 2 – Drainage layer: 100mm of gravel
Transition layer: 100mm of clean coarse sand
Cell 3 – Drainage layer: 900mm of pre-mixed material
Transition layer: 150mm of gravel beneath 150mm of clean coarse sand

Figure 6-10 Wakerley Bioretention planting (Modified from Water and Management City Design, 2007)

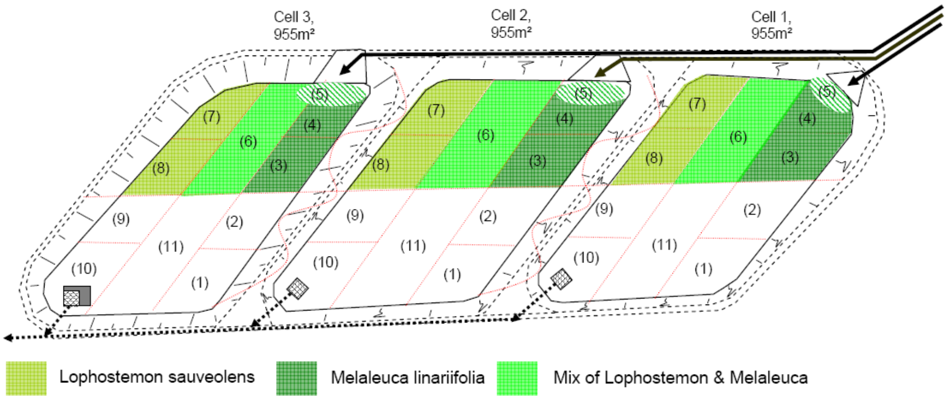


Figure 6-11 Wakerley Bioretention planting (Modified from Environment Management City Design, 2009)

Figure 6-12 Wakerley Bioretention (Dubowski and Dalrymple, 2012)

Figure 6-13 Wakerley Bioretention (Alcazar *et al.*, 2008)

6.5.4 Monitoring setup

Flows and water quality were monitored at the Wakerley site from April 2009 to March 2010; the location of each monitoring site is depicted in Figure 1. All flows were measured continuously on a 5 or 10 minute time step. Sigma 900 automatic samplers were used at the cell outlets (C1.2, C2.2, C3.2) and at the inlet to cell 3 (C3.1) to monitor flows and take flow weighted samples. Sigma 930 flow sensors (no samplers) were used to measure flows at the inlets to cells 1 and 2 (C1.1 and C2.1). Flow weighted samples were only taken at the inlet to cell 3 (C3.1) as concentrations of pollutants entering each cell was assumed to be uniform. Flows at the inlet of the sedimentation pond (SP) were measured with an Argonaut water flow monitoring device and samples were taken with a Sigma 900 automatic sampler. An Argonaut was required because of the irregular shape of the inlet channel leading into the sedimentation pond. Level sensors in each of the bioretention cells monitored the extended detention depth and were used to indicate high flow bypass occurrences. Event rainfall volume was recorded by a rainfall gauge located at the centre of the site.

6.5.5 Data available

Four events are currently available, one for basins 1,2 and 3 and one for basin 3. The available data consists of inflow and outflow data recorded at 5-minute intervals. Given the very limited data available and complexity of this site it may be a lower priority for calibration and validation but being located in Brisbane offers a higher rainfall climate than other assets.

6.6 Graham Bioretention Cell (EPA, 2019c)(Passeport *et al.*, 2009)

6.6.1 Site

Twin bioretention cells were constructed in the summer of 2005 at Graham High School in Alamance County, NC (Passeport *et al.*, 2009). The cells were constructed to reduce runoff and improve water quality from an adjacent parking lot and lawn, totalling 7100 m2 of drainage area. The available data for analysis is from the north cell of the bioretention.

The north bioretention cell was constructed with an underdrain configuration. The underdrain piping was outfitted with an upturned elbow, requiring the water depth in the storage layer to reach 0.45 m (from the native soil interface) before outflow occurs. This creates an internal storage zone (ISZ) in the bottom of the cell. The bottom 0.15 m of the cell is filled with gravel. The remaining 0.6 m of depth is filled with a combination of lightweight aggregate (80%), sand (15%), and compost (5%). The native soil beneath the bioretention cell is “loamy clay” (Passeport *et al.*, 2009). The cell is vegetated with Bermuda grass.

6.6.2 Climate conditions

Graham receives an annual precipitation of 1,137mm, with maximum average temperature of 25.4 degrees occurring in July and a minimum average temperature of 3.2 degrees in January. High rainfall coincides with higher temperatures, although there is significant precipitation in all months of the year. *Note: that the data provided as part of this study is* ***event-based****. Consequently, local climate is less influential than with studies that include extended periods of monitoring.*

6.6.3 Asset

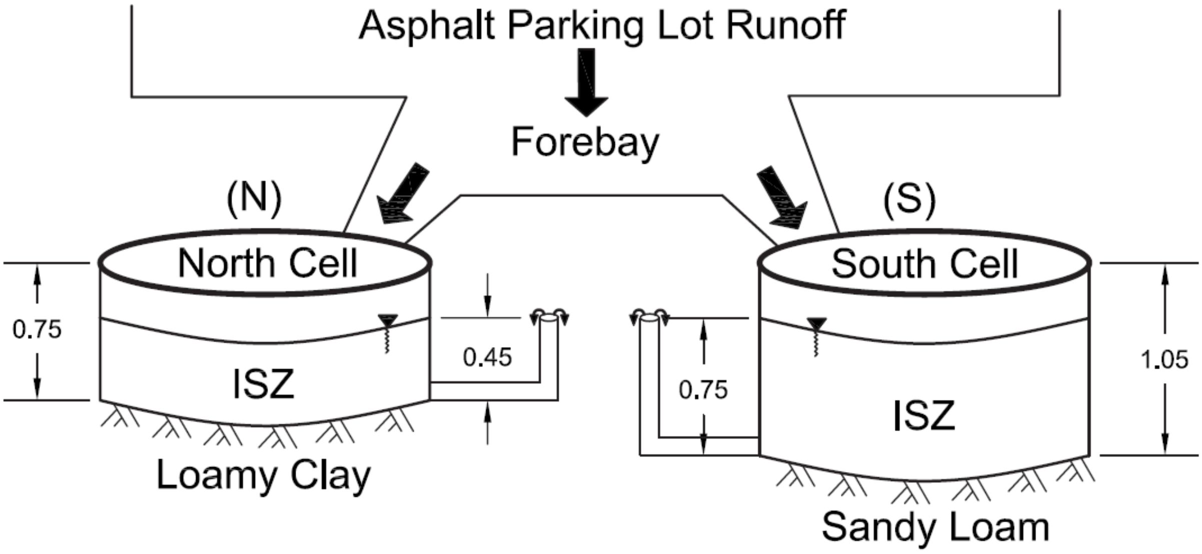


Figure 6-14 Schematic of Graham Bioretention Cell (Passeport *et al.*, 2009)

Figure 6-15 Graham Bioretention Cell (Google Maps, 2020)

6.6.4 Monitoring setup

Inflow measurements were recorded using a rectangular weir and an ISCO 730 bubbler module flow meter. Outflow was measured with a 90° V-notch weir and another ISCO 730 bubbler module. Inflow was measured on a 2-minute time-step while outflow was observed within 5-minute intervals.

6.6.5 Data available

Inflow and outflow data are available for 4 events, with durations ranging from 40mins to around 12 hours. Inflow rates are available on a 2-minute time-step while outflow was observed within 5-minute intervals.

6.7 Villanova Bioinfiltration Traffic Island

6.7.1 Site

The following site description was adapted from the EPA calibration study (EPA, 2019e).

Villanova's Bioinfiltration Traffic Island (BTI) was built in 2001 inside an existing traffic island on Villanova University's west campus (Lord, 2013). The biofilter cell receives runoff from an area of 0.52 hectare, approximately 44% of which is covered by impervious surface. To create the rain garden, the existing soil was excavated to form a large pit, and sand was mixed at a 1 to1 ratio with the existing soil and reintroduced to the cell, creating a 122-cm layer of soil media. The native in situ soil is classified as silt. The media is topped with hardwood mulch and planted with vegetation native to the New Jersey Coast. The traffic island was retrofitted into the shape of a shallow bowl that receives runoff from the adjacent parking lot and recreation area.

There are three inlets through which stormwater enters the cell: two storm drains on the west side and a curb cut on the east side. One of the storm drains on the west side also acts as an outlet for water exceeding the ponding depth 45.72 cm. It is equipped with a 90° V-notch weir installed 0.52 m above the lowest elevation in the basin. There is no gravel layer beneath the soil media nor is there an underdrain. The biofilter cell was designed to capture storms of approximately 2.54 cm. Runoff for events less than 2.54 cm infiltrates through the bottom and sides of the basin into in situ soil.

6.7.2 Climate conditions

Pennsylvania receives an annual precipitation of 1,041 mm, with maximum average temperature of 27.2 degrees occurring in July and a minimum average temperature of -7.2 degrees in January. Precipitation can fall as snow between December and March. *Note: that the data provided as part of this study is* ***event-based****. Consequently, local climate is less influential than with studies that include extended periods of monitoring.*

6.7.3 Asset

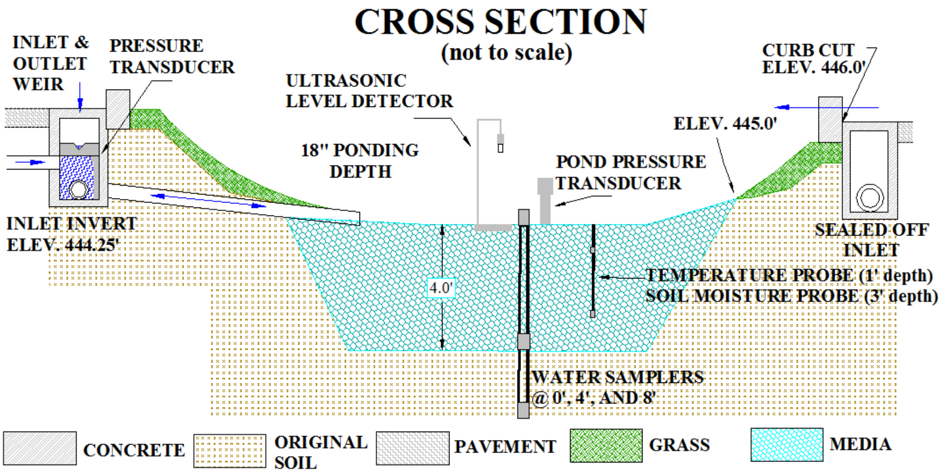


Figure 6-16 Villanova Traffic Island Bioretention Schematic (Lord, 2013)

Figure 6-17 Villanova Traffic Island Bioretention (Lord, 2013)

Figure 6-18 Villanova Traffic Island Bioretention (Lord, 2013)

Figure 6-19 Villanova Traffic Island Bioretention (VUSP, 2017)

6.7.4 Monitoring setup

Rainfall was monitored by an American Sigma Tipping Bucket Rain Gauge, Model 2149. A pressure transducer was used to record pond depth in the filter. Also, a pressure transducer was installed in the inlet side of the outlet storm drain to record stormwater depth in the basin and overflow over the weir (Lord, 2013). The inflow time series provided by researchers at Villanova University was created by combining measured inflow values through the western inlet with modelled inflow data for the east side curb cut.

6.7.5 Data available

The available data consists of 4 storms monitored between 2004-2012 with 5-minute intervals of inflow and outflow data. Events monitored vary between around 30 hours to 4 days. Measurements of water depth within the system are also available. From the data provided, it can be seen that several storms begin with existing standing water in the biofilter.

This site would be a good one to undertake calibration for, with potential for additional data to be obtained in future.

6.8 Kfar-Saba amphitheatre bioretention (Zinger, 2020)(Zinger and Deletic, 2013)

6.8.1 Site

The site for this asset is a park within a new “Green Neighborhood”, located in north west Kfar-Saba, about 17 kilometers north east of Tel Aviv in Israel

6.8.2 Climate conditions

Tel Aviv receives an annual precipitation of 562 mm in a highly seasonal pattern with most falling over the cooler 5 months. The maximum average temperature of 27 degrees occurring in August and a minimum average temperature of 14 degrees in January.

6.8.3 Asset

The bioretention asset was sited within an ‘amphitheatre’ setting in a public park within a new “Green Neighborhood”, located in north west Kfar-Saba.

The biofilter covers an area of 87 square meters. It is fully lined and has five layers of filter media, totalling 1.2 meters in depth. The bottom layer is permanently submerged and is enhanced with a cellulose-based carbon source to ensure effective denitrification (removal of nitrates). The top layer of the biofilter is free-draining loamy-sand (locally sourced) which supports plant growth and aerobic treatment processes. The biofilter system includes twelve different types of plants, of which 50% are Australian species that are known to be effective for pollutant removal while maintaining the filtration capacity of the system (de-clogging). The designed infiltration rate is between 300 and 400 mm/hr.

The asset is small for its catchment and inflows are regulated through a constrained inlet pipe.

The biofilter is a dual-mode system and receives urban stormwater during the wet season. In the dry season, groundwater is pumped into the system for irrigation and treatment of nitrates.

Figure 6-20 Kfar-Saba amphitheatre biofilter

6.8.4 Monitoring setup

Inflows and outflows are monitored.

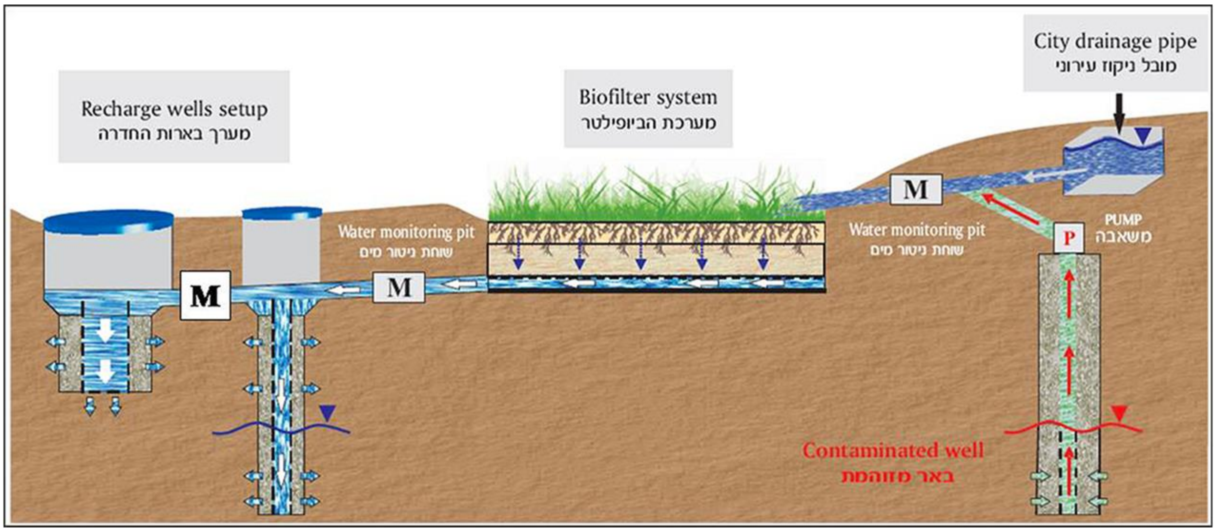


Figure 6-21 EOC Kfar-Saba amphitheatre biofilter monitoring pits

6.8.5 Data available

Approximately 2 years of data is potentially available.

This site could represent a challenge test for a model with a long dry period when flows are supplemented with groundwater.

6.9 Hamilton West Ecoroof (EPA, 2019d)

6.9.1 Site

The asset is constructed on the roof of the 10 storey Hamilton apartment complex in Portland, Oregon USA. The roof is split east to west, with each side draining to a separate outlet. The green roof received runoff from the paved terrace area, as well as direct rainfall.

The Hamilton Ecoroof uses an impermeable liner and contains between 10-12cm of soil for growing media. Therefore, this asset can be classed as an **extensive green roof** (<15cm of growing media). The west side substrate consists of 20% digested fibre, 20% coir fibre, 10% compost, 22% perlite, and 28% sandy loam (Portland 2010). Field capacity of the growing media was noted at 0.32.

The area of the west side of the roof is reported to be **243 m^2**. Flows exceeding the storage capacity of the growing medium flows to a roof drain as underflow or overland flow. The asset has a slope of approximately 2.1%.

