WHEN GREY MEETS GREEN – A HYBRID TREATMENT STORY

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ABSTRACT

Whilst water sensitive design (WSD) and Green Infrastructure are effective stormwater management solutions, proven to mitigate the effects of impervious development and urbanisation, they tend to occupy a large footprint. Additionally, due to the size of device required for effective treatment, the construction and maintenance costs can be significant and ongoing.

With the focus on urban intensification the cost of land has increased and the struggle to dedicate high-value, prime building land to green treatment devices or WSD is increasingly difficult to justify. Consequently, designers are inclined to revert to grey infrastructure and innovative proprietary solutions. However, in some situations grey infrastructure is the best practicable option to achieve effective treatment where space is constrained.

Grey infrastructure is an 'engineered' solution to a problem that, in terms of public preference, is better managed by a more natural solution. Often stormwater treatment for a site is designed as either grey or green infrastructure, however, there is opportunity to better incorporate the best of both grey and green to overcome the space and cost constraints. The benefits of using hybrid system includes reduced maintenance costs, aesthetically pleasing, reduced land requirement, improved treatment efficiency to name a few. There is also an opportunity to design each device, in a hybrid treatment train, to target different contaminants for challenging sites or retrofitting devices on existing site.

This paper will present case studies of projects where hybrid treatment systems has been applied. It will provide further discussion in regards to the benefits of using a hybrid design. In particular, performance, space constraints and costs.

KEYWORDS

Green Infrastructure, Grey Infrastructure, Hybrid, Stormwater Treatment Train, Maintenance, Innovation, Case Studies

PRESENTER PROFILE

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1 INTRODUCTION

The development and intensification of urbanised areas has fundamentally transformed the natural hydrological cycle by replacing once vast vegetated pervious spaces with now expansive impervious areas. The runoff's potential for infiltration into the ground, and evapotranspiration via vegetation has been significantly reduced (Figure 1). This has led to an increase in volume, peak flow and peak duration in the stormwater runoff originating from these now urban catchments and are attributed as the primary cause of flooding and stream erosion.

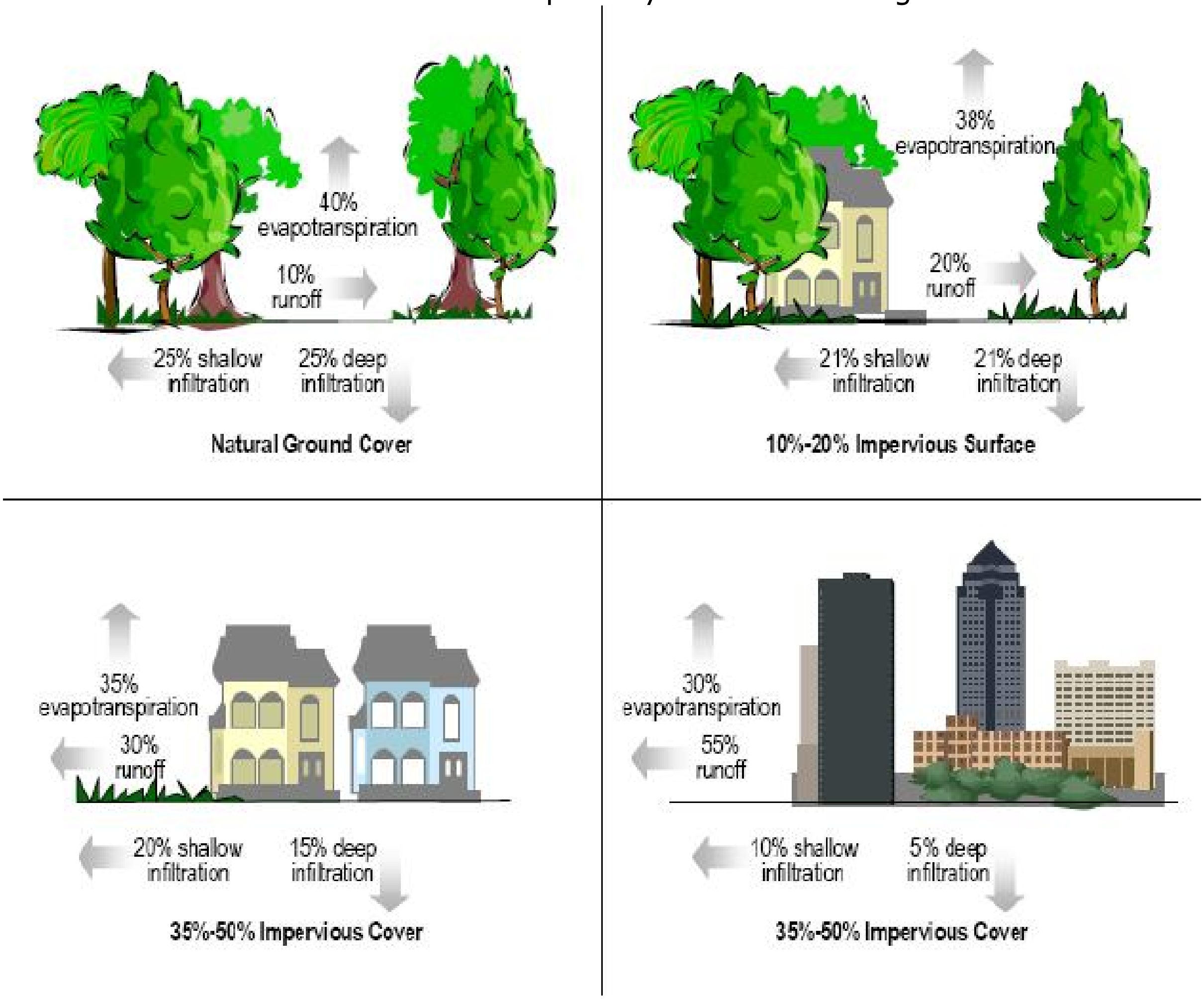

Figure 1: Impacts of Urbanisation on the water cycle (Source: United States Environmental Protection Agency, 2005)

Historical urban developments were built with very little or no consideration to the natural hydrology as stormwater runoff generated from these urban catchments was seen as a public nuisance. At this time, hard engineering solutions were considered the most appropriate approach to flood mitigation. Channelled/piped reticulations were constructed to ensure stormwater was discharged away from developed areas into receiving waterways, as quickly as possible, to reduce risk of flooding. However, this approach is increasingly regarded as creating adverse environmental effects to sensitive downstream receiving environments, and may contribute to disconnecting communities from their amenity and recreational opportunities (Ferguson, et al., 2014).

