Are bio-retention basins an example of cargo cult engineering?

Nigel Bosworth
Principal Engineer, Calibre Professional Services, Newcastle, NSW
E-mail: nigel.bosworth@calibregroup.com

Bio-retention basins are standard practice water quality improvement measures, particularly in residential land development. In part this is due to their suitability as "end-of-pipe" solutions downstream of traditional engineered drainage systems. Detailed design guidelines have been published by many councils, particularly those in growth areas. These design guides follow apparent precepts of scientific and engineering, outlining engineering requirements, maintenance path specifications, along with planting regimes and species. These design procedures give the appearance of serious, evidence based engineering, but there is little checking or feedback to see if these systems actually work in practice.

The question needs to be posed, as an industry are we fooling ourselves while spending millions of dollars of developers' money, adding to housing affordability issues? Have we created 'cargo-cult' engineering, where we are creating something that has the appearance of engineering 'natural' features, while not achieving the purpose?

Cargo cults are a phenomenon that has occurred most famously in the islands of the South Pacific where remote people's first encounter with western civilisation occurred during World War 2. The islanders would see these new people turn up, build infrastructure such as runways and control towers, which would then result in airplanes bringing materials and wealth to the island. They'd see this behaviour and think that all they have to do is build the infrastructure and planes would land with precious cargo. So they'd make things that looked like runways, build airplanes and towers, and they'd make headphones out of coconuts. This infrastructure would not have the desired result of bringing wealth to the islanders.

Bio-retention basins have become the standard water sensitive urban design feature for land development in Australia since the 1990s. To date there has been little information published on the overall effectiveness, constructability, maintenance and operation of the basins that is based on practical experience. Assessment of success and failure, and incorporation of lessons learnt into the design process is rarely undertaken by practitioners and designers. This approach should be seen as fundamental to the development of any new engineering discipline, such as stormwater treatment.

The design of bio-retention features is rarely assessed in terms of hydraulic operation during the range of rainfall events, or in terms of ongoing maintenance. This has often resulted in structures that do not operate as intended, create maintenance issues and are visually out of character with the 'natural' landscaped features.

Studies of the operational effectiveness of constructed detention basins are rare, with a severe lack of available data collected in the field. This lack of documented evidence of the effectiveness of these key pieces of water quality infrastructure should be concerning when taking into consideration of the cost of construction and maintenance.

The objective of this investigation is to highlight the lack of scientific rigour and basis behind the engineering that goes into the design of bio-retention basins.

This investigation involves the systematic review of bio-retention basin design process, primarily those of the industry leading NSW local government authority Blacktown City Council. This review of the design guidelines along with an assessment of development approval and construction certificate conditions of consent identifies fundamental issues relating to the design and assessment process. Design guidelines are often too detailed on aspects such as maintenance access paths, while completely ignoring basin hydraulics and plant health. Conditions of consent are often too prescriptive, not outcome focused and require construction of infrastructure that will not provide
stability during long-term wetting and drying periods. The health and viability of plants is not included in design guidelines or assessed as part of the approval process.

The results of this investigation highlight the need to undertake a review of the effectiveness of water quality measures in real world situations. Monitoring of the performance of these basins should be seen as a priority, with the likely cost of testing programmes anticipated to be orders of magnitude lower than potential cost savings in design and maintenance.

1. INTRODUCTION

Bio-retention basins are an attempt to use natural processes vegetated soil-based filters to improve water quality from developed areas. Bio-retention basins are standard practice water quality improvement measures, particularly in residential land development. In part this is due to their suitability as ‘end-of-pipe’ solutions downstream of traditional engineered drainage systems. The other driving factor behind their popularity is bio-retention systems usually require less land than other practices such as open water wetlands to achieve targeted pollutant removal rates.

Detailed design guidelines have been published by many councils, particularly those in growth areas. These design guides follow apparent precepts of scientific and engineering, outlining engineering requirements, maintenance path specifications, along with planting regimes and species. These formalities give the appearance of serious, evidence based engineering, but there is little checking or feedback to see if these systems actually work in practice. The result is that millions of dollars are being spent on civil and landscaping works with little to no accountability. As pressures on housing affordability continue, it may come to a head when an analysis of the cost of delivering lots is forced on the industry by Councils or government authorities.

The question needs to be posed, as an industry are we fooling ourselves while spending millions of dollars of developers’ money, adding to housing affordability issues? Have we created ‘cargo-cult’ engineering, where we are creating something that has the appearance of engineering ‘natural’ features, while not achieving the purpose?