6.9.2 Climate conditions

Portland receives an annual precipitation of 625mm, with maximum average temperature of 21 degrees occurring in August and a minimum average temperature of 5 degrees in December. *Note: that the data provided as part of this study is **event-based**. Consequently, local climate is less influential than with studies that include extended periods of monitoring.*

6.9.3 Asset

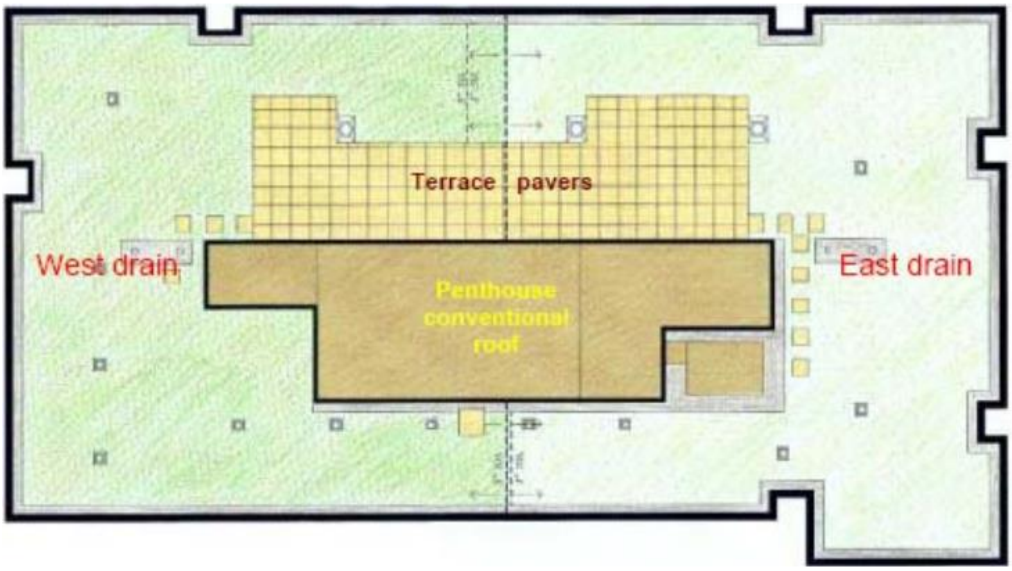


Figure 6-22 Hamilton Ecoroof (Portland Bureau of Environmental Services, 2000)

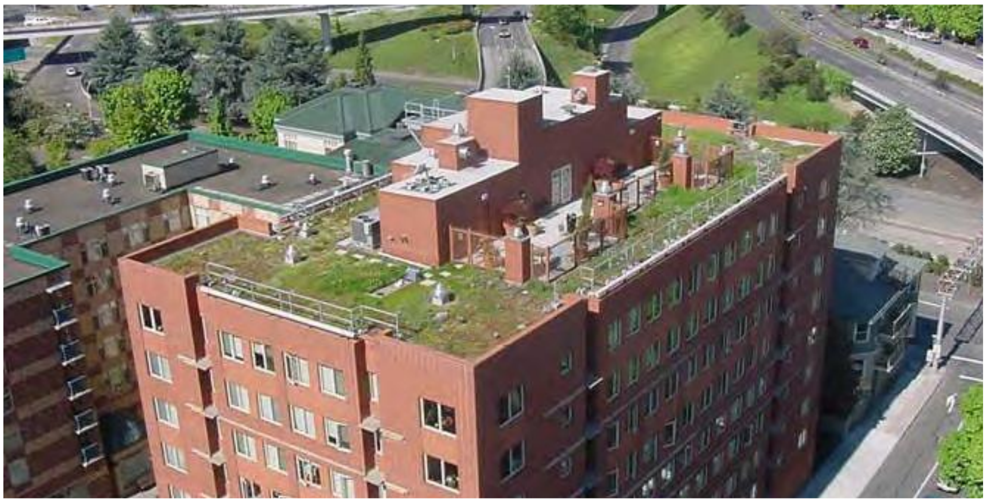


Figure 6-23 Hamilton Ecoroof (Portland Bureau of Environmental Services, 2010)

6.9.4 Monitoring setup

The flow monitoring equipment for the asset consists of a small, 60°, V-trapezoidal flume installed adjacent to and immediately upstream of each primary roof drain (Hutchinson et al., 2003; She and Pang, 2010). Water levels in the flumes are measured by American Sigma Model 950 bubbler-type flow meters and converted to flow values using a level-to-flow relationship specific to these flumes. A Hydrological Services tipping bucket rain gauge installed atop the conventional roof in the centre of the building collects rain data for the site (EPA, 2019d).

6.9.5 Data available

The available data from the EPA study consists of 4 storms monitored between 2004-2006 with 5-minute intervals of inflow and outflow data. The monitoring periods vary between 9 hours to 4 days.

https://edg.epa.gov/metadata/catalog/search/resource/details.page?uuid=%7B04561E97-088A-4612-9B0E-F04CB4799A8D%7D

6.10 Emergency Operations Centre green roof (EPA, 2019a)

6.10.1 Site

The Emergency Operations Center (EOC) Green Roof is located on the top of the EOC building complex in Seattle, WA. The vegetated area of the EOC green roof is 685 m^2. The roof only intercepts precipitation that falls on it; no additional runoff is received from adjacent areas. Outflow moves through the granular storage layer along the bottom of the green roof and, ultimately, out through a roof drain, where flow was measured during the monitoring study. All water from the roof that is not captured by the vegetation leaves the installation through the roof drains and drainage system.

The green roof is filled with 50mm of granular stone and 100mm of growing media. The media for the 50mm drainage layer is granular drainage media. The growing media is a proprietary soil mix described as moderately coarse with low silt content and moderately high moisture content at field capacity. The underlying drainage layer is described as a granular media with a high permeability and porosity greater than 0.2 (EPA, 2019a).

6.10.2 Climate conditions

Seattle receives an annual precipitation of 943mm, with maximum average temperature of 15 degrees occurring in August and a minimum average temperature of 7 degrees in January. *Note: that the data provided as part of this study is **event-based**. Consequently, local climate is less influential than with studies that include extended periods of monitoring.*

6.10.3 Asset

Figure 6-24 EOC Seattle Green Roof (Taylor Associates, 2012)

6.10.4 Monitoring setup

A flow-monitoring station measured flow using a Unidata tipping bucket gauge for low flow rates and an electromagnetic flowmeter a 5cm Unimag magmeter for higher flow rates. Precipitation was measured by a tipping bucket rain gauge on the adjacent fire station roof (EPA, 2019a).

6.10.5 Data available

The available data consists of 4 storms monitored between 2009-2010 with 5-minute intervals of inflow and outflow data. The monitoring periods vary between 12 hours to 3 days (EPA, 2019a).

This site is suitable for within event calibration for green roofs.

6.11 Fire station 10 green roof

6.11.1 Site

The Fire Station 10 Green Roof is located on the top of the Fire Station 10 (FS10) building complex in Seattle, WA. The vegetated area of the FS10 green roof is 595 m2. The roof only intercepts precipitation that falls on it; no additional runoff is received from adjacent areas. Outflow moves through the granular storage layer along the bottom of the green roof and, ultimately, out through a roof drain, where flow was measured during a 2008-2011 monitoring study. All water from the roof that is not captured by the vegetation leaves the installation through the roof drains and drainage system.

The green roof is filled with 50mm of granular stone and 100mm of growing media. The media for the 50mm drainage layer is granular drainage media. The growing media is a proprietary soil mix described as moderately coarse with low silt content and moderately high moisture content at field capacity. The underlying drainage layer is described as a granular media with a high permeability and porosity greater than 0.2 (EPA, 2019b)

6.11.2 Climate conditions

Seattle receives an annual precipitation of 943mm, with maximum average temperature of 15 degrees occurring in August and a minimum average temperature of 7 degrees in January.

6.11.3 Asset

Figure 6-25 FS10 Seattle Green Roof (Taylor Associates, 2012)

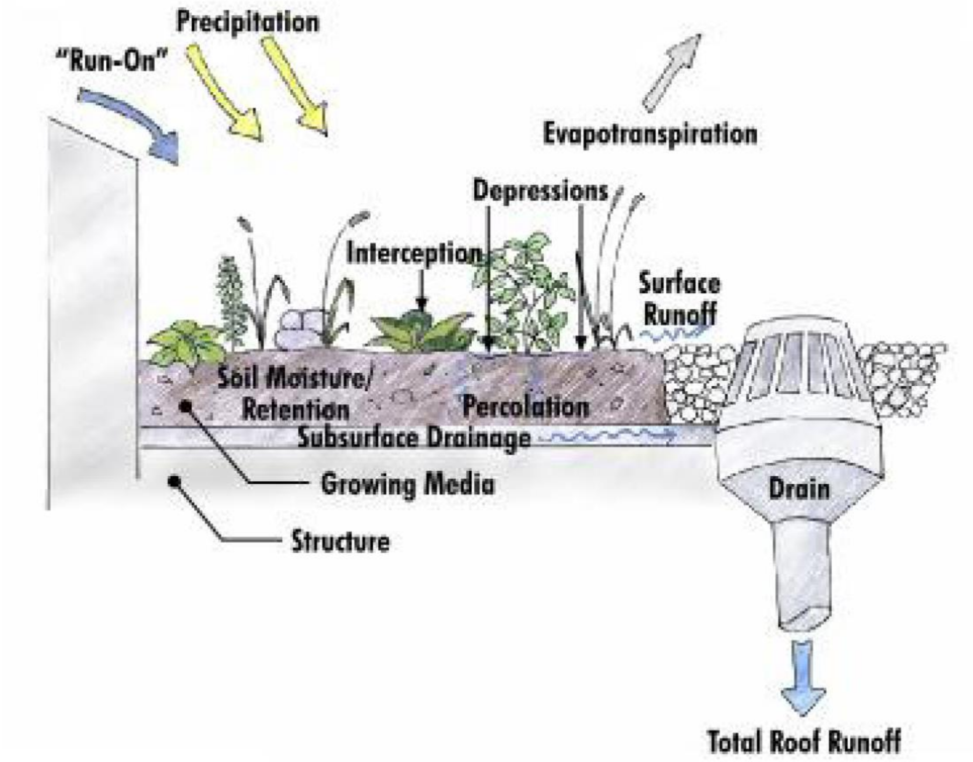


Figure 6-26 Green roof schematic (Taylor, 2008)

6.11.4Monitoring setup

A flow monitoring station measured flow using a Unidata tipping bucket gauge for low flow rates and an electromagnetic flowmeter (a 5.08-cm Unimag magmeter) for higher flow rates. Precipitation was measured by a tipping bucket rain gauge on the fire station roof (EPA, 2019b).

6.11.5Data available

The available data consists of 2 periods in 2009 and 2010.The data contains 5-minute intervals of inflow and outflow data. The monitoring periods are close to 3 months each (EPA, 2019b).

This data set is the longest continuous data available for green roofs currently available making it attractive for testing the inter-event representation of evapotranspiration. The mean annual rainfall is also quite close to Sydney, although climatic conditions differ.

6.12 Green Roof Diagnostics – Green roof laboratory

Contact has been made with Green Roof Diagnostics. The company operates a green roof laboratory with a rain simulator and series of intensively and accurately monitored test beds. The company generally undertakes contract monitoring of green roofs for clients including green roof suppliers. They hold a wealth of monitored data for events from their rain simulator for a wide range of events. They are also currently supporting a monitoring project commencing in Sydney with Western Sydney University.

Discussion with Brad Garner indicates that individual storm event data of interest for assessing detention and flood mitigation effectiveness is broadly applicable and existing or new data sets developed with the companies' rain simulator could be readily applied for use in Sydney. Conversely, climatic conditions are more specific to context (including rainfall, evapotranspiration and seasonality) and it is best to conduct local monitoring. They can offer advanced monitoring and diagnostic capabilities in this regard and have systems under monitoring in a number of countries around the world.

It is recommended that a dedicated project is established to collaborate with Green Roof Diagnostics to develop data of specific use in Sydney and also to undertake modelling and calibration using selected (or new) data from their rain simulator.

Figure 6-27 Green roof testing laboratory (Green Roof Diagnostics, 2020)

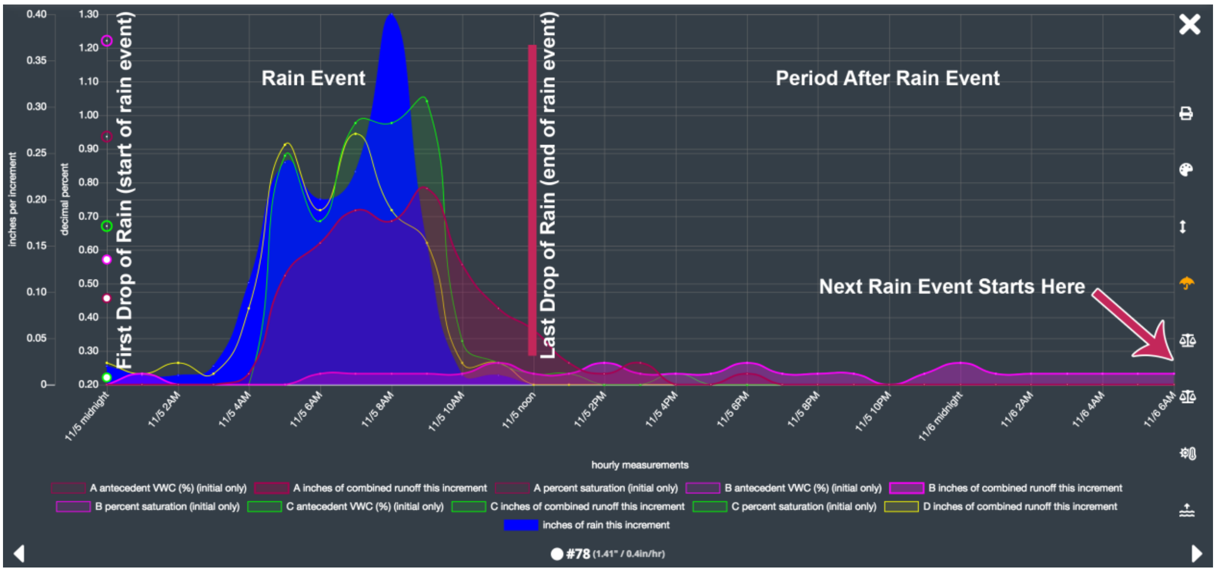


Figure 6-28 Green roof event monitoring (Green Roof Diagnostics, 2020)

6.13 Monash Tree Pits

6.13.1 Site

Four residential streets were selected for this study. Two are located in Glen Waverley and two in Oakleigh in Melbourne, Victoria.

6.13.2 Climate conditions

The monitoring period was September 2014-March 2016.

Long term mean annual rainfall for Glen Waverley is 835 mm/year (086303) and was 740 mm/year for the 3 years within which monitoring occurred. Total rainfall for Glen Waverley from the study was 880.2 mm for the monitoring period.

Long term mean annual rainfall for Oakleigh is 736 mm/year (086303) and averaged 649 mm/year (accounting for missing data) for the 3 years within which monitoring occurred. Total rainfall for Oakleigh from the study was 789.88 mm for the monitoring period.

6.13.3 Asset

The tree pit assets include a total of 36 tree pits across four streets of which 23 had infiltration trenches, 12 were controls and 1 was excluded due to construction works. The assets have a range of different combinations as follows:

- Soils: Sandy clay, clay
- Tree: Evergreen, deciduous
- Inlet types: Lintel, pit
- Type: Control, infiltration trench with lintel inlet, infiltration trench with pit inlet

The inlets were found to be a limiting factor for the retention that was achieved by the tree pits.

The same infiltration trench was used for both treatments with a two different inlet types. The surface area of each trench was 6 m^2 and the edge was 1.5 m from the base of the study tree. The trenches were filled with 20-40 mm diameter gravel. A weed mat and ~100 mm of topsoil was installed above the trench and sown with grass.

Two streets in Oakleigh classed as sandy clay had sandy loam topsoil to 100-300 mm and two in Glen Waverley had shallow sandy loam topsoil up to 100 mm depth while all sites have medium or heavy-textured clay subsoil.

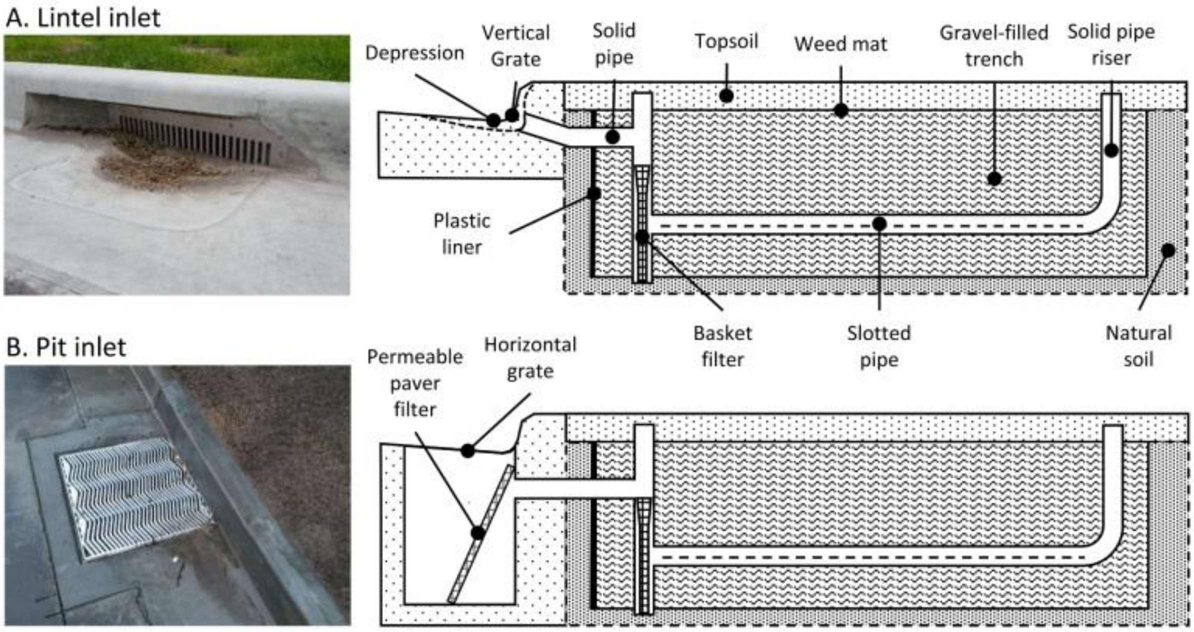


Figure 6-29 Monash inlet and tree pits schematic

6.13.4Monitoring setup

Rainfall data at a 6 minute interval was supplied by Melbourne Water from the Oakleigh South and Glen Waverley rainfall gauges for the sandy clay and clay sites respectively for the monitoring period (September 2014-March 2016). These were within 3 kilometres of the sites.