There is an increasing worldwide recognition that stormwater runoff in general is a major source of pollution, adversely discharged into downstream receiving waterways and sensitive environments, leading to degradation of water quality and ecology.

Stormwater is now considered a valuable natural resource or "liquid asset", rather than an urban by-product. There is a growing shift in the management of stormwater towards systems that can mimic the natural hydrological cycle and hydraulic conditions by reducing and attenuating flows, and treating stormwater borne contaminants, as opposed to historical systems designed principally for drainage.

There is a range of systems, best management practices (BMP) and techniques available to address and manage stormwater on a site. These can be loosely defined as being either engineered (grey infrastructure) or natural (green infrastructure).

2 GREY INFRASTRUCTURE

Grey infrastructure, also commonly known as traditional/conventional infrastructure or hard engineering, refers to the man-made engineered components of a system. These components often involve the use or manufacture of "hard materials" such as concrete, plastic and metal. Channels, culverts, pipes and storage tanks are common grey infrastructure components used in stormwater systems to collect and convey runoff to a centralised treatment system or directly to a receiving waterway.

Urban development has increased land values making available space a precious and expensive commodity. The demand for development has not allowed for space to be dedicated to natural land treatment systems, instead prioritising intensification. This has pushed industry to develop grey infrastructure solutions; designed to be compact for use where land availability is constrained.

Traditional grey infrastructure components can often restrict or eliminate the natural hydrological cycle including evapotranspiration, as vegetation is removed during construction, and infiltration, as pervious catchments are made impermeable. They can also contribute to pollution by preventing runoff naturally filtering through layers of soil due to the use of impervious materials and surfaces. Flood risk may also increase as these components are typically used to move stormwater quickly from inlet to outfall, which can lead to higher peak flows at shorter time of concentrations and at worst overload the associated infrastructure network.

Innovative proprietary technologies, manufactured from conventional hard grey materials, have been developed to overcome the problems of traditional grey infrastructure. These technologies are typically made up of small-footprint, high performance efficient devices, often located underground, and designed to mimic natural drainage paths and principles. They can be installed on new, or retrofitted on existing infrastructure especially where there are space constraints and maximum land-use is required. These devices tend to be classified in the broader grey infrastructure category, however they are increasingly being recognised worldwide as "Blue Infrastructure", a hybrid of grey-green, and can serve as a buffer between traditional engineered & natural solutions (White, 2014).

3 GREEN INFRASTRUCTURE

Benedict & McMahon (2002) have broadly defined green infrastructure as *'…an interconnected network of green space that conserves natural ecosystem values and functions and provides associated benefits to human populations. Green infrastructure is the ecological framework needed for environmental, social and economic sustainability – our nation's natural life support system'.*

In terms of stormwater management, green infrastructure has been further defined by Auckland Council as *'...products, technologies, and practices that use natural systems, or engineered systems that mimic natural processes, to maintain or enhance overall community and environmental values and provide utility services for stormwater management. This includes both built infrastructure (green devices) and non-built green infrastructure (such as plantings)'* (Mayhew, et al., 2016).

Green infrastructure is synonymous with Low Impact Development/Design (LID) and Water Sensitive Design (WSD) in terms of practices and systems. It differs from traditional 'grey infrastructure' in that it focuses on decentralised, at source stormwater management systems to incorporate, mimic or manipulate natural processes. These principles and systems may include the use of innovative engineered devices, such as proprietary biofiltration devices or permeable concrete paving, that may not be considered natural systems in their own right (Boyle, et al., 2014; Mayhew, et al., 2016).

Common green infrastructure devices directly used in stormwater management include permeable paving or surfaces, constructed wetlands or ponds, infiltration or recharge basins, raingardens (bio-retention & bio-filtration), swales, tree pits and living (green) roofs. Green infrastructure can be further expanded to indirect components and natural assets systems that are utilised in the wider stormwater management category for their function, social interaction and ecological benefits. These natural systems can include lakes, rivers, streams, valleys and natural overland flow paths or channels, riparian margins, flood plains, aquifers and other ground water systems, urban trees and forests.

Whilst green infrastructure is an effective stormwater management solution proven to mitigate the effects of impervious development and urbanisation, it tends to require a significant amount of dedicated space. With the focus on urban intensification and consequently the increased cost of land it is increasingly difficult to justify dedicating high-value, prime building land to green treatment devices or WSD. From a developer's perspective, the aim is to maximise profits and therefore all available space is often utilised for impervious development purposes. Additionally, due to the size of green infrastructure devices required for effective treatment, the construction and regular maintenance costs can often be significant and ongoing.

However, the good design and use of green infrastructure can provide a favourable and aesthetically pleasing public amenity that may outweigh the costs. Furthermore, green infrastructure tends to also have social, ecological, biological and habitat benefits. In terms of public and environmental preference, it is still preferential to manage stormwater through a more natural, green infrastructure solution.

4 HYBRID GREEN/GREY INFRASTRUCTURE

Often stormwater treatment for a site is designed as either grey or green infrastructure, however, there is opportunity to better incorporate the best of what both grey and green offer. A hybrid system is an integrated treatment approach that blends innovative engineered stormwater management technologies with more traditional land based water sensitive design practices and/or conventional landscaped areas to overcome the space and cost constraints.