Cargo cults are a phenomenon that has occurred most famously in the islands of the South Pacific where remote people’s first encounter with western civilisation occurred during World War 2. The islanders would see these new people turn up, build infrastructure such as runways and control towers, which would then result in airplanes bringing materials and wealth to the island. They’d see this behaviour and think that all they have to do is build the infrastructure and planes would land with precious cargo. So they’d make things that looked like runways, build airplanes and towers, and they’d make headphones out of coconuts. This infrastructure would not have the desired result of bringing wealth to the islanders.

These cargo cults may appear comical to outside observers, but the trap of basing construction on our observations from a position of limited understanding is universal. The stormwater and development industries have based designs of treatment measures on our observations of nutrient removal plants, even providing scientific testing of these nutrient removal characteristics on laboratory analysis. This has the appearance of genuine scientific and engineering analysis. Crucially, as an industry there is very little testing of the operation of real world basins, or even analysis of the health of basins once they have been installed.

Stormwater pollution treatment as the only outcome that is modelled and measured when assessing a drainage feature has resulted in reduced function and integration into urban systems. The outcomes delivered have reflected the narrower reductionist definition relating to simply treating stormwater to remove pollution (Mullaly, Penhallurick and Smart (2016)). As the stormwater industry develops and our understanding grows, there must be an assessment of the methodologies and desired outcomes for our designs.

The dominant paradigm of stormwater quality needs to be continually assessed and determined for its appropriateness. Projects which solely focus on stormwater quality objectives miss the true potential of such projects by being too narrow and insular in their focus.

Knights, McMillan (2015)

The argument put forward in this paper is that as an industry, we need to question whether we have
used scientific and engineering techniques to develop ‘natural’ treatment systems that have the appearance of what we think a pollutant removal system should look like but do not function as such due to the limitations of our understanding. Are we just building something we think looks like it should work but not checking to see whether or not it actually achieves the outcomes we are after?

2. CURRENT BIO-RETENTION BASIN DESIGN

At the precinct planning level, the detail required for practical construction and operation of water sensitive urban design infrastructure is often missed in water cycle management planning. At the other end of the scale, engineering design guidelines often focus too much on fine civil infrastructure detail. The result is that there is often no direct connection from strategy through to the detailed design.

2.1. What is a bio-retention basin?

Bio-retention basins (also known as bio-retention systems, bio-filters, and rain gardens), along with any natural water treatment, are an attempt to use natural processes to achieve an ‘unnatural outcome’. Bio-filtration systems are a popular stormwater treatment technology, using vegetated soil-based filters to attenuate flows, reduce runoff volumes, and improve water quality through sedimentation, filtration, sorption, and biological uptake (Davis et al., 2009, Hatt et al., 2009).

Bio-retention basins aim to use the natural processes of biological responses by the vegetation, soil, microorganisms (terrestrial and aquatic), to provide treatment of stormwater runoff. This has a benefit as natural systems typically require fewer operational personnel, consume less energy, and produce less sludge than mechanical systems (WEF, 2001). Bio-retention basins are an attempt to engineer conditions suitable for these biological responses to remove pollutants from stormwater runoff.

2.2. Typical design procedure

Local councils produce guidelines to assist in the design and assessment of civil engineers infrastructure within their jurisdiction. These planning documents are essential for the engineering industry, as they provide guidance and cover all aspects of civil design, including drainage. They provide a framework to allow consideration of operation, maintenance and constructability. A leading example of the guidelines produced by one of the largest development councils in western Sydney is Blacktown City Council, which is used throughout NSW as a design guide.

The typical design process for a stormwater basin that incorporates bio-retention within a greenfield urban development follows these steps:

- Set aside 3–5% of the catchment in an area at the lower end of the catchment, usually at the outlet
- Design the road layout to maximise developable area
- Design the pit, pipe and overland flow stormwater system
- Calculate the treatment area required to meet pollutant removal targets using MUSIC software, along with detention requirements, usually in software such as XP-RAFTS or DRAINS
- Earthworks design of the basin to allow for detention, bio-retention area, including maintenance access path for gross pollutant trap and bio-retention area
- Inlet and distribution structures are usually designed according to Council standard drawings
- Once the earthworks and civil design is complete, the design is handed over to architects to incorporate plants from an approved species list.

This process involves little overall modification to the standard design procedure of an urban development, with the water quality solution essentially being designed as an end-of-pipe add-on to the standard engineering design.