Runoff into the tree pits was estimated based upon effective rainfall (>0.5 mm).

Water level was monitored in each trench at 6 minute intervals using Dataflow Systems Limited capacitance water level sensors (0.5 m long).

6.13.5 Data available

Data available include rainfall and water levels for a period from September 2014-March 2016. Inflows and outflows were not monitored although retention was estimated based on water levels.

This site is considered to have the better design configuration and monitoring data available of the available tree pit data sets for Szota (2019a)and Grey (2018).

6.14 Barrow Street tree pits

Tree pits in Barrow Street, Moreland. To be documented if data obtained and found to be useful. (Grey, Stephen J Livesley, *et al.*, 2018).

6.15 Villanova Infiltration Trench (Traver, Dean and Emerson, 2005; Emerson, 2008; EPA, 2019e)

6.15.1 Site

Site description adapted from EPA calibration study (EPA, 2019e)

The infiltration trench retrofit at Villanova University was constructed in 2004 and receives drainage from a parking garage. The total drainage area is approximately 1895 m^2. The excavation for the trench was 1.8 m deep. It is lined with a nonwoven geotextile and filled with crushed stone to create a void space of approximately 40%. Eco-pavers are used on the trench surface and provide approximately 17% pervious area per square meter. The inflow enters via a single 10-cm pipe that empties into an adjacent monitoring bench. There is 15-cm overflow pipe that connects the storage bed to the existing inlet. The storage bed begins to overflow when the water is approximately 1.58 m deep.

6.15.2 Climate conditions

Pennsylvania receives an annual precipitation of 1,041 mm, with maximum average temperature of 27.2 degrees occurring in July and a minimum average temperature of -7.2 degrees in January. Precipitation can fall as snow between December and March. *Note: that the data provided as part of this study is **event-based**. Consequently, local climate is less influential than with studies that include extended periods of monitoring.*

6.15.3 Asset

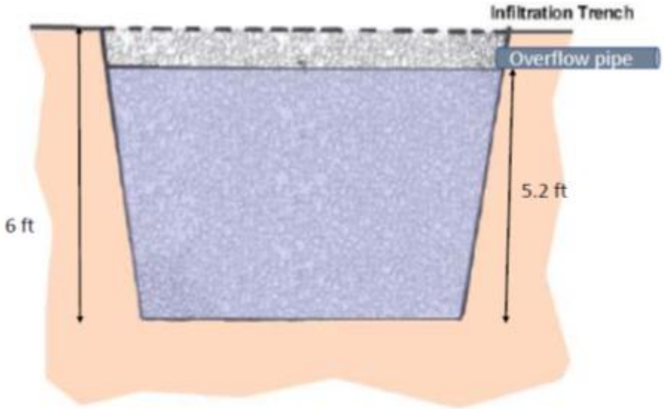


Figure 30 System cross-section (Emerson, 2008)

Figure 31 Completed infiltration trench (Emerson, 2008)

6.15.4 Monitoring setup

The equipment in the monitoring bench includes a V-notch weir and pressure transducer. A pressure transducer also was installed in a monitoring well in the trench itself to monitor the depth of water in the storage media. Rain was monitored by a tipping bucket rain gauge located in the parking garage.

6.15.5 Data available

The available data consists of 3 storms monitored in 2004 with 1-minute intervals of inflow and observed storage height within the trench. Events monitored vary between around 17 hours to 3 days.

7. Modelling and calibration

This project has focussed on monitored data for green infrastructure while it is anticipated a subsequent project will focus on modelling, calibration and validation. A brief outline is provided for context.

There are a range of models available for green infrastructure. The most commonly used ones are:

- MUSIC
- SWMM

MUSIC was developed by the Cooperative Research Centre for Catchment Hydrology and is maintained by eWater. It is the most commonly used stormwater model in Australia and is widely accepted as the model used for development approvals across most of Australia.

The SWMM model is developed and maintained by the US EPA as a freely available open-source stormwater model. In recent years, its capability for simulating green infrastructure has improved significantly, however it is not yet widely used in Australia. More sophisticated user interfaces are also available through private providers such as PC-SWMM (CHI) and Info SWMM (Innovyze).

There are also a range of commercial, public and research models in existence that may also be considered. Initial models of potential interest include:

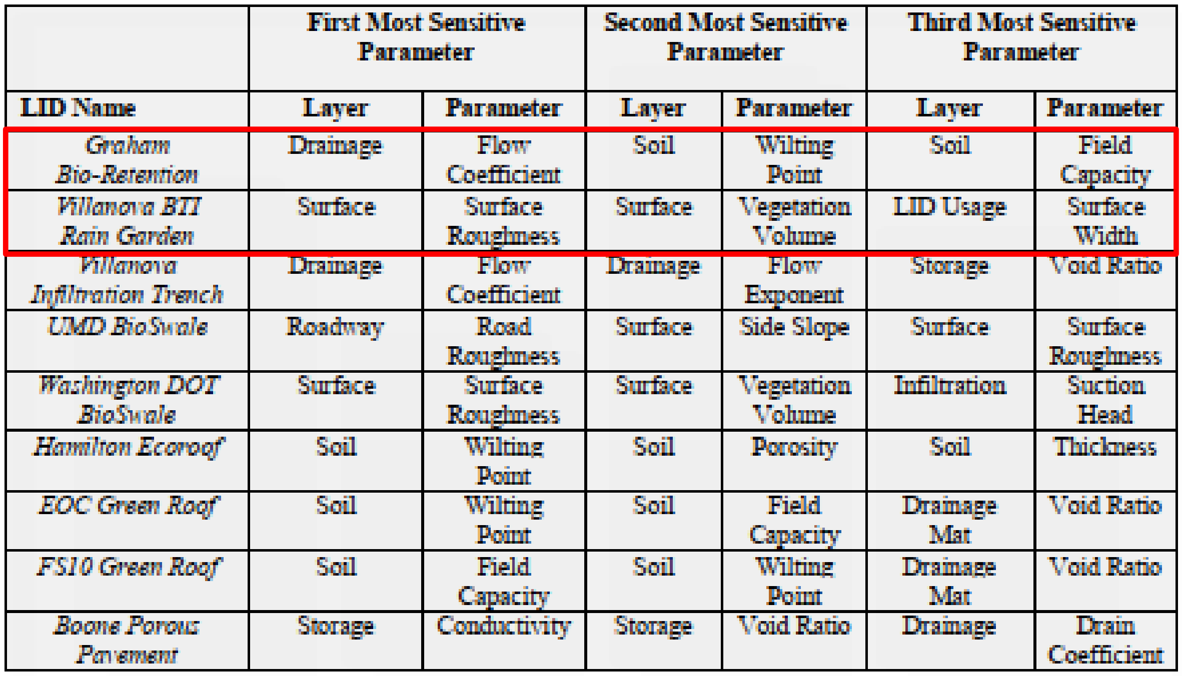
- Monash bioretention model
- University of Sheffield green roof model

7.1 Bioretention models and calibration

The US EPA recently undertook calibration of the SWMM model (Platz, Simon and Tryby, 2020) using selected data for a range of green infrastructure including two bioretention assets. While the study focused on matching SWMM's hydrograph results to an observed monitoring period of the two bioretention systems, the data for these periods are available including inflow and outflow hydrographs. These assets are discussed in Chapter 6 - Detailed data sets.

This section provides a preliminary summary of selected efforts to understand the differences in bioretention performance based on statistical analysis and calibration of process-based models.

The US EPA recently undertook calibration of the SWMM model using selected data for a range of green infrastructure including two bioretention assets. About four storm events were calibrated for each assets and the key influencing SWMM model parameters were identified. The study focussed on matching peak flows and found that the flow coefficient and surface roughness were most influential followed by the filter media wilting point and the vegetation volume (which is related to the surface storage capacity) then the field capacity and surface width. Many of the parameters relate to the focus on peak flows while the ‘vegetation volume’ points to the surface storage capacity and the wilting point and field capacity to the filter media water storage capacity as key influencing parameters.



	First Most Sensitive Parameter		**Second Most Sensitive Parameter**		**Third Most Sensitive Parameter**	
LID Name	**Layer**	**Parameter**	**Layer**	**Parameter**	**Layer**	**Parameter**
Graham Bio-Retention	Drainage	Flow Coefficient	Soil	Wilting Point	Soil	Field Capacity
Villanova BTI Rain Garden	Surface	Surface Roughness	Surface	Vegetation Volume	LID Usage	Surface Width
Villanova Infiltration Trench	Drainage	Flow Coefficient	Drainage	Flow Exponent	Storage	Void Ratio
UMD BioSwale	Roadway	Road Roughness	Surface	Side Slope	Surface	Surface Roughness
Washington DOT BioSwale	Surface	Surface Roughness	Surface	Vegetation Volume	Infiltration	Suction Head
Hamilton Ecoroof	Soil	Wilting Point	Soil	Porosity	Soil	Thickness
EOC Green Roof	Soil	Wilting Point	Soil	Field Capacity	Drainage Mat	Void Ratio
FS10 Green Roof	Soil	Field Capacity	Soil	Wilting Point	Drainage Mat	Void Ratio
Boone Porous Pavement	Storage	Conductivity	Storage	Void Ratio	Drainage	Drain Coefficient

Figure 7-1 Sensitivity of parameters based on SWMM calibration studies (Platz, Simon and Tryby, 2020)

Davis (Davis *et al.*, 2012) reviewed a selection of assets and performance data in the US and developed a range of equations to estimate volumetric performance for events. They found that as there were wide differences between systems with different configurations it was necessary to develop different equations for the following configurations:

- No underdrain
- Underdrainage
- Underdrainage with (unlined) submerged zone
    - Slow draining soils
    - Quick draining soils

Davis approach and equations may be worthy of further consideration and potential refinement.

This paper points to a key challenge with bioretention that different configuration may fundamentally behave very differently and that attempting to develop statistical relationships or numerical equations across these may be problematic. It is therefore considered that it may be preferable to categorise the available bioretention data across key different configurations. At a minimum these may include bioretention with:

- No underdrain and infiltration
- Underdrainage and infiltration
- Underdrainage and no infiltration
- Underdrainage with unlined submerged zone
- Underdrainage with lined submerged zone

Consideration may then need to be given to whether different categories are needed for different underlying soils.

A challenge with this approach is that there are already few datapoints for bioretention to support statistical analysis and categorising further reduces this.

The paper also found a fairly clear threshold of potential capture emerged with inflow volumes reaching this threshold before outflow occurred in the majority of events followed by a linear relationship between inflow and outflow, see Figure 7-2.

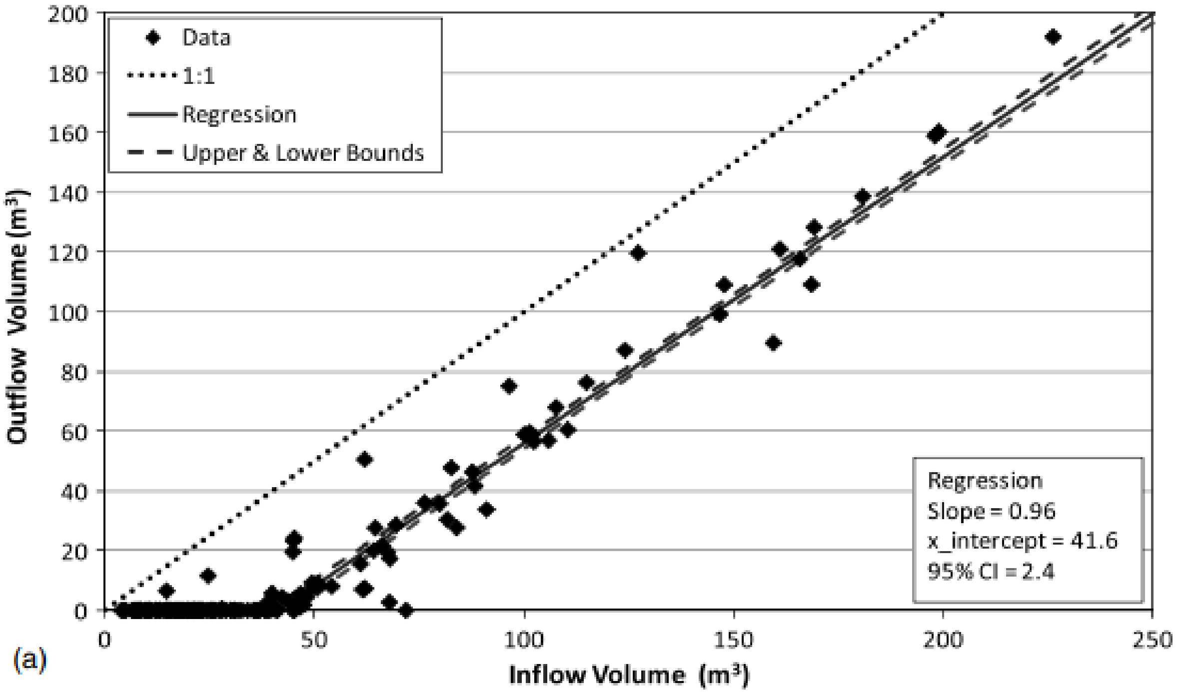


Figure 7-2 Relationship between inflow and outflow (Davis *et al.*, 2012)

7.2 Green roof models and calibration

The US EPA recently undertook calibration of the SWMM model (Platz, Simon and Tryby, 2020) using selected data for a range of green infrastructure including three green roof assets. The study focused on matching SWMM's hydrograph results to observed events. Two studies have event data and the third has continuously monitored data available for two three month periods. The data for these are available and the assets are discussed in Chapter 6 Detailed data sets.

7.3 Passively irrigated tree pit models and calibration

Specific models for passively irrigated tree pits were not researched. The bioretention modules in models such as MUSIC and SWMM may be used but require modified parameterisation to better represent the differences in media surface area, pond storage surface area and canopy (evapotranspiration surface) area.

Calibration for these assets may be of greater importance to improve the accuracy of representation for stormwater volume reductions.

8. Discussion of data and application for Sydney

The primary use of the data will be for application in the Greater Sydney region. Within this area, the western suburbs and growth areas are of particular interest given substantial projected future growth and an identified need to manage stormwater volumes to protect waterway health.

8.1 Climate

Climate conditions for Western Sydney have previously been assessed (E2Designlab, 2016) and the mean annual average rainfall was found to be 781 mm/year and 952 mm/year for two rainfall bands broadly covering the western suburbs as shown in Figure 8-2.

8.2 Soils in Sydney

The Sydney region is diverse with a range of soil conditions from heavy clays in Western Sydney through to sandy areas adjacent to the river and coastline. However, a significant proportion of the areas of interest (in Western Sydney) are in clay soil areas. These have a range of potential issues including:

- Poor drainage / low infiltration rates – These may inhibit the infiltration of stormwater to achieve volume reductions
- Reactivity – Reactive clay soils shrink and swell with drying and wetting conditions which can adversely impact on buildings and other infrastructure if not carefully managed
- Salinity – High salinity levels can adversely impact upon vegetation health when groundwater levels rise and result in saline inflows entering waterways
- Sodicity – Sodic soils have a high proportion of sodium relative to other cations which can lead to poor soil structure and drainage.
- Dispersivity – Dispersive soils have low strength and are susceptible to erosion when exposed to saturated conditions

A significant proportion of the Western Sydney area is identified as having a moderate or high risk of salinity based on broad scale mapping, see Figure 8-3 and Figure 8-4.

Generally, infiltration is not recommended in saline landscapes due to the potential to either increase groundwater levels or transport salts resulting in impacts on infrastructure, waterways or vegetation.

However, as noted by Hoban et al. (Hoban *et al.*, 2020), *this must be balanced with the greater risk of degradation of waterways posed by urban stormwater runoff*. In the Western Sydney context, reducing urban stormwater runoff is recognised as being essential for the protection of waterways such as South Creek.

The soils throughout the area are heterogenous with significant variations. While it is often assumed that infiltration practices are not feasible in Western Sydney areas due to the soil conditions, this assumption needs to be more closely examined and actual conditions assessed to understand the potential for different stormwater management practices involving infiltration to be used.

Furthermore, the overall objective of stormwater management for volume control is to achieve waterway hydrologic conditions that approximately mimic the natural conditions. It is recognised that urbanisation will reduce evapotranspiration and infiltration and increase stormwater surface runoff. To reverse this process necessarily requires that both evapotranspiration and infiltration are restored to at least some extent. An important recognition here is that most of the changes from urbanisation are reductions in evapotranspiration (including evaporation from soils and transpiration from plants and trees) while a less proportion is from reductions in infiltration due to paving of the soil surface.

There are also potential beneficial effects of trees and Hoban (Hoban *et al.*, 2020) cites the Western Sydney Salinity Code of Practice referring to the cumulative effects of vegetation loss within a catchment contributing to a changed water cycle which can result in (dryland) salinity. Revegetation and planting with trees can potentially address this by helping to draw down water tables.