This hybrid approach is effectively a 'treatment train' (Figure 2) as a combination of sequential stormwater management practices are used and integrated as part of a comprehensive stormwater management system (ARC, 2003; NZTA, 2010).

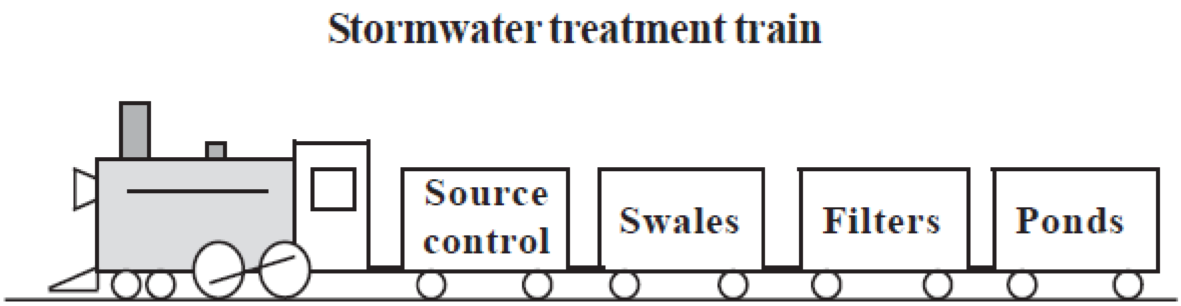

Figure 2: Treatment Train Schematic (Source: ARC, 2003)

Upstream devices act as pre-treatment; targeting, treating and removing multiple contaminants of concern in addition to prolonging the operating life of downstream devices. Multiple device combinations can be utilised to achieve pollution capture (treatment), detention (peak flow attenuation), infiltration and retention (volume reduction and water re-use) objectives. Furthermore, landscape features can be aesthetically designed to provide social, ecological and biodiversity benefits.

The advantages of using hybrid system includes reduced maintenance costs, aesthetically pleasing landscapes, reduced land requirement and improved treatment efficiency to name a few.

Although there are many benefits to incorporating hybrid solutions to stormwater management hydraulic challenges, capital cost and differing maintenance requirements with different devices are some of the constraints that they present.

The following section provides case studies on Hybrid Grey/Green infrastructure. Each case study presents various combinations of sequential treatment devices that were designed to respond to the specific needs of the individual situation.

5 CASE STUDIES

5.1 **Waimahia Inlet Housing Development, Auckland, New Zealand – Gross Pollutant Trap to Constructed Wetland**

Construction of a new greenfield residential development in south Auckland commenced in late 2013 with overall completion planned for 2017. This project involved the building of approximately 300 new affordable dwellings, comprising various community housing and private tenure, and was the very first development to be granted consent under the Special Housing Accord (SHA).

As part of this project, stormwater runoff from a large 12 hectare catchment was required to be treated for gross pollutants, total suspended solids and heavy metals prior to being discharged to the Waimahia Inlet, and ultimately to the Manukau Harbour. A large constructed wetland was originally chosen by the consulting engineer, however there were concerns that debris and gross pollutants could be discharged to the wetland and prove difficult to remove/maintain. The client and Iwi requested a pre-treatment device upstream of the wetland to capture the gross pollutants and provide additional treatment on top of the TP10 type standard.

The solution was to install a proprietary gross pollutant trap (GPT) upstream of the proposed wetland (Figure 3). The chosen GPT combined the proven sediment removal capability of hydrodynamic separation with litter, organic debris, and neutrally buoyant material capture via a submerged perforated swirl (indirect) screening technology. An internal ‘offline’ bypass weir was incorporated into the device to divert higher peak flows around the device and prevent resuspension or release of captured material. The compact nature of the total treatment train ensured maximum land was available for housing development.