2.2.1. Designed to achieve pollutant removal, not overall catchment export

The metric by which water sensitive urban design features are assessed, measured and ultimately approved is predicted pollutant removal, i.e. the effectiveness by which they are able to intercept and
trap contaminants generated by urban development. As a result, the objectives and the compliance with them using MUSIC incentivise sites that develop in a manner that produces more pollution and then treats it, rather than the intuitively more logical outcome of incentivising sites that avoid creating pollution in the first instance (Mullaly, Penhallurick and Smart (2016)).

This design methodology and assessment leads to discouragement of less intensive land use and encouragement of end of pipe solutions. The implications for design of stormwater systems is summarised in Liebman et al, 2016.

The dominant design paradigm, largely driven by various State and Council policies, remains a Best Management Practice (BMP) approach with localised variations of the same targets. These targets include removal of at least 80-85% of total suspended solids (TSS), 40-65% of total phosphorus (TP), and 40-45% of total nitrogen (TN). A multinational review of policy targets by Liebman et al, 2009 showed most countries focus solely on removal of TSS and that Australia is the only country to adopt removal targets which include TSS, TP and TN. Removal of TSS is relatively easy and current non-blocking filtering technology is well proven within the industry and removal targets are easily met. TP, mostly particulate in nature (IEAust, 2005) is also relatively easy to remove, as it too can be mostly screened or finely filtered. Orthophosphate, a dissolved form of Phosphorus (P) is readily exchanged and adsorbed by various types of filter media making it easy to target for removal.

Liebman, Tippler, and Noble (2016), in a paper discussing the reliance on modelling to calculate the removal of total nitrogen, rather than the more relevant, bio-available dissolved nitrogen that typical stormwater policies require the removal of 45% of TN and do not discriminate between dissolved or particulate nitrogen.

Liebman et al (2004) questioned the sustainability of stormwater targets including the BMP targets which are now over 40 years old and identified that one of the key problems with the load reduction approach that is so widely adopted is that it rewards the most polluting sites and makes it hard for the least polluting sites to comply. This was explained with an example which showed that it is relatively easy to remove 45% of a very high load rate and relatively hard to remove 45% of a very low load rate. The outcome of this is that this discourages land practices that generate low loads of pollutants.

2.3. Lack of investigations of effectiveness of basins as designed and constructed

The catchment pollutant export rates within the MUSIC modelling software are based on twelve catchments in Melbourne and are used within the software, to be applied throughout all of Australia. This data was obtained in the 1990s and hasn’t been updated, despite the universal application of MUSIC as the basis for assessment of water quality improvement measures throughout Australia.

The use of this data to base models that basins are designed and assessed, often to the 0.1% pollutant removal reduction is clearly pushing beyond the limits of accuracy.

There is a lack of actual studies into effectiveness of constructed bio-retention basins in operation within the urban environment. This is a factor of the relatively recent development of these systems, the complexities encountered in measuring basin inflows and outflows, along with the difficulties in designing a standard testing regime for the wide variety of basin arrangements.

2.4. Outcome of current design practices

The outcome of current bio-retention basin design practices are that the process results in an engineered feature that to an engineer looks like it should work, but most likely doesn’t. This ‘cargo cult’ outcome where from one perspective it looks like we assume a treatment system should look, but does not function as a pollutant removal device or as habitat.

The use of engineering guidelines by designers and councils can lead to a situation of ‘curve fitting’ and ‘box ticking’ where designs are fine tuned to achieve certain guidelines. Basins are designed with specific water quality targets in mind, while the assessments of the basins seem to be undertaken by a checklist approach, rather than by investigating how they will be constructed, operate and be
integrated within the urban landscape.

Conditions imposed in engineering design guidelines are often too prescriptive, not outcome focused and do not provide for the flexibility required for detailed civil design or have any analysis of the likelihood of plant health and ecosystem function.

2.4.1. Engineered structures, designed for maintenance

As a result of the prescriptive design requirements in engineering design specifications, bio-retention basins are often designed as engineered features, with maintenance and vehicular access as the primary goal. Bio-retention maintenance paths are often required to be concrete vehicle path 3–4 metres in width with very specific limits on gradient and large turning circles for rigid vehicles result in basins that are visually unappealing, have issues with increased heat stress on plants and are not suitable as recreation or habitat. The analogy related to the impact of engineers on the human environment would be the failures involved in letting highway engineers design a city i.e. that the end result is a city that is not suitable for pedestrian activity and does not function as a ‘liveable’ city.

There are also issues with using models like MUSIC for landscape and habitat details when they are only suitable for broad brush analysis. The use of MUSIC as a design tool to achieve pollutant removal to within a modelled accuracy of 0.1% is not suitable given the errors inherent in the measurement of catchment runoff parameters.