Significant green areas are proposed to be established within the Western Parkland City with aspirations for a 40% canopy target. The establishment of vegetation will help to maintain groundwater levels. The judicious passive and active irrigation of this landscape can potentially increase evapotranspiration rates to compensate for the evapotranspiration lost from the balance 60% of area that is paved. This can contribute to restoring both the hydrologic balance by reducing stormwater volumes and the energy balance through maintaining the cooling effects of shading from trees as well as evapotranspiration and the corresponding latent heat flux. These areas can also allow for infiltration to occur which reduces stormwater volumes and helps to leach salts from the soils down into groundwater and away from vegetation.

Review of the salinity data indicates that areas of higher salinity risk are often concentrated around waterways where heavier and poorly draining soils may be encountered. This indicates that it may be preferable *to achieve infiltration in areas distributed through a catchment* and to avoid concentrating infiltration efforts within flood plain corridors towards the end of the drainage system. This may necessitate some change in thinking and approach with respect to the placement of biofilters allowing infiltration.

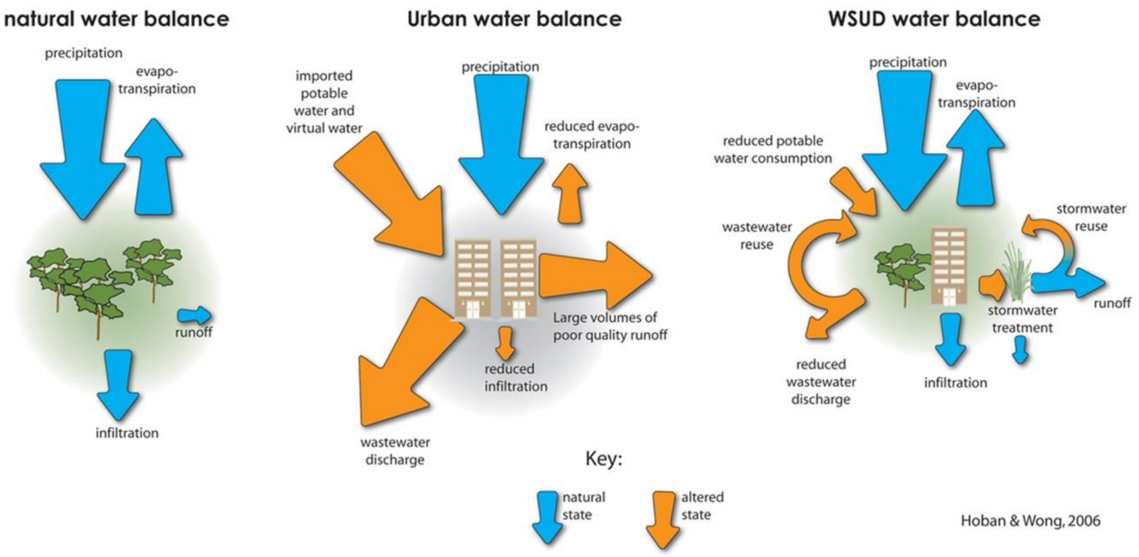


Figure 8-1 Water balance showing change from natural state to urbanised and with WSUD (Hoban and Wong, 2006)

8.3 Commentary from the literature

The primary objection to infiltration practices is that they will be ineffective in slow draining areas. Argue (Argue and Pezzaniti, 2003) make the point that while this does not preclude infiltration there will be a greater economic cost in slower draining soils so the question is primarily one of economics rather than possibility.

Researchers working under Tim Fletcher (Hamel *et al.*, 2011; Poelsma, Fletcher and Burns, 2013a) have shown that significant, albeit more limited, infiltration can be achieved even in heavy clay soils through well-designed biofilters including the use of underlying storage.

The monitoring studies assessed in this report have generally confirmed this with a number of authors reporting better than expected infiltration volumes or significant outcomes even in heavier and slow draining soils. For example, Winston (Winston, Dorsey and Hunt, 2016) expected low infiltration rates for the soils underlying the bioretention assets monitored at Holden Arboretum and Ursuline College. However, they still delivered significant volume reductions. Szota (Szota *et al.*, 2019a) also observed low but significant retention for tree pits in clay soils with the best performing tree pit achieving 43.7% retention with an exfiltration rate of just 0.16 mm/hr.

In terms of design, low infiltration rates can be compensated for with a larger treatment footprint and use of a temporary submerged zone below the underdrain.

8.3.1 Infiltration pathways

Lateral infiltration

A further consideration is potential infiltration pathways. Some authors such as Winston and Hamel (Hamel *et al.*, 2011; Winston, Dorsey and Hunt, 2016) have reported that lateral exfiltration from biofilters was significant or even the dominant pathway for infiltration, contrary to the popular wisdom that water infiltrates downwards with gravity. Lateral exfiltration can occur through adjacent soils that may be vegetated, better structured and more freely draining than deeper underlying soils. This potentially makes the water available to surrounding vegetation and trees. Hamel (Hamel *et al.*, 2011) attempted to better understand this at the Rangeview Road biofilter in Mt Evelyn but was unable to show significantly greater evapotranspiration close to the biofilter than further away, likely due to prevailing wetter conditions at the time of the monitoring. A caveat on this study by Hamel is that it was later found that a hard-pan layer may have further exacerbated the lateral exfiltration (Pers. Comm, Tim Fletcher), although similar outcomes without this feature was also observed by Winston. Szota (Szota *et al.*, 2019a) tested infiltration rates at a range of depths and observed much higher infiltration rates at shallow depths than deeper, which would encourage greater lateral exfiltration.

Browne (Browne *et al.*, 2008) has shown that lateral exfiltration comprises a significant proportion of the water balance for infiltration trenches and that it needs to be considered to accurately estimate potential flows. The importance of lateral exfiltration has also been flagged through calibration of the SWMM model (Platz, Simon and Tryby, 2020). This study found the lack of representation of lateral exfiltration processes in the model inhibited calibration. This suggests that this needs to be considered for future modelling.

It is noted that lateral exfiltration from a bioretention submerged zone is approximated in MUSIC although not from the filter media itself.

‘Urban karst’

In urban areas, sub-surface flows can be facilitated through the extensive service trenches established for utilities and pipelines. Bonneau et al. introduce the concept of the urban karst where they posit that urban areas can be likened to limestone where water is able to freely move through the numerous trenches present (Bonneau *et al.*, 2017). In seeking to assess the level of infiltration occurring from the Wicks Reserve bioretention asset and its effect on groundwater levels, it was found that a sewer line appeared to divert some flows away from the area. This is a probable situation in many locations where WSUD assets allowing infiltration may be planned. For this reason, it should be assumed that a proportion of infiltrated flows will return to drainage and waterways as low flows.

As long as these flows are attenuated through vegetation and soils such as raingardens, they can most likely be treated as beneficial low flows that help to sustain baseflows in the waterway although consideration of potential impacts on ephemerality and ‘cease to flow’ days may also be needed for smaller tributaries. Research has previously shown that flows through an adequately sized biofilter can ‘mimic’ natural hydrology (DeBusk, Hunt and Line, 2010).

Surrounding vegetation

Study of the same site (Bonneau *et al.*, 2020) found through monitoring of groundwater levels that the well-established native eucalypt trees within the reserve downslope of the bioretention were effectively evapo-transpiring water from the groundwater down-slope of the bioretention basin. As a result, the recharge of groundwater occurring was relatively minimal. This wasn’t the intended outcome as it was anticipated the bioretention would help to recharge groundwater to maintain low flows within the waterway. However, it clearly demonstrates the value of positioning bioretention in proximity to and ideally upslope of deep-rooted vegetation such as trees to maximise the amount of evapotranspiration that occurs. This could be applied through the planting of trees within and adjacent to bioretention with consideration of slope and likely groundwater flow directions to achieve the best outcomes. Assets such as passively irrigated tree pits inherently leverage this by providing a canopy area over what is typically a smaller surface area for stormwater infiltration.

The effect of ‘adjacent’ vegetation for lateral infiltration and evapotranspiration from surrounding soils and groundwater are not yet well understood but could yield significant benefits and this is an area warranting further research. Sufficient evidence exists for an approach of pursuing adjacent planting to be adopted as a ‘no regrets’ strategy expected to have upside benefits.

8.4 Design and configuration

There are clear differences in outcomes with different configurations. Since infiltration is the dominant pathway to reduce stormwater volumes in biofilters and passively irrigated tree pits, the use of unlined assets will be preferred. For green roofs, they comprise a large proportion of their catchment and as a result evapotranspiration is the dominant retention pathway.

In Western Sydney, there will also be a need to provide soil moisture for plant survival which points to the use of ‘submerged zone’ bioretention assets. In this respect, the use of unlined submerged zones within any biofilter assets is likely to be effective for retaining moisture within assets (recognising infiltration rates will be low and surrounding soils will retain moisture) and encouraging greater volumes of infiltration.

Further research into such designs in the context of Western Sydney to more precisely quantify expected volumes of evapotranspiration, infiltration, lateral and subsequent evapotranspiration and groundwater recharge would be desirable.

8.5 Summary

It is important to recognise there are significant opportunities and benefits to be realised in delivering on both a parkland city and healthy waterways and at the same time significant and difficult challenges to be overcome for stormwater practices including infiltration to be adopted through the Western Sydney area. They are essential for supporting vegetation and for maintaining a natural level of infiltration, groundwater recharge and low flows within the waterways and provide an additional mechanism for reducing damaging stormwater volumes into the waterways.

Stormwater management practices including infiltration will constitute an important part of efforts to restore the natural hydrology. Given the anticipated challenges, the following recommended principles are proposed:

- Specific soil conditions should be considered and areas with known or high salinity risks, reactive soils close to infrastructure and dispersive soil areas generally avoided or minimised
- Assets should be designed to maximise evapotranspiration. This preferences adoption of larger assets relative to catchment designed for stormwater volume management rather than stormwater quality management to provide broader distribution of water
- The use of distributed assets across a catchment is preferred to infiltration in floodplain areas where salinity risks may be higher
- The use of trees which can establish canopy beyond the bounds of the asset should be considered for smaller assets
- Infiltration should be combined with vegetation where possible. This provides opportunity for infiltrated water to be used by vegetation and to increase evapotranspiration to provide both stormwater volume reductions and latent heat fluxes to improve urban micro-climate. This may involve placing trees within, downslope and in proximity to assets.
- Infiltration should be pursued to an extent proportional to that which would naturally occur
- Preference is for infiltration to be distributed and to occur over large areas rather than being highly concentrated. For example, distribution over an entire lawn area would be preferable to concentration into a small raingarden and the use of several smaller assets preferred over a single end of line asset.

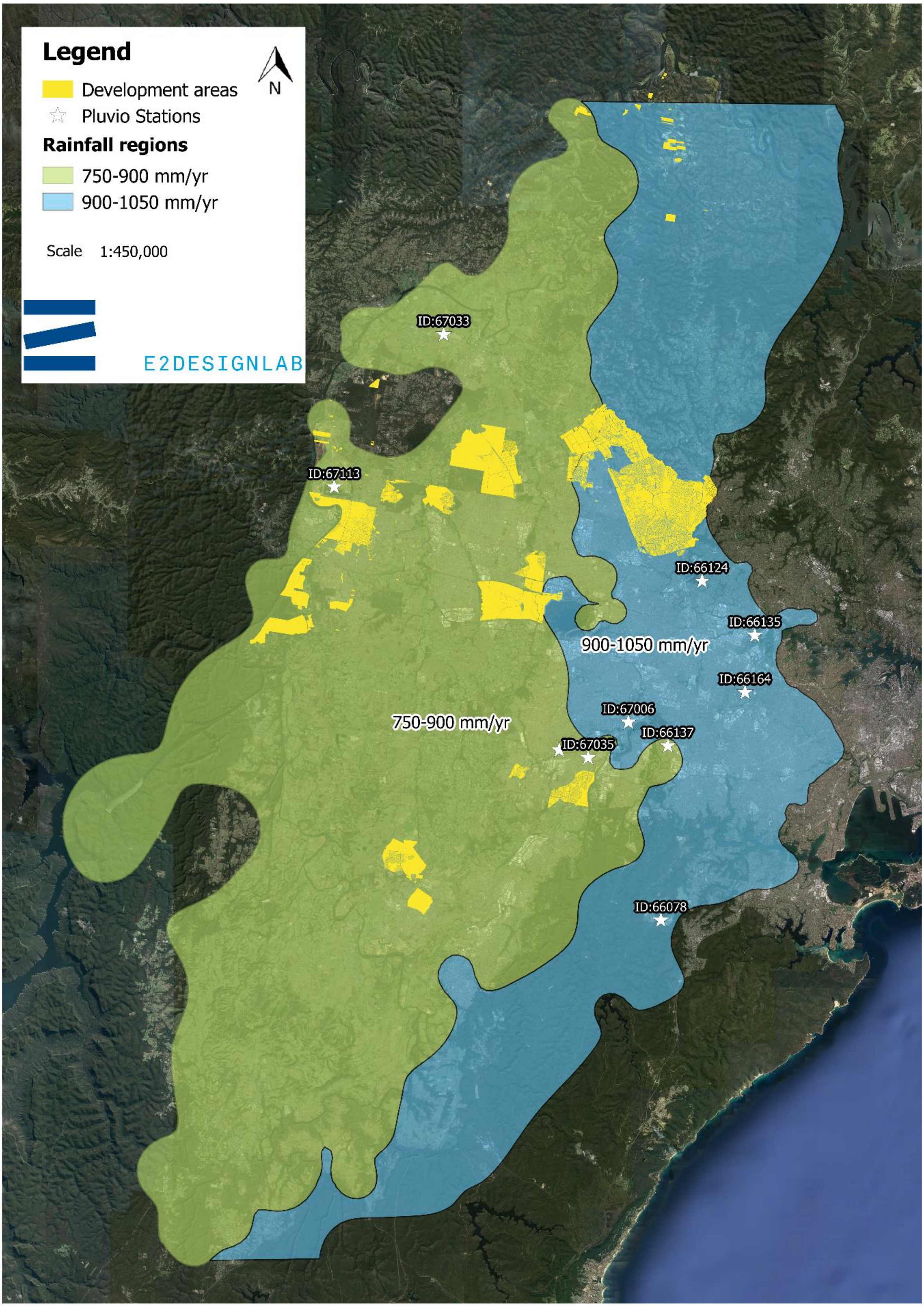


Figure 8-2 Rainfall regions for Western Sydney

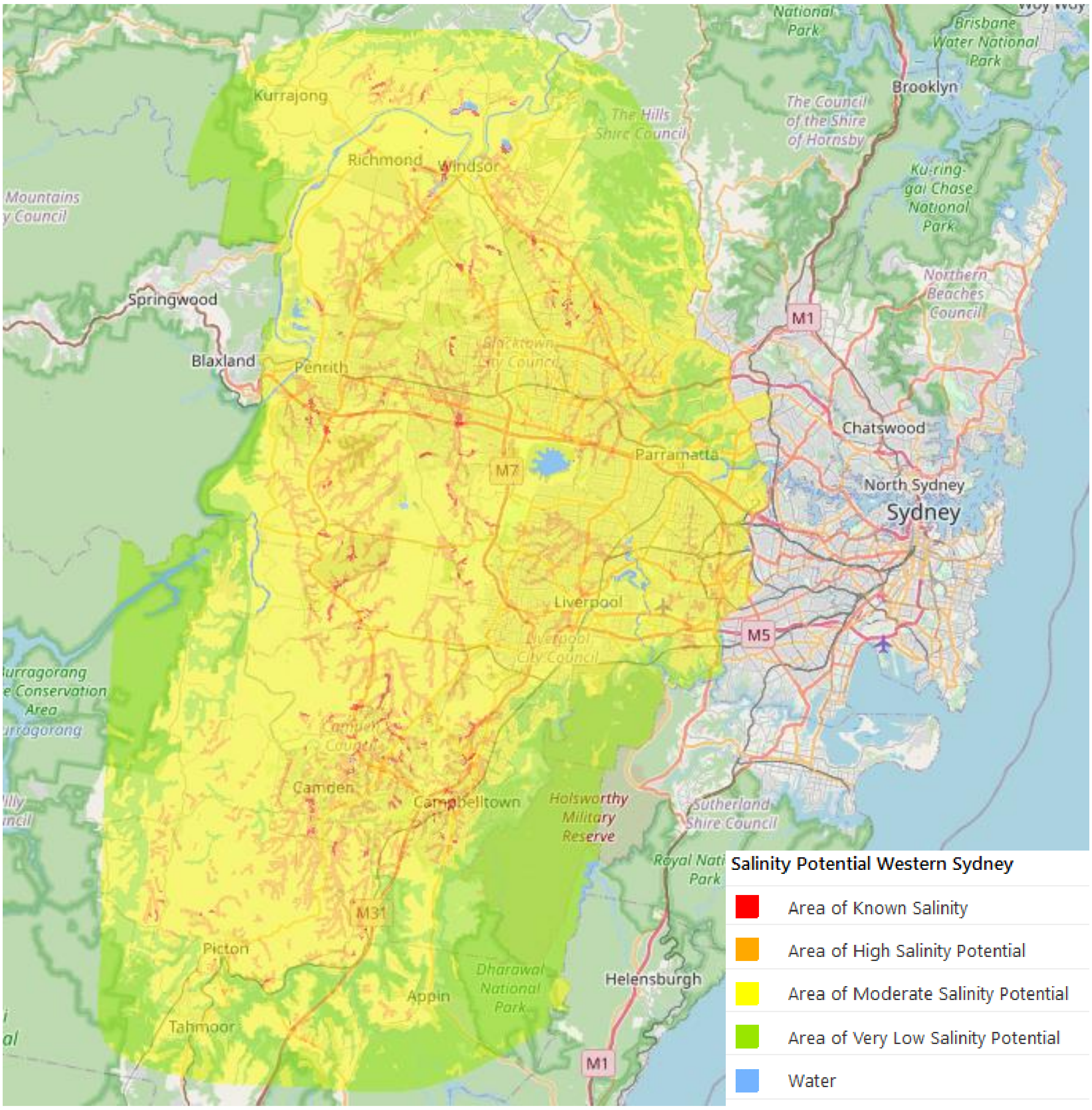


Figure 8-3 Salinity potential (NSW Government, 2020)