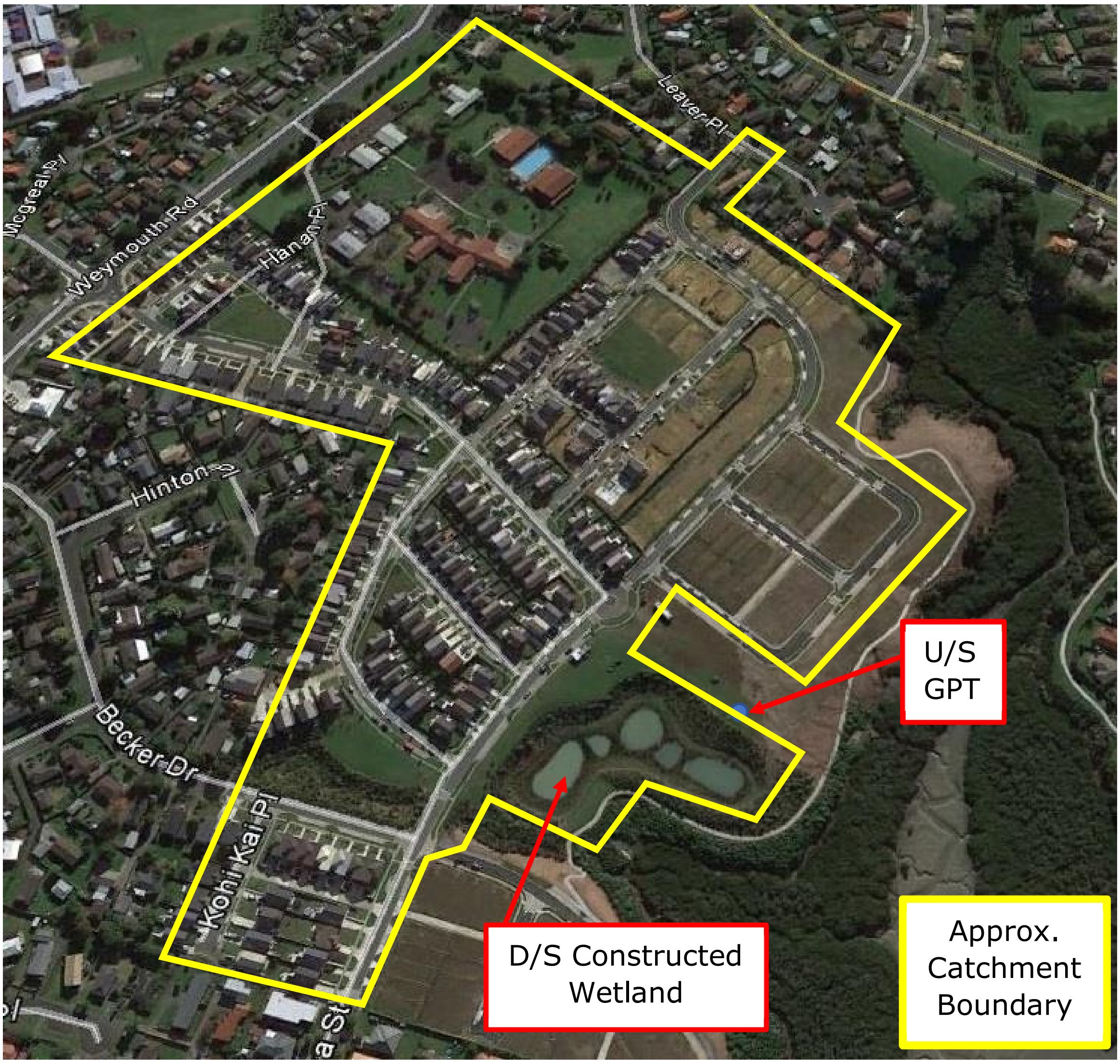

Figure 3: Aerial View (2016) of Waimahia Inlet Housing Development (Source: Google)

5.2 SH16 Motorway Causeway, Auckland, New Zealand – Swale to Proprietary Cartridge Filter

The causeway upgrade project was a 4.8km, major roading project on Auckland's North-western Motorway (SH16) between Great North Road Interchange and Te Atatu Interchange, alongside the Waitemata Harbour. It involved raising and widening a section of the existing motorway causeway to prevent flooding and provide additional vehicle capacity.

The project's alliance team were tasked with implementing stormwater treatment along the causeway in accordance with strict resource consent conditions. Further constraints in regards to the width of the road corridor, due to environmental impact and construction costs, were also in place. This meant limited options were available for stormwater treatment purposes.

As such, using only conventional land based WSD treatment devices was not a practical option. Additionally, using only drainage pipes and engineered devices, was not feasible because of limited driving head and lack of fall due to the close proximity to the sea.

A hybrid treatment train solution was implemented to overcome these issues and meet the consent requirements. The approach consisted of vegetated swales for conveyance and pre-treatment purposes, upstream of a 'scruffy dome' entry proprietary cartridge filtration device (Figure 4).

The swales were designed and built undersized due to the limited space. Whilst they met the conveyance needs of the project, they were unable to meet the TP10 type treatment requirements as a standalone device. Regardless, the swales provide pre-treatment of contaminants, promote infiltration and aid in reducing total runoff volume.

The downstream filtration device completes the treatment train by providing the final 'polishing' stage of contaminant removal to meet consent conditions. The use of a scruffy dome top inlet entry helps reduce the depth to outlet invert, ensuring the device is unaffected by tidal sea influx. The compact nature of the device allows it to fit within the upstream swale width, enabling the causeway width to be kept minimal. The pre-treatment provided by the upstream swale will aid in prolonging the life of the filter cartridges, and reducing annual maintenance costs.

Figure 4: Photo of hybrid Swale & 'scruffy dome' entry Filtration device treatment train (Source: Causeway Alliance)

5.3 Albany Busway Station, Auckland, New Zealand – Swale/Bioretention to Proprietary Cartridge Filter to Bioretention

The Albany park and ride bus station in Auckland, New Zealand was first opened in November 2005 catering for 370 carpark spaces. Two separate carpark extensions in 2007 and 2012 have since increased the total parking capacity to approximately 1,100 spaces. The total developed catchment area, from the bus station, car park facilities, roading infrastructure and surrounding grassy areas, is approximately 14.29 ha (95.7% impervious) which discharges into the downstream Lucas Creek via multiple culverts.

Stormwater runoff from the catchment was required to be treated for minimum of 75% total suspended solids (TSS) removal prior to discharge in accordance with resource consent conditions. A catchment policy of the territorial council required at least 8% of the total catchment to be dedicated to bioretention devices (including raingardens and swales with bioretention trenches). There was no provision required for extended detention or flow attenuation as the site is located at the lower end of the catchment.

A hybrid treatment train solution using a combination of green (swales, bioretention and wetland) and engineered (proprietary catchpit inserts & filtration media cartridge) devices (Figure 5) were originally installed, prior to the post 2012 upgrades, to satisfy the resource consent conditions and mitigate adverse environmental effects to the receiving Lucas Creek. The upstream raingardens and swales were designed to satisfy the 8% bioretention area conditions and provide pre-treatment of runoff prior to discharge to the downstream proprietary filtration media cartridge device. The proprietary device was the principal component of the treatment train to provide full TSS treatment and contained an active media to target removal of particulate and dissolved heavy metals. A constructed wetland, a further provision required by the subdivision consent, was installed as the last device in the treatment train to provide additional treatment prior to final discharge to Lucas Creek. High flow diversion structures had been installed to divert higher peak flows around the downstream devices to prevent scour and resuspension of collected material.

In 2012, the existing wetland was removed and backfilled to make way for a large carpark extension, approx. 550 additional spaces, located in the lower half of the development catchment. New on-site bioretention swales were installed on the extension that discharge to a new bioretention raingarden (approx. 1300m2 footprint) prior to discharge to Lucas Creek. The raingarden was constructed offsite on a downstream neighbouring lot, across the road and opposite the development, due to space constraints. The existing proprietary device was retained to treat the upper catchment of the development, and now discharges directly to Lucas Creek via a culvert.