2.4.2. Unhealthy or dead plants, algae and moss, systems lacking in microbiota

The result of designing basins to engineering guidelines has been assessed as part of this investigation, including assessment of designed bio-retention systems. Plant health in many of the systems analysed found poor plant health, often with large areas of dead vegetation, with the bio-retention media covered with algae or weeds.

Without plants, bio-retention systems function more like sand filters with reduced stormwater quality treatment performance in comparison to vegetated bio-retention systems with active soil biota. Plants in bio-retention systems are also essential for the realisation of a range of other benefits including for example amenity, microclimate management and habitat (e.g. Hatt et al. 2007 and Henderson et al. 2005).

The reduced biodiversity of macro invertebrates within stormwater runoff impacted areas is a well-documented phenomenon. In a study of forty-five waterways in the Hawkesbury Nepean catchment Chessman and Williams (1999) that urbanisation had a marked impact on the diversity of macro invertebrates and identified urban expansion as the greatest threat to biodiversity in waterways, Knights, McMillan (2015).

2.4.3. Trees are excluded from the basin, natural systems have trees which protect plants and avoid conditions suitable for algae/moss

In natural low lying areas that are periodically inundated by water. trees provide cover and protect the species used in bio-retention basins. Trees tend to avoid burning the vegetation from excessive heat or sunlight and prevent excessive drying out. They also serve to prevent conditions that lead to algae growing on the soil surface.

Plant species we select for bio-retention systems are based on what is found in the local area, e.g. western Sydney floodplain species used in planting lists throughout development council local government areas. These species are selected based on locality with no notice is taken of the context that these species are found within the floodplain. Sedge species are not found in open ponded areas, as they are used within bio-retention basins. More often, they are found under open tree canopies or at fringes of tree canopies, providing shelter from extreme heat and drying and continual sunlight.

The use of trees in bio-retention basin design is actively encouraged by engineered design guidelines. This issue has been summarised

An example of this is the perceived dilemma about putting trees in rain gardens. A position which states that trees cannot be used in bioretention systems because the treatment system will need to be rectified in twenty years is an example of the
dominant paradigm ignoring more immediate benefits. It prioritises stormwater treatment over all else and ignores the substantial synergistic benefits of trees in rain gardens, which are achieved in a much shorter time frame. The exclusion of trees in treatment systems may well be justified where the treatment system is treating water discharging to a sensitive receiving environment and the treatment device is playing a critical role in ameliorating the impacts of stormwater on the environment. However in most circumstances this is unlikely to be the case.

Engineering design guidelines are often actively prohibitive towards the use of trees, with guidelines requiring and additional volume allowances for basins designed with trees. This allowance can often be as high as 150% of the required storage volume.

2.4.4. Result is that basins rarely work as intended
Audits of the operation of basins undertaken for this investigation have found that bio-retention basins showed that there were varying areas within all the basins assessed that were not functioning correctly. Large areas of dead plants were apparent in all basins, with issues encountered primarily at inlet and outlets of basins.

McCann et al (2015) stated that stormwater quality improvement device dysfunction can be generally categorised into three areas:
- Poor design – including site selection, device configuration, and plant selection
- Incorrect or incomplete construction including incorrect set-out, inappropriate media, poor workmanship.
- Lack of maintenance and monitoring.
McCann et al (2015) listed the most common symptoms of failed stormwater devices are: excessive sediment, weed invasion, scour, poor water quality. The field investigations undertaken as part of this systematic qualitative assessment were based on readily observable measures of bio-retention basin health and operation.

The findings of the site investigations were surprisingly consistent across the basins. The same issues were encountered at all basins in some form, with none of the basins audited judged to be operating as the designer had intended.

3. RECOMMENDATIONS FOR DESIGN

The design of bio-retention basins is now entering a more mature phase, as the industry approaches twenty years of age. The question posed by this paper is, should we remove engineering from this altogether and focus on landscaping and vegetation health, or should we pursue a more detailed engineering method including computational fluid dynamics, modelling of flow into and around the basin and through the media? This engineered approach will be highly complicated and expensive questions need to be raised as to whether it would achieve better outcomes?

A comprehensive, more detailed approach, may be suitable for large scale basins, where construction costs could be minimised through detailed analysis. The approach would also require the development of highly specialised model with no software currently available on the market. This may be a market opportunity for future versions of the MUSIC software package. There are few issues with engineering consultancies having suitable computing power and engineering understanding to develop and run models, as the complexities of large-scale two dimensional flood modelling are well understood and appreciated.