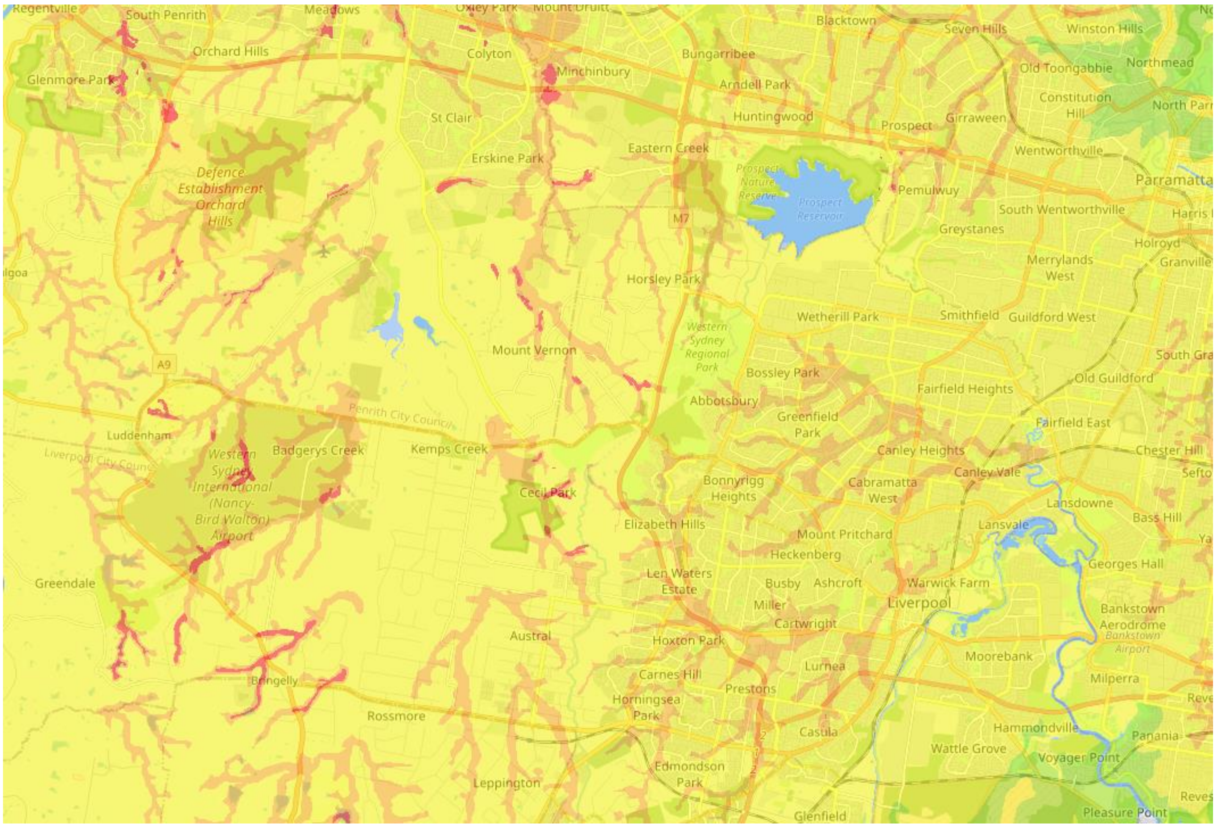


Figure 8-4 Salinity potential around Aerotropolis (NSW Government, 2020)

9. Next steps

This study has identified literature available to quantify green infrastructure stormwater retention performance with a focus on bioretention and green roofs and extracted learnings from these with respect to the relative importance of different pathways of infiltration and evapotranspiration. It has collated several detailed data sets that can potentially be used for model calibration. The outcomes were considered in the context of Western Sydney and potential implications identified.

The following next steps are planned:

- Publish findings and data collected and distribute to stakeholders. This may be through a website and/or journal paper.
- Model calibration and validation
    - Establish assumptions
    - Data and event selection
    - Model selection
    - Calibration and validation
- Develop tools for industry to better assess stormwater retention for green infrastructure assets
- Recommend performance outcomes based on data interpretation
- Inform planning decisions

10. Glossary

Evaporation

Evaporation describes the process of water changing form into vapour, driven by the sun's energy on the surface that the water is contained.

Evapotranspiration

Evapotranspiration represents the sum of evaporation and plant transpiration, accounting for the movement of water from the soil and, through the vegetation leaves to the atmosphere.

Filter media

Filter media represents the soil that is installed with assets that rely on drainage to function. The media is generally an engineered material designed to achieve a certain permeability, to promote drainage but maintain water moisture to support vegetation.

Penman-Monteith

The Penman-Monteith equation generates an approximation for evapotranspiration, using daily mean temperature, relative humidity and solar radiation as input variables.

Transpiration

Transpiration represents the movement of water through vegetation from the root zone to the leaves, where it is returned from the leaf area to the atmosphere.

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12. Appendix A – Bioretention

12.1 Bioretention paper summary

Table 12-1 Bioretention monitoring papers (Purple indicates retention data extracted)

Authors	Year heading	Paper title	Location
Bonneau, J., Fletcher, T.D., Costelloe, J.F., Poelsma, P.J., James, R.B. and Burns, M.J.	2020	The hydrologic, water quality and flow regime performance of a bioretention basin in Melbourne, Australia	Melbourne, VIC
Davis, A	2008	Field Performance of Bioretention: Hydrology Impacts	Maryland, US
Davis, A	2012	Hydrologic Performance of Bioretention Storm-Water Control Measures	US
De Macedo et al	2019	Stormwater volume reduction and water quality improvement by bioretention: Potentials and challenges for water security in a subtropical catchment	Brazil
EPA	2020	Supplemental Material A: Graham Bioretention Cell, North Carolina	North Carolina, USA
EPA	2020	Supplemental Material B: Villanova's BioInfiltration Traffic Island - Villanova Bioretention	Philadelphia, USA
Hamel, P, Fletcher, T D, Walsh, C J, Plessis, E	2011	Quantifying the restoration of evapotranspiration and groundwater recharge by vegetated infiltration systems	Mt Evelyn, Melbourne
Hamel, Perinne	2013	Restoring Catchment Low Flow Hydrology by Infiltration-based Stormwater Source-control systems	Melbourne, VIC

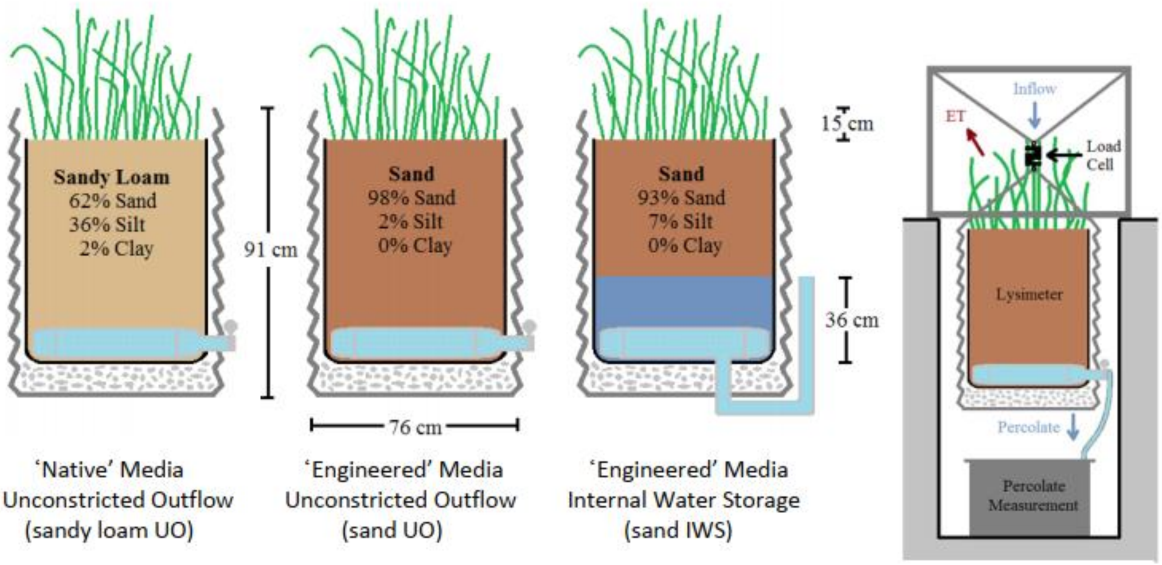
Authors	Year heading	Paper title	Location
Hatt, B. E., Fletcher, T. D., & Deletic, A.	2009	Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale. Journal of Hydrology	Melbourne, VIC, McDowell QLD, Bracken Ridge, QLD
Hatt, B., Poelsma, P., Fletcher. T.D., Deletic, A.	2012	Evaluating the performance of a stormwater biofiltration system: Walker St, Clifton Hill stormwater treatment train	Melbourne, VIC
Hess, A., Wadzuk, B. and Welker, A.	2019	Predictive Evapotranspiration Equations in Rain Gardens	Philadelphia, Pennsylvania, US
Hess, A.J.	Apr-14	Monitoring of evapotranspiration and infiltration in rain garden designs, Master of Science in Civil Engineering	Philadelphia, Pennsylvania, US
Hess, A.J.	May-17	Rain Garden Evapotranspiration Accounting, PhD Thesis	Philadelphia, Pennsylvania, US
Hoban, A., Gambirazio, C.	2018	Implications of recent research on stormwater quality targets and practices	-
Hunt, W., Jarrett, A. R., Smith, J. T., & Sharkey, L. J.	2006	Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina. Journal of Irrigation and Drainage Engineering	NC, USA
Lucke, T., & Nichols, P. W. B.	2015	The pollution removal and stormwater reduction performance of street-side bioretention basins after ten years in operation. Science of The Total Environment, 536, 784-792.	Qld
Mahmoud, A., Alam, T., Rahman, Y.A., Sanchez, A., Guerrero, J., Jones, K.D.	2019	Evaluation of field-scale stormwater bioretention structure flow and pollutant load reductions in a semi-arid coastal climate	McAllen, Texas
Mangangka, I. R., Liu, A., Egodawatta, P. & Goonetilleke, A.	2015	Performance characterisation of a stormwater treatment bioretention basin. J Environ Manage, 150, 173-8	Coomera Waters, Gold Coast, QLD
McKenzie-McHarg, A., Smith, N., & Hatt, B.	2008	Stormwater gardens to improve urban stormwater quality in Brisbane.	Qld
Nall, J.	2011	Monitoring water balance of a rain garden by installation of flow monitoring devices on a residential property	Kansas City, Missouri, USA

Authors	Year heading	Paper title	Location
Parker, Nathan	2010	Assessing the effectiveness of water sensitive urban design in South East Queensland. (Master of Engineering), Queensland University of Technology	Qld
Passeport, E., W.F. Hunt, D.E. Line, R.A. Smith, and R.A. Brown.	2009	Field Study of the Ability of Two Grassed Bioretention Cells to Reduce Storm-Water Runoff Pollution. Journal of Irrigation and Drainage Engineering-ASCE, 135(4): 505-510.	Ohio, USA
Peljo, L., Dubowski, P., & Dalrymple, B.	2016	The Performance of Streetscape Bioretention Systems in South East Queensland. Paper presented at the Stormwater 2016.	Bells Reach, Caloundra, Qld
Peter J. Poelsma, Tim D. Fletcher, Matthew J. Burns	2013	Restoring natural flow regimes: the importance of multiple scales	Melbourne, VIC
Roberts, S., Fletcher, T.D., Garnett, L., Deletic, A.	2012	Bioretention saturated zones: do they work at the large scale?	Brisbane, QLD
Shrestha, P., Hurley, S.E., Wemple, B.C.	2018	Effects of different soil media, vegetation, and hydrologic treatments on nutrient and sediment removal in roadside bioretention systems	Burlington, Vermont, USA
Trowsdale, S. A. & Simcock, R.	2011	Urban stormwater treatment using bioretention. Journal of Hydrology, 397, 167-174.	Auckland, NZ
Wang, M	2019	Assessing Hydrological Effects of Bioretention Cells for Urban Stormwater Runoff in Response to Climatic Changes	China
Winston, R., Dorsey, J., Hunt. W.	2016	Quantifying volume reduction and peak flow mitigation for three bioretention cells in clay soils in northeast Ohio	Ohio, USA

Notes: Both Parker, 2010 and Mangangka 2015 report on the Coomera Waters Bioretention. Parker data adopted as covers a larger range of events while only a selection with water quality data considered in Mangangka.

12.2 Evapotranspiration in bioretention

One study, (Hess, Wadzuk and Welker, 2019) has looked closely at evapotranspiration for bioretention using weighing lysimeters to measure evapotranspiration. Three different bioretention configurations were considered, sandy loam with underdrainage and lining, sand with underdrainage and lining and sand with underdrainage, lining and a submerged zone (referred to as an internal water storage in the study), see Figure 12-1. The saturated hydraulic conductivity of the filter media used was 21 mm/hour for the sandy loam and 37.5 mm/hour for the sand respectively which are quite low relative to Australian guidelines of 100-300 mm/hour (Payne *et al.*, 2015).



‘Native’ Media
Unconstricted Outflow
(sandy loam UO)

‘Engineered’ Media
Unconstricted Outflow
(sand UO)

‘Engineered’ Media
Internal Water Storage
(sand IWS)

Figure 12-1 Rain garden weighing lysimeters (Hess, Wadzuk and Welker, 2019)

Two potential models for evapotranspiration were considered, the ASCE Penman-Monteith equation which is considered robust but is quite demanding in terms of parameterisation and the simpler Hargreaves model.

The observed evapotranspiration (ET) was found to be between 28-52% of inflow volume over the three year period monitored and 16-30 mm per storm event. The unmodified evapotranspiration equations were found to provide adequate estimates of ET that were only slightly better than using the average observed rate.

With further modifications including crop coefficients and a soil moisture extraction function (for assets without a submerged zone only), models using the equations were developed with a higher predictive power and providing good estimates of storm-scale ET. It was found that the crop coefficient was in the expected range (0.3-1.5) for the systems with underdrainage only but were higher for the system with a submerged zone (1.6-2.0). It is noted that the latter is relatively consistent with the ‘PET Factor’ of 2.1 adopted in MUSIC based on estimation drawing on the FAWB Biofilter columns (But noting that this is multiplied by PET or areal potential evapotranspiration rather than the reference crop evapotranspiration, Eto). The areal potential evapotranspiration is is defined as the evapotranspiration that would take place, under the condition of unlimited water supply, from an area so large that the effects of any upwind boundary transitions are negligible and local variations are integrated to an areal average and is calculated using Mortons wet-environment ET (Bureau of Meteorology, 2011).

Use of both predictive models on a daily scale has potential use in continuous simulation, as in most cases the ET estimations predicted by the equations provided a better estimate than the average of the observed daily ET rates.

The outcomes of this study are significant as they indicate that evapotranspiration may be a more substantial component of stormwater retention in bioretention assets despite a number of other studies with infiltration and estimation of the evapotranspiration (i.e. not measured) suggesting that most of the volume infiltrates rather than evapotranspires.

Taken together with the relatively high stormwater volume reductions observed, this study suggests that evapotranspiration from bioretention assets may be higher than is often anticipated.

It is also significant that the average evapotranspiration rates for bioretention with a submerged zone (IWS) are 50% greater than those without. This both confirms the value of the submerged zone in increasing water availability to plants (Rainfall in Philadelphia is about 1,100 mm/year) and increasing the evapotranspiration that occurs.

Table 12-2 Summary statistics for evapotranspiration for 3 year study of total inflow (Hess, Wadzuk and Welker, 2019) (above – all data, below – growing season excluding winter)

Lysimeter	Sandy Loam UO (n=689)	Sand UO (n=776)	Sand IWS (n=776)
Daily Mean [mm/d]	2.86	2.72	4.42
Standard Deviation [mm/d]	2.19	2.25	3.40
95% Confidence Interval [mm/d]	(2.69, 3.02)	(2.56, 2.88)	(4.18, 4.66)

Lysimeter	Sandy Loam UO (n=610)	Sand UO (n=667)	Sand IWS (n=667)
Daily Mean [mm/d]	3.02	2.96	4.97
Standard Deviation [mm/d]	1.99	2.11	3.10
95% Confidence Interval [mm/d]	(2.74, 3.29)	(2.68, 3.23)	(4.56, 5.38)

The study also looks at the potentially available or creditable void space within bioretention considering both evapotranspiration and infiltration. It finds this would be in the order 26% to 29% for sandy loam and 33-36% for sand depending on the period between events (6 or 12 days respectively). It estimates the gravity and ET available soil moisture storage volumes to be 0.23-0.3 and 0.09 to 0.14 (vol/vol) respectively for materials including sand, loamy sand and sandy loam.