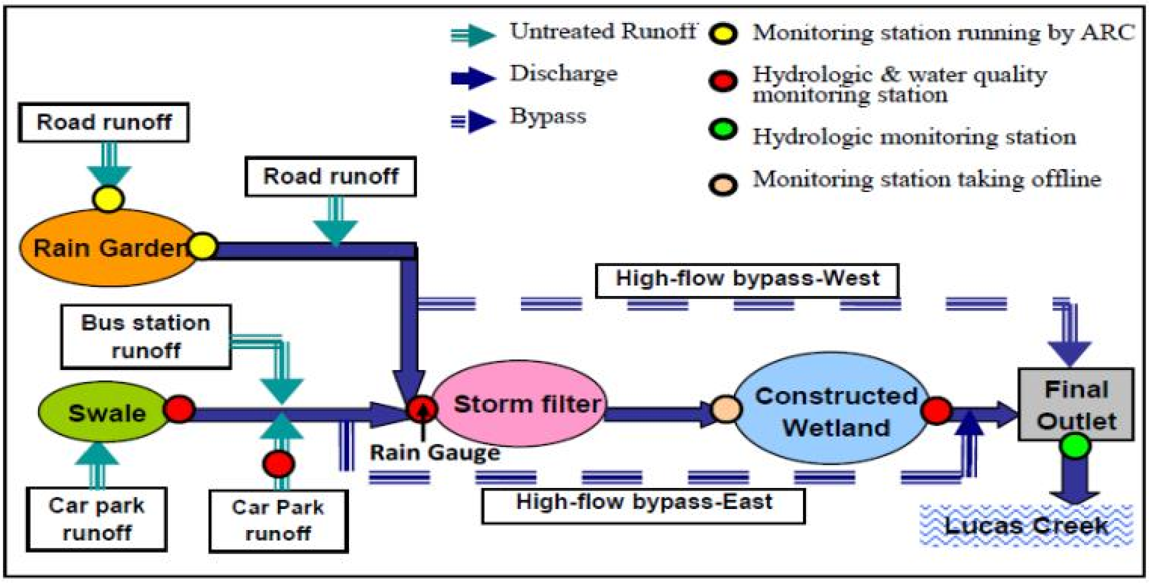

Figure 5: Pre-2012 Schematic of Albany Busway Station Park N Ride Hybrid Stormwater Treatment Train (Source: Fassman, et al., 2009)

5.4 Point Defiance Regional Treatment Retrofit, Tacoma, Washington, USA – Hydrodynamic Separator to Proprietary Bio-Filtration

Urbanisation and industrial activities have contributed to polluted stormwater discharges and degradation of water quality in Puget Sound near Tacoma, Washington, USA. To help mitigate these effects, the city of Tacoma joined together with Metro Parks Tacoma to construct an innovative regional stormwater treatment facility at the Point Defiance marina. The total treatment catchment is approx. 305Ha with the furthest upstream point being approx. 3.2km away.

The project partners shared a vision to provide stormwater treatment through a park amenity, to be located at the entrance to Point Defiance Park. The chosen treatment system needed to be both functional and aesthetically pleasing. With over 2 million visitors each year, the city of Tacoma wanted this to be an educational piece for the public and make the community self-aware of the need for stormwater BMP's.

Multiple options were analysed and evaluated to fix the problem. One of the proposed solutions was to install a localized conventional bioretention cell on every street corner in the catchment. However, this was not an option due to space constraints and cost involved with retrofitting in an urban area.

A hybrid treatment solution using an engineered hydrodynamic separator and a rapid biofiltration media system (Figure 6) was chosen to meet the project criteria and overcome space and cost constraints. The Hydrodynamic separator was designed to provide pre-treatment to remove the majority of trash and big floatables to prolong the life of the downstream biofiltration device and ensure aesthetic appeal. The downstream bioretention treatment facility consisted of a series of cascade pools, distribution channels and treatment cells. The treatment train captures and immobilizes pollutants, which in turn are then decomposed, volatilized and incorporated into the biomass of the biofiltration system's micro/macro fauna and flora. The treatment facility can treat up to 30,000m^3 per day of runoff. Treated flows from the system are discharged into a bioswale that conveys the treated stormwater runoff towards the outfall.

Figure 6: Photo of cascading rapid biofiltration treatment cells at the Point Defiance Stormwater Treatment Facility (Source: Contech Engineered Solutions)

5.5 Residential Development, Edmonton Road, Henderson, Auckland, New Zealand – Conventional Landscaped Garden to Proprietary Cartridge Filter

A small residential housing development in west Auckland required a stormwater treatment device to treat a 1200m^2 combined roof/road/pervious catchment area. The site had limited space for a treatment device and a conventional land based treatment system could not be used as land was required for housing and a private right of way.

The solution was to install an underground proprietary media filtration cartridge device in a landscaped garden with diverse planting, including large trees, located in the developments cul-de-sac (Figure 7). A grated inlet was constructed on the proprietary device to accept sheet flow from the catchment. The garden provides a ponding area, for infiltration and detention storage, as well as pre-treatment of contaminants to prolong the maintenance life of the downstream device. The rain garden is aesthetically pleasing to surrounding houses while also serving as a roundabout.

This treatment train configuration has reduced maintenance costs significantly. The filter media in the proprietary device was observed to be clean, and still operational, 5 years after it was first installed in 2007. There is also easy maintenance access, with no confined space, to the garden and proprietary device.

Figure 7: Photo of Raingarden/Proprietary Media Filtration Cartridge hybrid treatment train at Henderson, Auckland (Source: Stormwater360 NZ)

5.6 **Buffalo Niagara Medical Campus, New York, USA – Proprietary Membrane Filter to Bioretention**

Construction of the innovation center at the Buffalo Niagara Medical Campus in New York, USA was undertaken in 2001. The project involved redevelopment of an existing 8000m^2 impervious catchment, comprising a mixture of footpaths, road and hardstand areas.