3.1. Simplification of smaller basin designs to reduce construction and maintenance costs
Several councils and government authorities (Blacktown City Council as the most prominent in NSW) have provided standard drawings for basin designers to use and reference in an attempt to simplify the design process, with the aim to have better basin outcomes. These designs are often quite complex, difficult to procure and construct (e.g. porous pipe not readily available in Australia).
These standard designs often are designed around maintenance by heavy vehicles and often contain saturated zones. These zones increase the complexity of bio-retention systems in design, construction and assessment thereby adding to the financial cost of bio-retention systems, prolonging timeframes and increasing carbon footprint (Dubowski et al 2016).

Simplification of standard designs, based on habitat create and minimising construction and maintenance requirements is possible and can standardise and reduce costs. Simple catchment size to basin size relationships, standard gross pollutant trap, siltation pond (with capacity for eduction debris removal) and outlet and spillway from pre-cast features should all be incorporated into standard guidelines.

3.2. Use of natural templates – observe what works and what doesn’t

Bio-retention basins are attempts to use natural processes to remove nutrients. Similar, non-designed, ‘natural’ systems include a greater variability in hydraulic conditions, vegetation types and species mixes, often including aspects such as ponded water and trees. These aspects should be included in the design of bio-retention basins.

Observation of one layer of vegetation, such as the sedge type grasses used in bio-retention basins focuses on the nutrient removal function of the plants, ignoring the ecosystem and habitat function. It is this functional misunderstanding above all other issues that has led to bio-retention basins being able to be seen as ‘cargo cult engineering’.

Observation of natural systems found that trees often formed natural embankments around areas of ‘natural bio-retention’. Several of the sites investigated as part of this study had embankments that had developed through the growth of trees, in particular casuarina and eucalyptus species (e.g. eucalyptus benthamii, eucalyptus amplifolia). These unplanned systems were used as a template for basin design, with the stable, unmanaged and non-maintained features assessed for suitability for treatment systems.

This use of trees as embankments is totally at odds with an engineered water embankment structure, where trees are excluded due to the possibility of piping failure or total failure of the embankment if a tree falls. With bio-retention systems, the volume and depth of ponded water is small, which would result in fewer issues as a consequence of failure of an embankment. The habitat, shading and aesthetic benefits of trees are significant enough for their use as embankments to be considered, with embankment failure analysis (dam break studies) being undertaken if required.

3.3. Maintenance to be designed to be done by landscaping contractors, not earthworks contractors

Engineering guidelines and standard design tools often require maintenance paths to be designed first, with no regard to habitat function. Basins should be designed to be maintained by landscaping staff on foot from a nearby light vehicle. Heavy vehicle maintenance, such as removal of filter media will by it’s very nature destroy the basin. While consideration of constructability and media removal should be considered, the use of concrete paths around all sides of a bio-retention basin should not lead the design.

3.4. Plant health above all other concerns

Basin designers need to consider what plants require to thrive and function to remove pollutants, i.e. the right amounts of soil, sunlight and water, along with appropriate wetting and drying cycles. The use of MUSIC as a tool to size basins does not consider whether plants are getting enough water. An example of this is when a model is created with too large a bio-retention area for the catchment, pollutant removal rates do not change, even though such a system would result in widespread plant death, particularly in times of drought.

Plant establishment periods are determined by councils. Several months of establishment are usually required for a basin prior to hand over to council. Determining authorities should consider more...
species, season and weather appropriate measures for plant establishment. These may have shorter or longer timeframe, less intensive ongoing work, with some species even requiring watering and fertiliser during establishment phase to allow plants to thrive.

3.5. Create an ecosystem, including trees

Desirable attributes for raingardens across all residential streets were large, well-established trees with a lush green understorey (Dobbie, 2015). This is not possible with existing council guidelines as trees are not able to be planted within filter media as they would damage the media and earthworks. Most of the ‘natural’ systems investigated as part of this study had trees within the basins and embankments.

Observation of the overall ecosystem that includes the nutrient removal species used in bio-retention basins is essential to the establishment of a treatment ecosystem. A narrow approach that focuses on the nutrient removal function of the plants, ignoring the ecosystem and habitat function, will not create long term conditions for plants to thrive and perform the desired function. A healthy functioning ecosystem will delay or even remove entirely the need for heavy vehicle or civil maintenance, saving costs and improving basin performance.

4. REFERENCES


IEAust, 2005 Australian Runoff Quality