Key conclusions for the study were that evapotranspiration comprises 30%, 31%, and 53% of the total water budget for the sandy loam, sand and sand with submerged zone systems, respectively.

It was found that the modified Hargreaves and Penman-Monteith equations could estimate evapotranspiration well with modification to crop factors and (for bioretention without submerged zone) use of a soil moisture extraction function.

13. Appendix B – Green roofs

13.1 Green roof paper summary

Table 13-1 Green roof monitoring papers

Authors	Year	Title	Publication type	Study location
Beattie, D., Jarrett, A.	2009	Green Roofs for Stormwater Runoff Control	Journal	North Carolina, USA
Berghage et al	2009	Green Roofs for Stormwater Runoff Control	Technical	Chicago, IL
Berkompas et al	2008	A Study of Green Roof Hydrologic Performance in the Cascadia Region	Conference	Seattle, WA
Berndtsson, J	2009	Green roof performance towards management of runoff water quantity and quality: A review	Journal	Sweden
Bliss et al	2009	Storm water runoff mitigation using a green roof	Journal	Pittsburg, PA
Carpenter and Kaluvakolanu	2011	Effect of roof surface type on storm-water runoff from full-scale roofs in a temperate climate	Journal	Southfield, MI
Carson et al	2013	Hydrological performance of extensive green roofs in New York City: observations and multi-year modelling of three full-scale systems	Journal	New York, NY
Carter and Rasmussen	2006	Hydrologic behavior of vegetated roofs	Journal	Athens, Greece
Cipolla et al	2016	A long-term hydrological modelling of an extensive green roof by means of SWMM	Journal	Bologna, Italy
Cirkel, D.G., Voortman, B.R., van Veen, T., Bartholomeus, R.P.	2018	Evaporation from (Blue-)Green Roofs: Assessing the Benefits of a Storage and Capillary Irrigation System Based on Measurements and Modeling	Journal	Netherlands

Authors	Year	Title	Publication type	Study location
Connelly et al	2006	BCIT Green Roof Research Program, Phase 1 Summary of Data Analysis: Observation Period – Jan. 1, 2005 to Dec. 31, 2005	Technical	Vancouver, Canada
Ebrahimian et.al.	2019	Evaporation in Green Stormwater Infrastructure Systems	Journal	Villanova, PA USA
EPA	2020	Supplemental Material E: Hamilton Ecoroof, Portland, Oregon	Report	Portland, Oregon, US
EPA	2020	Supplemental Material F: Emergency Operations Center Green Roof, Seattle, Washington	Report	Seattle, Washington, US
EPA	2020	Supplemental Material G: Fire Station 10 Green Roof in Seattle, Washington	Report	Seattle, Washington, US
Fassman-Beck, E.	2012	4 Living Roofs in 3 Locations: Does configuration affect runoff quality or quantity?	Journal	NZ
Fassman-Beck et al	2013	4 living roofs in 3 locations: does configuration affect runoff mitigation?	Journal	Auckland, NZ
Gregoire and Clausen	2011	Effect of a modular extensive green roof on stormwater runoff and water quality	Journal	Storrs, CT
Hakimdavar et al	2014	Scale dynamics of extensive green roofs: quantifying the effect of drainage area and rainfall characteristics on observed and modeled green roof hydrologic performance	Journal	New York, NY
Hathaway et al.	2008	A field study of green roof hydrologic and water quality performance	Journal	Goldsboro, and Kinston, NC
Hutchinson et al	2003	Stormwater Monitoring Two Ecoroofs in Portland, Oregon, USA. Greening Rooftops for Sustainable Communities, Chicago,	Conference	Portland, Oregon
Kasmin, H., Stovin, V.R., Hathway, E.A.	2010	Towards a generic rainfall-runoff model for green roofs	Journal	UK
Kurtz	2008	Flow monitoring of three ecoroofs in Portland, Oregon	Conference	Portland, Oregon
Liu and Minor	2005	Performance Evaluation of an Extensive Green Roof. Greening Rooftops for Sustainable Communities	Conference	Toronto, Canada
Locatelli et al	2014	Modelling of green roof hydrological performance for urban drainage applications	Journal	Denmark
Marasco, D.	2014	Quantifying Evapotranspiration from Urban Green Roofs: A Comparison of Chamber Measurements with Commonly Used Predictive Methods	Journal	USA

Authors	Year	Title	Publication type	Study location
Mentens, J, Raes, D., Hermy, M.	2005	Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century?	Journal	Germany
Moran et al	2005	Green roof hydrologic and water quality performance from two field sites in North Carolina	Conference	Goldsboro and Raleigh, NC
Palla et al	2011	Storm water infiltration in a monitored green roof for hydrologic restoration	Journal	Genova, Italy
Speak et al	2013	Rainwater runoff retention on an aged intensive green roof	Journal	Manchester, UK
Spolek	2008	Performance monitoring of three ecoroofs in Portland, Oregon	Journal	Portland, Oregon
Stovin, V	2013	A modelling study of long term green roof retention performance	Journal	UK
Stovin, V.	2011	The hydrological performance of a green roof test bed under UK climatic conditions	Journal	UK
Teemusk and Mander	2007	Rainwater runoff quantity and quality performance from a greenroof: the effects of short-term events	Journal	Tartu, Estonia
TRCA	2006	Evaluation of an Extensive Green roof	Technical	Toronto, Canada
Versini et al	2015	Assessment of the hydrological impacts of green roof: from building scale to basin scale	Journal	Paris, France
Voyde et al	2010a	Quantifying evapotranspiration rates for New Zealand green roofs	Journal	Auckland, NZ
Wadzuk, B.M., Schneider, D., Feller; M., Traver, R.G.	2013	Evapotranspiration from a Green-Roof Storm-Water Control Measure	Journal	Philadelphia, Pennsylvania, US
Yang et al	2015	Saturation-excess and infiltration-excess runoff on green roofs	Journal	Beijing, China
Zaremba et al	2016	Impact of drainage on green roof evapotranspiration	Journal	Villanova, PA

Notes:

Both Carson 2013 and Marasco 2014 report on the same green roof. Carson data adopted while Marasco focusses on evapotranspiration. Marasco paper of interest for evapotranspiration monitoring and calculation.

14. Appendix C – Passively irrigated tree pits

14.1 Passively irrigated tree pit paper summary

Table 14-1 Passively irrigated tree pit monitoring papers (Purple indicates retention data extracted)

Authors	Year heading	Paper title	Location
Thom, et al	2020	Transpiration by established trees could increase the efficiency of stormwater control measures	Melbourne, VIC
Szota, et al	2019	Street tree stormwater control measures can reduce runoff but may not benefit established trees	Melbourne, VIC
Grey et al	2018	Establishing street trees in stormwater control measures can double tree growth when extended waterlogging is avoided	Melbourne, VIC
Sapdhare et al	2019	A field and laboratory investigation of kerb side inlet pits using four media types	Adelaide, SA

15. Appendix D – Sample data

A sample of event data available is provided in this Appendix.