A federal mandate for the reduction of combined sewer overflow (CSO) volumes entering the Buffalo river, applied to this project. The development was also now required to meet present day stormwater quality standards.

Traditional grey infrastructure was explored as a standalone stormwater option for the site. However, runoff sheet from the existing site flowed to the southern end of the site and did not have existing catchpits. Construction of new pipelines would prove to be expensive. The limited available hydraulic head on the site was a further constraint.

A standalone bioretention facility, using the existing sheet flow drainage scenario, was initially proposed to meet the local water quality regulations and provide runoff volume reduction. However, the facility required a large footprint; space that which was earmarked for the redevelopment.

To meet the cost, aesthetic and environmental requirements the proposed solution was to use a hybrid green and grey treatment train approach by incorporating a proprietary membrane filtration device upstream of a bioretention cell (Figure 8). The proprietary device would receive sheet flow runoff via a kerb inlet and provide pre-treatment of sediment laden runoff. It would also capture litter, debris and hydrocarbons, prior to discharging treated runoff through an open back outlet over riprap into the bioretention cell. The bioretention cell would provide further stormwater treatment and volume reduction (infiltration and evapotranspiration) prior to discharge to receiving water bodies. Without the upstream pre-treatment function, the bioretention media could easily be prone to premature clogging which would not only create an eyesore but would also compromise the treatment trains overall ability.

Figure 8: Photo of Hybrid treatment train at Buffalo Niagara Medial Campus (Source: Contech Engineered Solutions)

5.7 Carol Lee Place, Albany, Auckland, New Zealand – Modified Raingarden to Modular underground tank

A stormwater pond was constructed in 2004 at Carol Lee Place, Albany Heights, Auckland in order to meet stormwater quality, extended detention and peak flow attenuation objectives for an approximate 3 hectare residential catchment (Roa, et al., 2012). Intensification of urban development in the contributing catchment resulted in the pond becoming significantly undersized to achieve the intended function objectives and meet resource consent conditions. A decision was made by the local council to redevelop the non-compliant pond to achieve the original objectives.

The Stormwater pond surface footprint required to meet the legislative and treatment needs meant extending the pond from the original 320m2 to a total area of 1060m2. Due to the development of the catchment since original installation the site now provided limited space within the existing drainage reserve for the construction of a fully compliant pond or wetland. Its close proximity to nearby housing further complicated the ability to extend.

The proposed solution, constructed in 2012, was a hybrid green and grey infrastructure approach using traditional rain garden overlying a proprietary modular plastic storage system (Figure 9). The biofiltration media provided the full water quality treatment whilst the underlying plastic storage system effectively moved the quantity and attenuation function to below ground. This option eliminated the need for a deep permanent pond or wetland, complied with the consent conditions and objectives to the best practicable degree, and aimed to improve the aesthetic and safety values of the original treatment system (Roa, et al., 2012). The compact design allowed the system to be retrofitted to the existing land constraints.

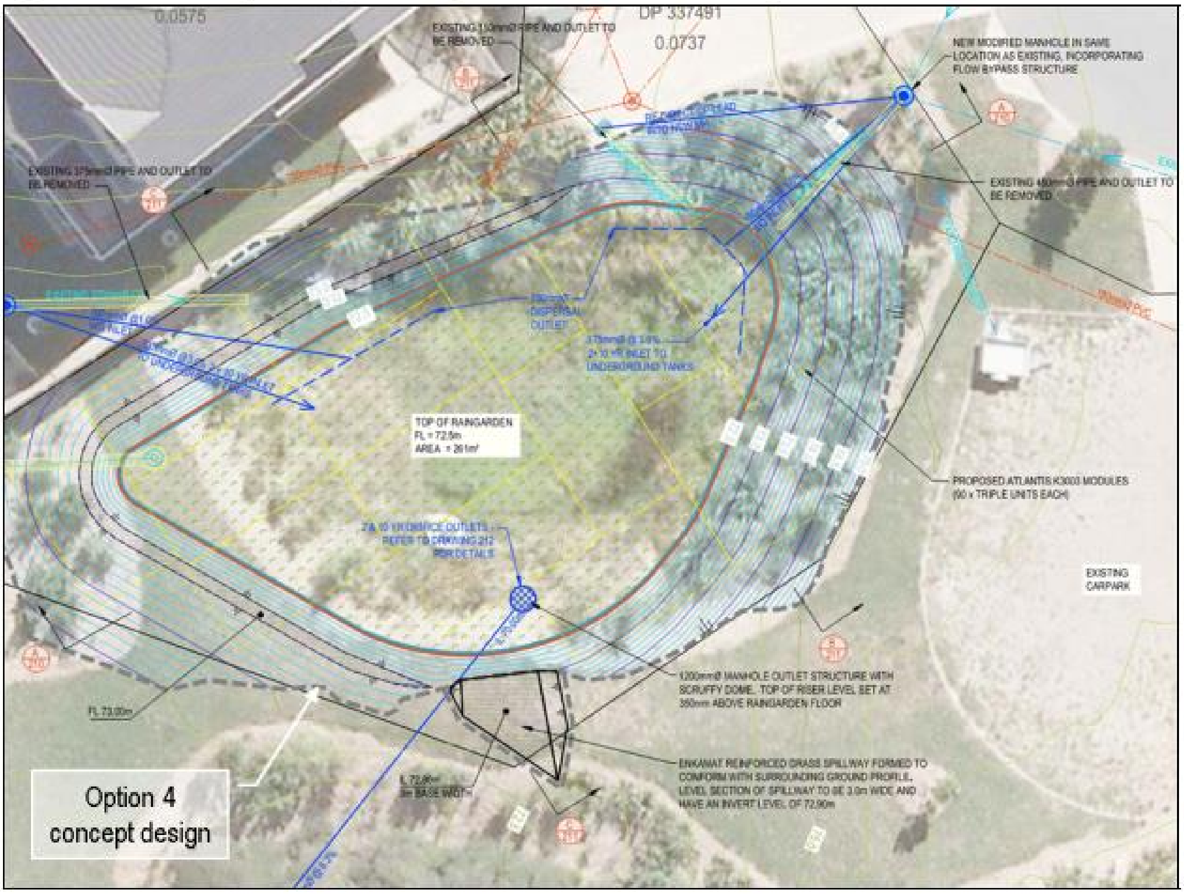

Figure 9: Preliminary drawing of Hybrid Raingarden Option for Carol Lee Pond, North Shore, Auckland, NZ (Source: Roa, et al., 2010)

6 DISCUSSION

6.1 Performance

TSS is a good benchmark to the performance of a BMP as it is the most regulated and evaluated pollutant across stormwater treatment devices. It is widely considered the simplest contaminant to remove from stormwater runoff, which itself, is complex (Hannah, 2006).

In most cases, it is difficult for one practice/device to provide for multiple benefits (NZTA, 2010) and achieve treatment efficiencies and objectives. Not all devices are capable of targeting and treating, at least to the same level, all the contaminants found within stormwater runoff. Summaries of stormwater contaminant removal efficiencies for common treatment devices, including innovative engineered stormwater treatment and land based water sensitive design devices, are widely available (Semadeni-Davies, 2008). Analysis of BMP performance data needs to be carried out carefully and credibly considering many different factors. In the end the results of all methods need to be evaluated and weighted up against each other (Hannah, 2006). The International BMP database is a common resource used by stormwater practitioners to compare stormwater treatment devices.

Hybrid systems show an opportunity to achieve higher treatment efficiency than if grey and green infrastructure are working individually. A treatment train approach, using a combination of multiple sequential stormwater management devices/practices, is increasingly becoming more common for this purpose. This approach allows different devices with different containment removal abilities to be constructed in series to treat stormwater runoff. Allowing stormwater to be repeatedly treated, providing a reduction of sediment and contaminant mass load, as it discharges down the train. The Waimahia Inlet, Albany Busway and Point Defiance case studies as previously discussed are examples of a hybrid treatment train approach used to meet water quality objectives for multiple contaminants.

The total removal efficiency of a given stormwater contaminant for two or more devices in a treatment train can be estimated using the following simplified equation (NJDEP, 2004);

$$R = A + B - [(A \times B)/ 100] \qquad (1)$$

Where:

R = total treatment train removal rate

A = Removal rate of the first or upstream practice

B = Removal rate of the second or downstream practice

As the simplified equation uses a percentage removal it should be applied with care. Although a good tool for estimation purposes, percent removal does not reflect the reality of how treatment trains and individual devices actually perform in the field (Lenhart, 2007). Throughout a storm event, the percent removal rate will vary with influent concentration i.e. as influent concentrations increase, removal percentages will also increase.

Modelling of contaminant removal is recommended to further quantify the performance of a hybrid approach. For the SH16 causeway study, preliminary modelling with the Model of Urban Stormwater Conceptualisation (MUSIC) was undertaken using the undersized swale and proprietary media filter. The results showed that TSS removal across the treatment train could exceed 90%; greatly exceeding the environmental objectives and the removal expectations from an individual device approach.

6.2 Space Constraints

Space constraints are a common problem faced by developers and designers of urbanised developments. There is an increasing need for stormwater treatment devices to be compact whilst also being cost effective (capital and long term operational costs), high performance efficient, durable, resilient, and easily maintainable. The cost of land is increasing, and space is usually at a premium, particularly on intensified brownfield urbanised catchments. For Developers, the aim is to maximise profits from the land, which more often than not involves maximising building footprints and vast construction of sealed impermeable surfaces earmarked for carparks, roads and hardstand spaces.

This has led to innovative engineered technologies and green/grey hybrid treatment trains increasingly used to address these space constrained challenges. The use of innovative engineered technologies is well suited to retrofitting or connecting to existing grey infrastructure and traditional piped drainage systems. When used in combination with green infrastructure, either for pre-treatment or principal treatment, they provide for space efficient treatment trains as seen in the above Carol Lee Place and SH16 Causeway case studies. This allows the treatment train to mitigate the adverse impacts of urbanisation, whilst conforming to regulatory environmental objectives in a space-efficient manner.

WSD devices are land dependant and typically require large footprints to implement as standalone systems. However, with good design and planning, WSD principles can easily be retrofitted and integrated into space-constrained sites and operate effectively (USEPA, 2014). Especially in a treatment train as shown in the hybrid case studies above.

6.3 Maintenance

Maintenance is an important factor in the selection of stormwater BMP’s in a treatment train system. Device sizing, treatment performance efficiency, ease of maintainability, and the site contaminant mass loads are all important factors to consider.

Engineered proprietary solutions are typically analogous in manufacture, basic operation and have standardised maintenance requirements and procedures (Tipene, 2008). Land based WSD devices are typically bespoke, designed to tie-in with the surrounding environment, and as such the layout, function and operation of these devices can vary significantly from site to site. This leads to

dissimilar installation, operation and maintenance procedures; factors that are often not compared and certified against the original bespoke design.
The maintenance frequency of a device will be largely dependent on the anticipated mass sediment loads generated from land use activities on the contributing catchment. Auckland Council's TP10 stormwater guidelines (2003) provides suggested contaminant loading ranges for various land uses (Table 1) that can be used for estimating purposes.

Table 1: Contaminant loading ranges for various land uses kg/Ha/yr (Source: TP10 2003)

Land Use	TSS (kg/ha/yr)
Road	281 - 723
Commercial	242 - 1369
Residential (low)	60 - 340
Residential (high)	97 - 547
Terraced	133 - 755
Bush	26 - 146
Grass	80 - 588
Pasture	103 - 583

Bed and gross pollutant loads, also known as gross solids or coarse sediment, are often overlooked in the design of stormwater treatment systems. These loads can double the suspended solid load by mass and be significantly more by volume because of their larger particle size (Hannah, 2005). This can have significant implications for the long-term performance and maintenance of treatment devices. At worst, premature failure can occur as the device does not have the storage capacity. This can lead to increase maintenance costs and more frequent maintenance activities. Consideration of bed and gross Pollutant loads in design and operation will lead to more efficient stormwater management (Hannah, 2005; Fitzgerald & Bird, 2010).