15.1 Monash Biofilter

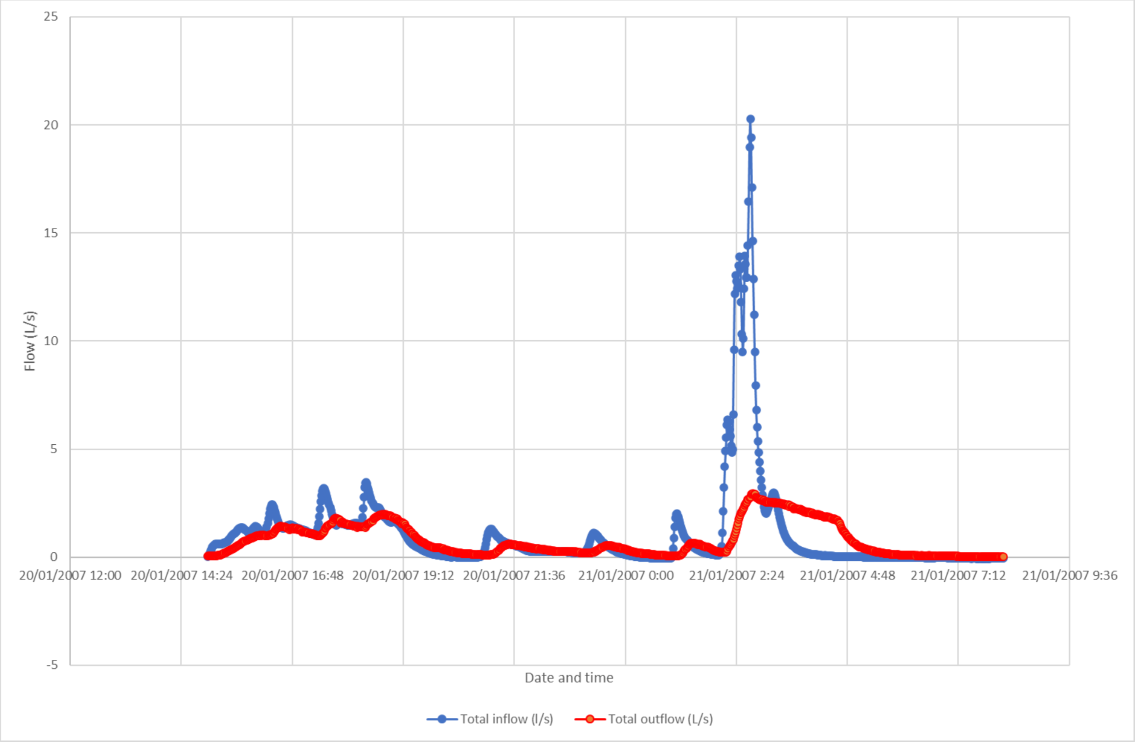


Figure 15-1 Monash biofilter 20/01/2007

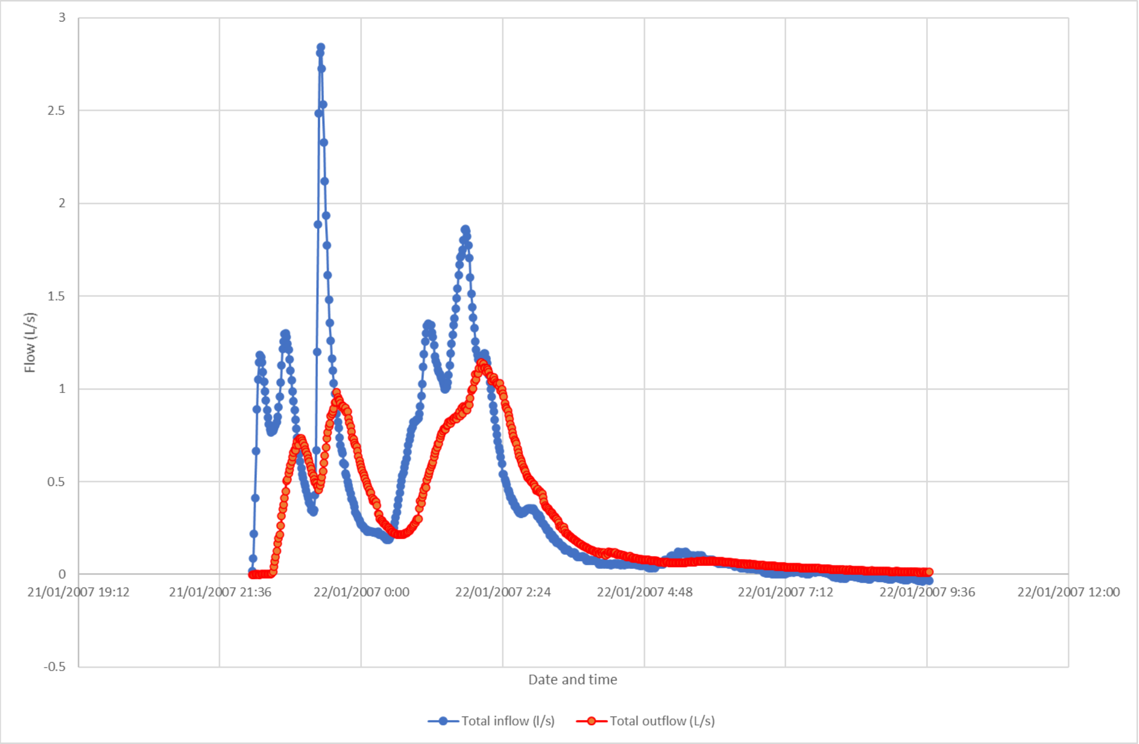


Figure 15-2 Monash biofilter 21/01/2007

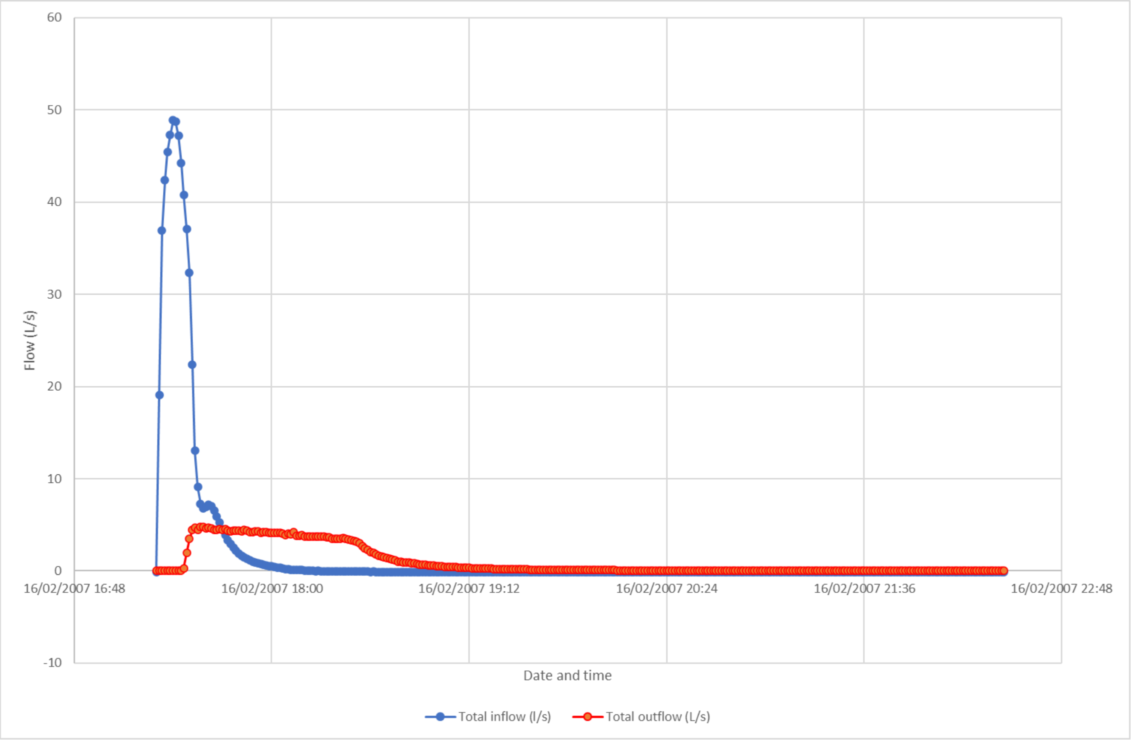


Figure 15-3 Monash biofilter 16/2/2007

15.2 Hereford Road Biofilter

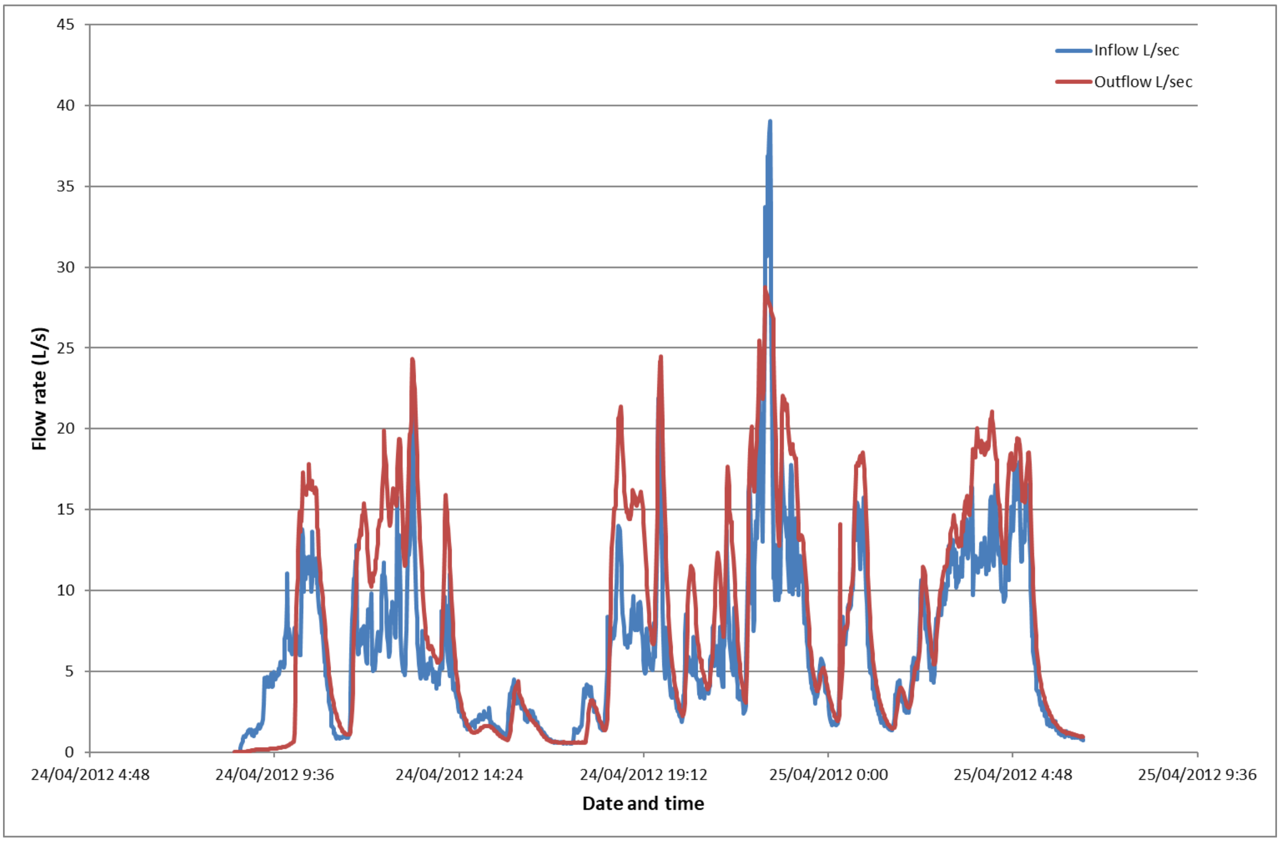


Figure 15-4 Hereford Road biofilter 24/4/2012

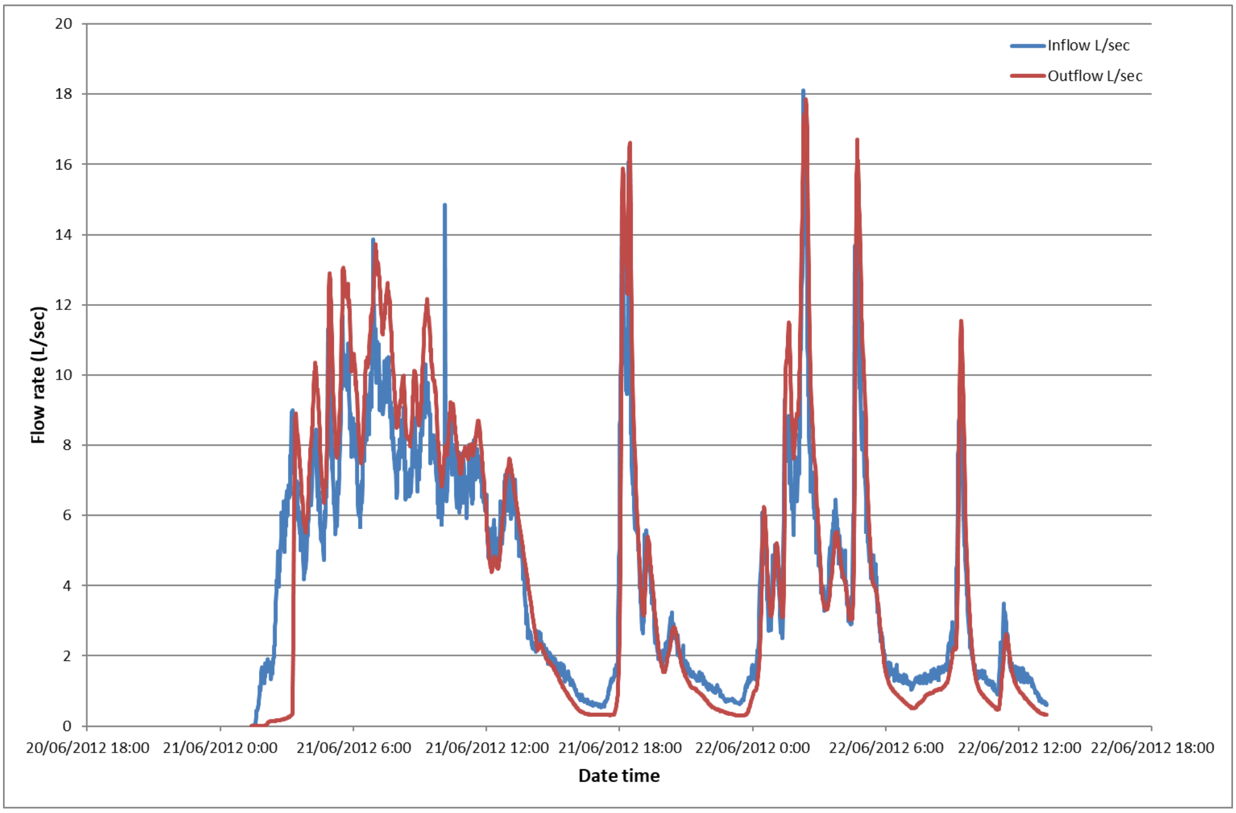


Figure 15-5 Hereford Road biofilter 21/6/2012

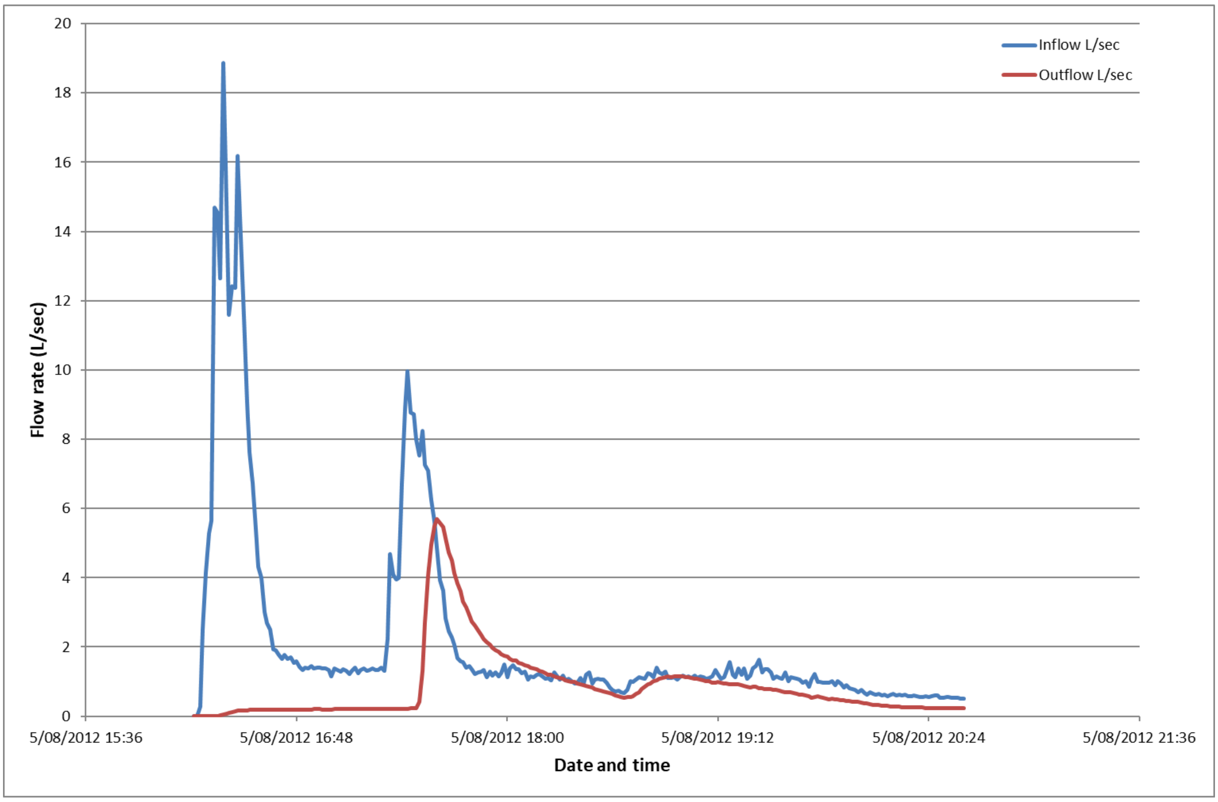


Figure 15-6 Hereford Road biofilter 5/8/2012

Table 15-1 Walker St Clifton Hill Bioretention – Event summary (Hatt *et al.*, 2012)

event	rainfall (mm)	Inlets 1&2 (m^3)	Outlets 1&2 (m^3)	Bypass (m^3)	Total runoff (m^3)	% retained 1 & 2
2009 Sept 26th	5.2	31	33	0	31	-4%
2009 Sept 27th	0.2	4	3	0	4	23%
2009 Sept 28th	3.8	107	100	0	107	6%
2009 Oct 6th-a	2.2	38	21	0	38	43%
2009 Oct 6th-b	1.2	4	2	0	4	59%
2009 Oct 7th	1.8	11	6	0	11	48%
2009 Oct 13th	0.8	16	5	0	16	68%
2009 Oct 14th	2.0	30	18	0	30	39%
2009 Oct 15th-a	1.6	6	2	0	6	60%
2009 Oct 16-17th	1.4	32	24	0	32	24%
2009 Nov 3rd	1.0	6	2	0	6	73%
2009 Nov 21-23rd	74.2	1425	1483	333	1758	-4%
2009 Nov 26th	2.6	48	31	0	48	35%
2009 Nov 26-27th	4.6	104	101	3.7	108	4%
2009 Nov 27-28th	2.6	50	38	0	50	25%
2009 Nov 28-29th	4.4	85	72	0	85	15%
2009 Nov 29th-a	4.8	94	89	0	94	6%
2009 Nov 29th-b	5.4	16	15	0	16	6%
2009 Nov 29th-c	0	32	28	0	32	13%
2009 Nov 29-30th	4.8	128	118	0	128	7%
2009 Dec 8-9th		310	278	0	310	10%
2009 Dec 10-11th		363	304	63	426	16%
2009 Dec 17-18th		299	254	12	311	15%
2009 Dec 24-25th		209	178	0	209	15%
2010 Jan 31st	2.0	5	0	0	5	100%
2010 Feb 4th	1.8	4	0	0	4	100%
2010 Feb 4-5th	3.8	21	9	0	21	55%
2010 Feb 5th	6.0	44	25	0	44	42%
2010 Feb 12th	1.8	48	47	0	48	3%
2010 Feb 14th	1.2	65	48	0	65	26%
2010 Mar 8th	2.2	49	48	0	49	4%
2010 Mar 8-9th	1.2	44	45	0	44	-2%
2010 Mar 9th	1.4	28	31	0	28	-10%
2010 Mar 29th	6.8	133	75	0.64	133	44%
2010 Apr 11th	2.4	36	29	0	36	21%
2010 Apr 23rd	1.2	12	5	0	12	59%
2010 Apr 24th	1.4	42	32	0	42	25%
2010 Apr 29th	0	4	0	0	4	100%

event	rainfall (mm)	Inlets 1&2 (m^3)	Outlets 1&2 (m^3)	Bypass (m^3)	Total runoff (m^3)	% retained 1 & 2
2010 May 4-5th	5.8	110	79	1.7	112	29%
2010 May 6th	1.6	28	21	0	28	24%
2010 May 7-8th	3.8	56	43	0	56	24%
2010 May 11th	3.8	66	49	0	66	26%
2010 May 13th	0.6	9	3	0	9	62%
2010 May 24th	1.6	3	0	0	3	100%
2010 May 24-25th	3.4	34	19	0	34	45%
2010 May 25th-a	0.0	2	0	0	2	100%
2010 May 25th-b	1.4	35	23	0	35	34%
2010 May 29th	1.0	8	2	0	8	80%
2010 Jun 5th	9.0	275	194	1.9	276	29%
2010 Jun 6th	10.8	159	145	0	159	9%
2010 Jun 7th	1.0	4	0	0	4	100%
2010 Jun 12th	0.8	24	12	0	24	51%
2010 Jun 25-26th	0	332	263	1.9	334	21%
2010 Jun 26-27th	0	222	205	0	222	8%
2010 Jun 30th	0.6	11	4	0	11	63%
2010 Jul 2nd	4.2	105	76	3.1	108	28%
2010 Jul 13th	1.0	13	3	0	13	74%
2010 Jul 14th	4.4	137	100	0.22	137	27%
2010 Jul 18-19th	7.2	165	138	0	165	16%
2010 Jul 19th	0	2	0	0	2	100%
2010 Jul 22-23rd	1.4	24	7	0	24	70%
2010 Jul 28th	3.4	35	19	0	35	46%
total	224.6	5844	5003	421	6265	14.4%