Hybrid treatment trains typically have significant maintenance benefits over single treatment device options. The upstream device provides pre-treatment of the receiving stormwater runoff and can aid maintenance activities by concentrating the bulk of contaminants in an easily accessible location. The pre-treatment device is usually proportionally smaller than the downstream principal treatment device, meaning more frequent maintenance of the pre-treatment device is required (Lehman, 2009). The mass sediment load is anticipated to decrease after each device, prolonging the need for maintenance of downstream devices, given that the coarse solids comprise the highest proportion of incoming sediments in terms of total volume (ARC, 2003; Hannah, 2005; Lehman, 2009). The Waimahia Inlet and Point Defiance case studies as previously discussed are examples of a hybrid treatment train approach where pre-treatment and load reduction have been used to meet maintenance objectives.

6.4 Cost

The supply, construction and maintenance cost of a device can vary greatly depending on numerous factors including: treatable catchment area, type of devices, size of devices, target contaminants, site conditions, site location and labour rates etc. (Hannah, 2012; Kettle & Kumar, 2013). Further cost comparison needs to be considered for the land value and development costs for extra housing or carpark spaces vs land dedicated to treatment devices.

There is a general perception that WSD is generally more expensive when compared with conventional solutions in both implementation and operation (Kumar, et al., 2015; Ira, et al., 2015; Mayhew, et al., 2016). Life cycle cost analysis undertaken in New Zealand suggest that there are a number of WSD devices that have comparable construction costs, however have higher maintenance cost (Hannah, 2012; Kettle & Kumar, 2013; Ira, et al., 2016).

The cost of providing WSD is also considerably more expensive than a conventional landscaped garden (Kettle & Kumar, 2013). This is typically due to higher design, construction and maintenance costs commonly associated with WSD features: engineered soils, deeper excavations, need for retaining walls and/or structural soils/aggregates, drainage systems & structures etc. There are also additional costs associated with longer plant establishment time due to the limited plant palette available in WSD devices.

Hybrid treatment trains have the potential to lower both capital and maintenance costs whilst achieving both WSD objectives and innovative engineered or conventional functionality. When used as pre-treatment devices, engineered solutions can significantly lower the maintenance costs typically associated with WSD (Hannah, 2012).

Life cycle costing is an important tool that can be used in evaluating stormwater BMPs whether it is a green, grey or hybrid device. However, it is only one parameter in the evaluation process and, although universally hard to measure, needs to be considered alongside environmental, cultural, social and ecological values (Hannah, 2012).

6.5 Cultural, Social and Ecological values

Maori culture recognises that environmental management has integral links with the mauri (life force) of the environment and concepts of kaitiakitanga (guardianship); principles which are echoed throughout the Resource Management Act and consenting process. The Maori world view in regards to relationships with the natural environment promotes stewardship and protection. Outcomes that, in regards to stormwater management, are generally attributed to green rather than grey infrastructure. Often this ideological approach to green infrastructure is in fact detrimental to the overall health of the system and therefore an unintended contradiction to the principles of stewardship and protection.

For example, due to the nature of contaminants (e.g. heavy metals) that originate from some contributing catchments, the quality of stormwater that the green infrastructure is expected to treat and manage is by default of a very poor quality. This is often directly fed into the green infrastructure where there is pressure on nature and the natural green infrastructure environment (e.g. a wetland) to filter out, and by default, absorb them. Whilst this approach works well for the bigger picture and enhances the quality of water discharged to the receiving environment it leaves behind a sort of natural cesspit which has impacts on the habitual ecosystem. In these cases, the use of green infrastructure protects the existing environment by creating a new sacrificial 'green' environment.

Adoption of hybrid systems can work to avoid this unintended outcome by utilising grey infrastructure for the harsher treatment process. Situating a grey treatment approach at the beginning of the treatment train works to reduce the level and concentration of harsh contaminants before they enter the green infrastructure at the end of the train. This results in the creation of an overall cleaner, and more natural stormwater treatment environment; an environment more in keeping with the mauri ideology.

An additional benefit of a hybrid system like this is the enhancements to the surrounding community in regards to social values and associated aesthetic provisions. Aesthetics is an important factor for public perception and acceptance of stormwater BMP's. Through good design, BMP's can blend into the site environment, provide for increased biodiversity and be an amenity to the community. The Edmonton road residential development and the innovative medical campus case studies as previously discussed are examples of a hybrid treatment train approach has been used for aesthetic values.

In addition, The Carol Lee and Waimahia case study above are examples where the BMP has been designed to incorporate a secondary use in the form of public recreational space. However, if these are highly visible and poorly designed, they can be a scar of the landscape (ARC, 2003). Regular maintenance of BMP's can enhance the visual appearance and public appeal, as well as improving function of the device.

7 CONCLUSIONS

Often stormwater treatment for a site is designed as either grey or green infrastructure. In the broader grey infrastructure category, innovative engineered devices can serve as a bridge between the traditional grey infrastructure and the evolving green infrastructure.

There is opportunity to better incorporate the best of what both grey and green offer. A hybrid system is an integrated treatment approach that blends innovative engineered stormwater management technologies with more traditional land based water sensitive design practices and/or conventional landscaped areas to overcome space and cost constraints. There is also an opportunity to design each device, in a hybrid treatment train, to target different contaminants for challenging sites or retrofitting devices on existing site.

The benefits of using a hybrid system not only includes reduced maintenance costs, aesthetically pleasing, reduced land requirement and improved treatment efficiency but also presents opportunity to enhance social, cultural and ecological values.

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