15.3 Walker St, Clifton Hill Biofilter 1 & 2

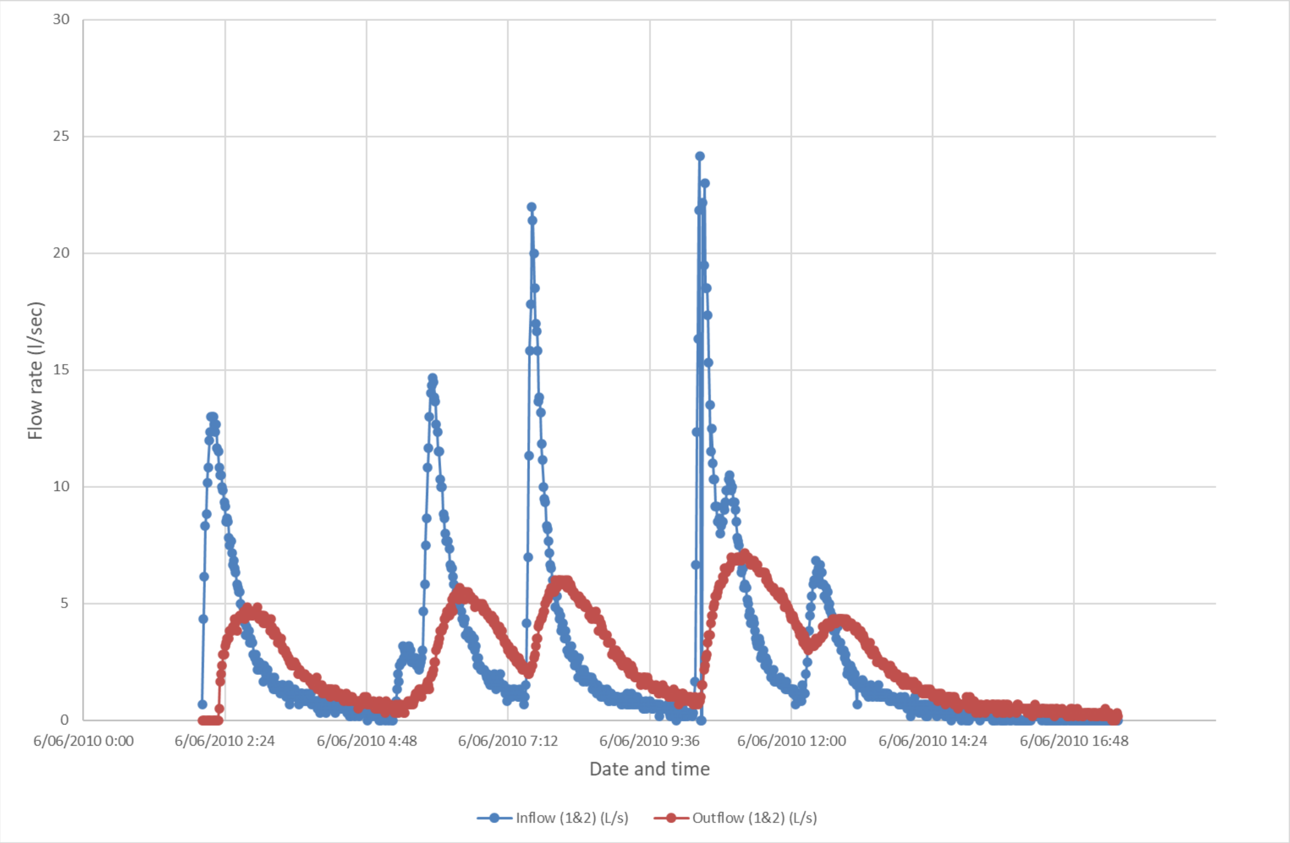


Figure 15-7 Walker St biofilters 6/06/2010

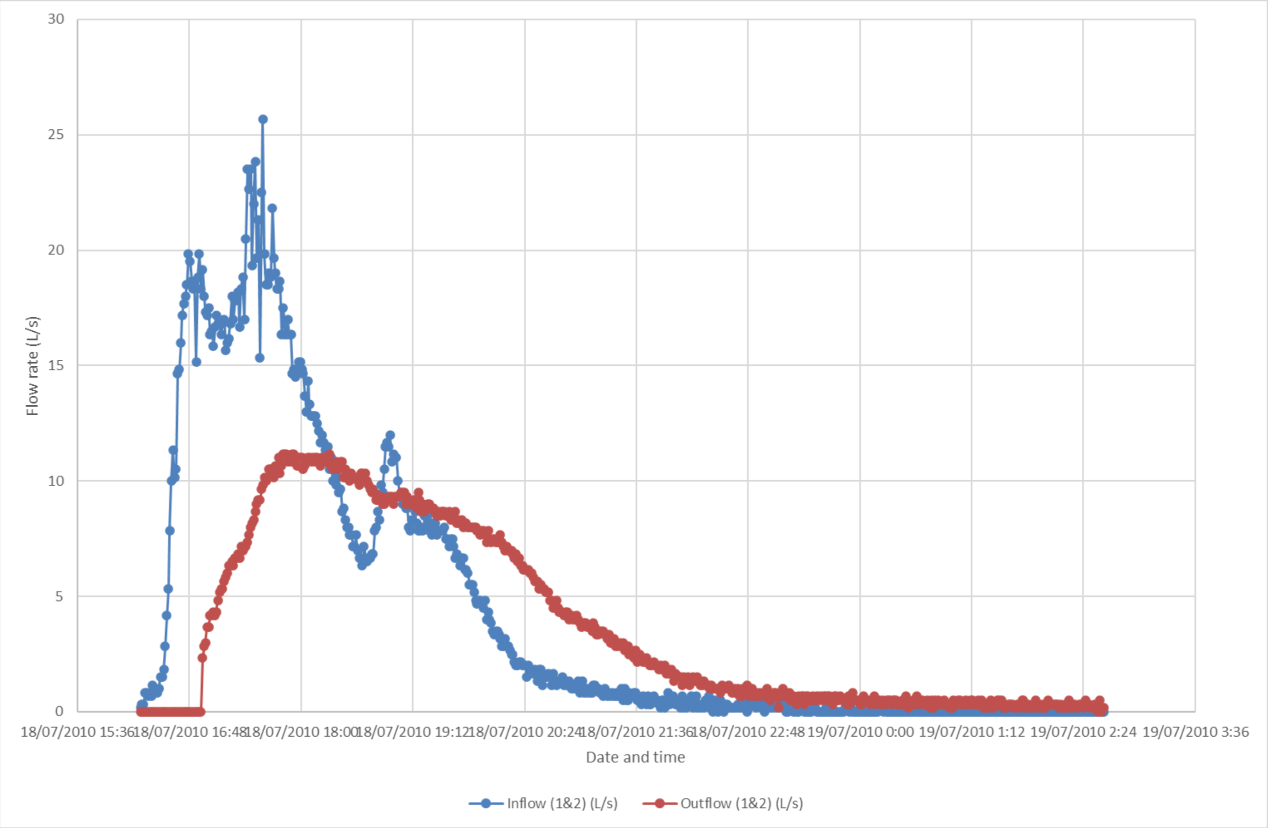


Figure 15-8 Walker St biofilters 18-19/07/2010

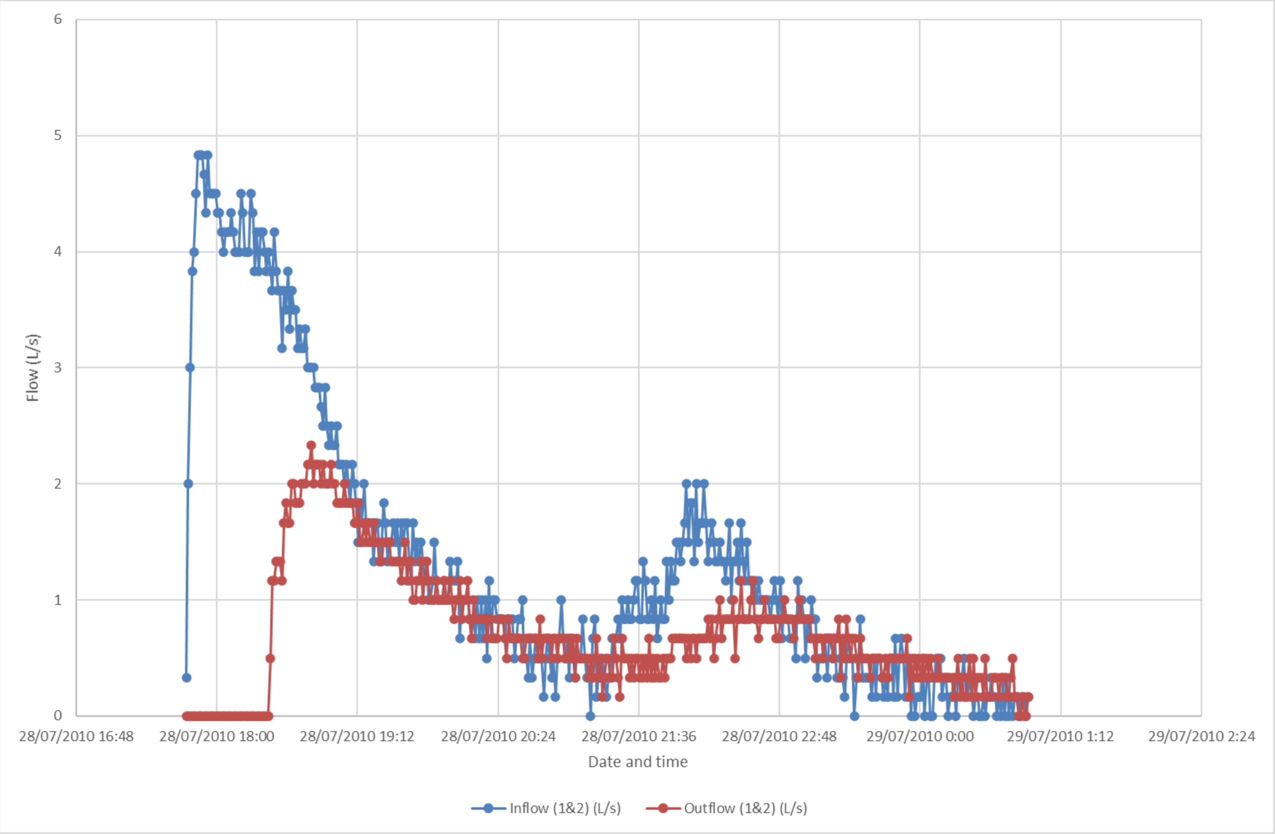


Figure 15-9 Walker St biofilters 28/07/2010

15.4 Emergency Operations Centre Green Roof

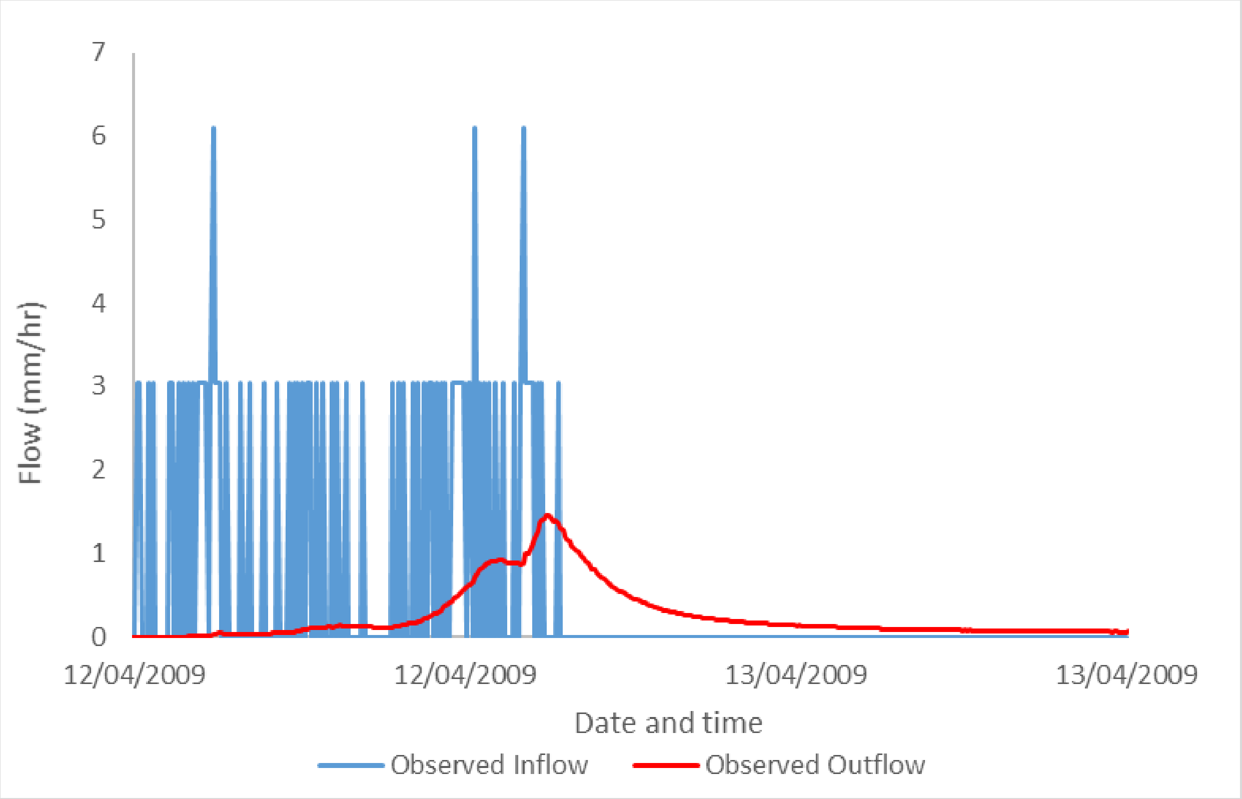


Figure 15-10 Emergency Operations Centre Green Roof 12/04/2009

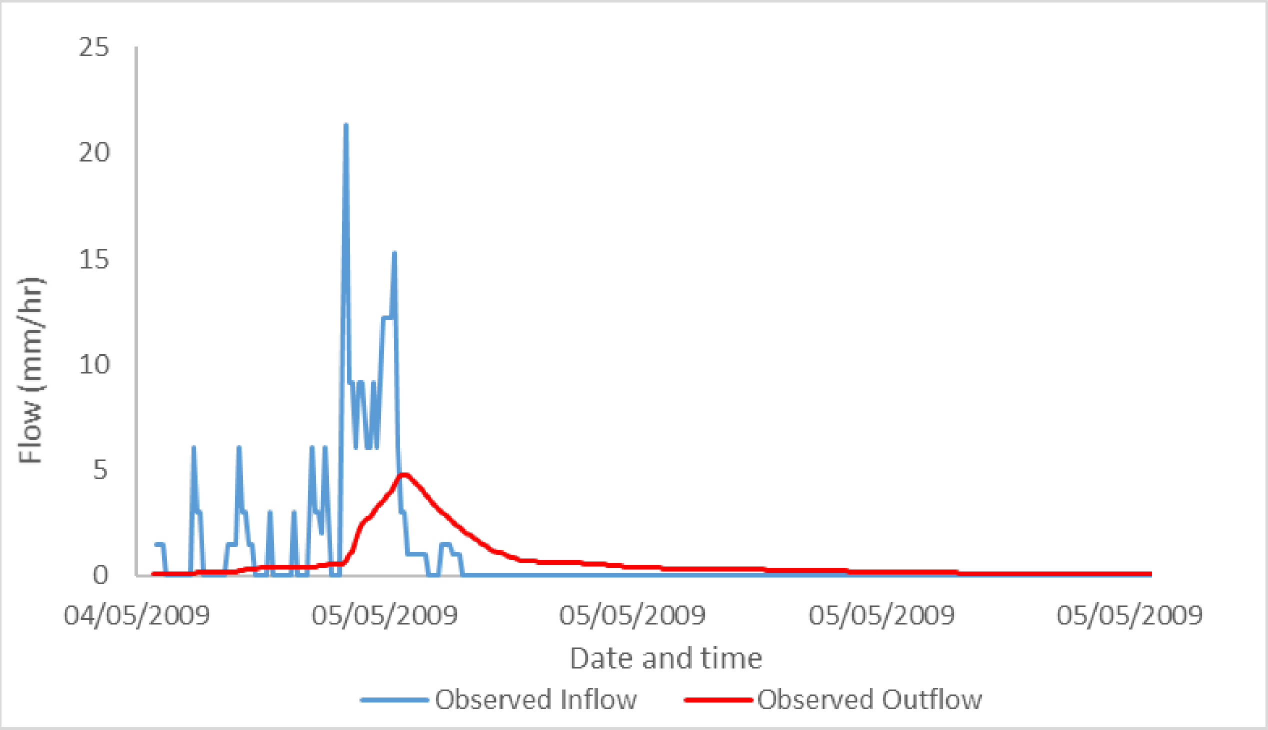


Figure 15-11 Emergency Operations Centre Green Roof 5/05/2009

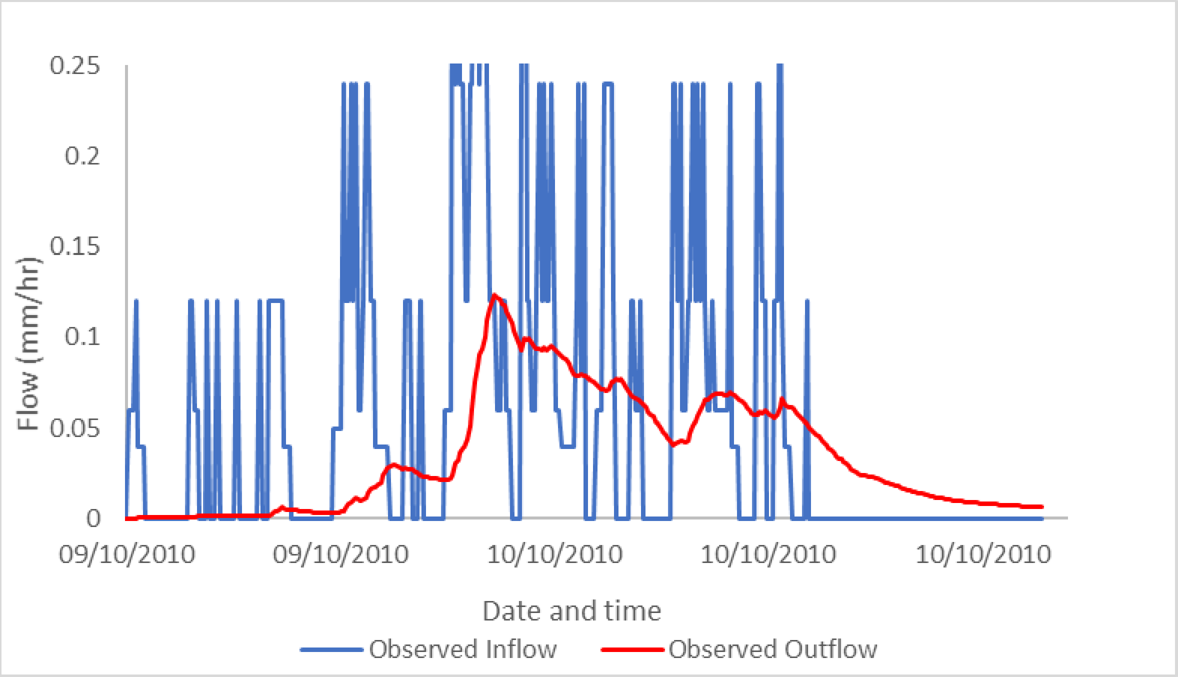


Figure 15-12 Emergency Operations Centre Green Roof 9-10/10/2010

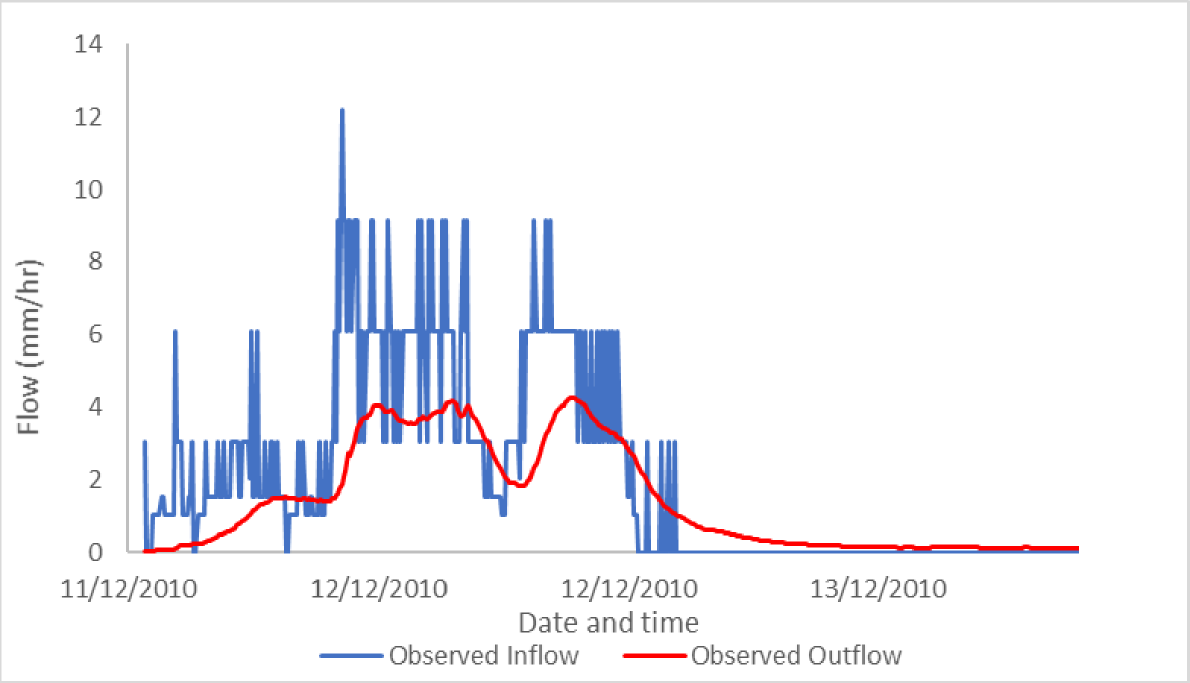


Figure 15-13 Emergency Operations Centre Green Roof 11-12/12/2010