EPA VICTORIA

Review of stromwater science

Publication 1919 | October 2020

VICTORIA State Government

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Review of stormwater science

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Australian Government
Department of Industry, Innovation and Science

Business
Cooperative Research Centres Programme

Review of stormwater science

Project: P118279_V02_R02_EPA Stormwater Review

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Produced for EPA Victoria in collaboration with Alluvium Consulting and Monash Engineering.

Publisher

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Date of publication: September 2018

An appropriate citation for this document is:

Ewert, J., O'Halloran, D., Lintern, A., Weber, T and McCarthy, D., 2018, Review of stormwater science, Melbourne, Australia: Cooperative Research Centre for Water Sensitive Cities

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Executive Summary

Since the introduction of the Urban Stormwater Best Practice Environmental Management (BPEM) Guidelines in 1999, the scientific community's understanding of the science of stormwater has grown with the understanding of what the community values about our waterways and bays. In 2013/14 DesignFlow undertook a review of BPEM, taking into account supporting science and modelling to recommend updated BPEM pollution reduction targets for total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), litter and flow.

The Victorian Government has recently made a series of commitments to improve stormwater management which includes both reviewing the coverage of the Victoria Planning Provisions and updating the BPEM guidelines. This review looks at the science undertaken since 2013/14 to understand how that could influence future policy and regulation in relation to stormwater management.

The table below summarises the research topics for this review, what the current approach is and whether recent science confirms or changes about that approach and knowledge gaps.

Research topic	Summary
Waterway values and place-based objectives	In 2013 the Healthy Waterways Strategy (Melbourne Water, 2013) defined objectives for waterway values including Birds, Fish, Frogs, Macroinvertebrates, Platypus, Vegetation and Amenity. The values identified within the Draft Healthy Waterways Strategy (2018) have grown to include "Community Connection" and "Recreation" recognising the better understanding and appreciation of the social values of waterways. This is consistent with other notable waterway values strategies, including Healthy Land and Water, 2017, 2018b, 2018a) in South East Queensland.
Place based objectives	Social, ecological and economic values are location specific and require tailored responses to ensure their values are protected. The Draft Healthy Waterways Strategy (2018) sets place-based objectives for waterway values as well as location specific targets for stormwater harvesting and infiltration. In this sense there is a general appreciation that place based objectives represent an improved ideal approach, compared with uniform targets. Further, Action 5.5 of the Department of Environment, Land, Water and Planning's Water for Victoria document (2016) that includes Action 5.5. to "Improve stormwater management for greener environments" by "leading the development of local place-based targets for stormwater management". The review of the literature identifies local and international examples where scientific approaches have led to the successful protection of individual values. There is however greater complexity associated with the development of objectives and targets for the protection of multiple values. A lack of data is also identified as a potential barrier to objective setting in some cases.

Flow	The flow related regulation within the BPEM is to maintain discharges for the 1.5-year ARI at pre-development levels. Flow is a critical threat to urban waterway values and evidence to support this continues to grow. There are numerous indicators that can reflect the impact of flow, with 'total annual runoff volume' identified as being a functional indicator, given its correlation with stream health. Protecting or restoring values in an urbanised catchment may require something in the order of 50-90% reduction in total annual runoff volume., with stormwater harvesting, reuse and infiltration a key contributor to reaching such a target. There is limited information on whether lesser percentage reductions are suitable where protecting pre-development values is not the objective.
Quality	The literature since the previous review of BPEM suggests that TSS, TP, TN and gross pollutants are important pollutants to remove from urban stormwater, both for protecting the health of receiving waters, and for protecting public health. As well as the annual load, the timing of loads, seasonality of loads and concentrations of pollutants are also important factors and the removal of TSS, TP and TN. The removal of TSS has also been associated with the remove other stormwater contaminants (e.g. heavy metals), however the results of this relationship are variable across sites and conditions. Gaps in understanding include a clear assessment of the impact of the current BPEM targets on waterway and public health while noting that monitoring capability continues to improve opening up opportunities to better understand the relationship between stormwater quality and waterway values.
Stormwater management objectives and the performance of urban stormwater treatment measures	Performance data for WSUD assets like biofilters and wetlands has grown since 2013 but remains variable. Biofiltration performance in terms of concentration reduction is variable, with load reductions often driven through volumes loss. Constructed stormwater treatment wetlands also exhibit variable reductions in concentrations of TN and TP with sedimentation highlighted as an important element of the treatment process. The performance of WSUD systems within smaller catchments is relatively well researched, however there is a gap in understanding regarding the performance of WSUD when applied at the catchment scale. The Little Stringybark Creek project continues to provide valuable data to this point. It is encouraging that the condition, performance and aesthetic of WSUD assets has improved since 2014. Integrated water management, through stormwater harvesting and infiltration and rainwater tanks, are increasingly recognised avenues to the reduction of pollutant loads going to Port Phillip Bay and the restoration of a more natural catchment hydrology. Climate change will influence catchment behaviour and therefore the design and performance of WSUD. There has been a significant shift in the rainfall-runoff relationship in catchments after extended periods of drought, with implications for catchment modelling approaches. In terms of stormwater quality climate change will result in an increase in pollutant export from urban areas due to increased flow from larger events. Other management mechanisms include offsets. Melbourne Water has applied these primarily in relation to nitrogen, with the aim of applying stormwater management actions at least cost. Whilst there has been successful application, some research has identified potential shortcomings where offsets target pollutant loads at the catchment scale while not accounting for local waterway impacts and values.

Introduction

Victorians place significant value on their waterways and bays as places to recreate and relax. Waterways also offer some of the last wild environments within cities. In urban areas waterways and linear green corridors also provide opportunities to connect to nature, while providing habitat for fish, birds, platypus and macroinvertebrates. Indigenous Australians maintain cultural, spiritual and economic connections to waterways and for these reasons waterways deliver social, cultural, economic, and ecological value to all Victorians.

The urbanisation of Melbourne and other towns and centres across Victoria increases the impervious proportion of catchments. This is turn increases the volume of stormwater reaching our waterways and the pollutant loads it carries. The altered catchment also creates ‘flashy’ flows, with higher peak flow rates and velocities.

This change in urban hydrology has altered urban waterways and bays, affecting the values that today’s community associate with them. Managing stormwater is therefore critical to improving the condition of waterways and bays and protecting the broad range of values that they provide.

Background

The Victorian community’s appreciation of the impact of stormwater on receiving waterbodies is documented within the Port Phillip Bay Environmental Study (CSIRO, 1996). The results of the Port Phillip Bay Environmental Study were incorporated into the first Port Phillip Bay Environmental Management Plan. This landmark study quantified chemical and biological processes within the Bay, enabling practitioners to predict the impact of catchment changes on ecological function. The key outcome from that study was the need to reduce 1,000 tonnes of nitrogen from reaching Port Philip Bay per year, with half of this being achieved via upgrades to the Western Treatment Plant, the other half from in-catchment stormwater improvement works. Duncan (1999) provided a statistical overview of urban stormwater quality to provide an understanding of the ‘broad scale behaviour of urban runoff quality, and its interactions with land use and other catchment characteristics’.

These investigations preceded the introduction of the BPEM which contained water quality and flow targets. Figure 1 below summarises the BPEM targets and the objectives associated with those targets. BPEM requirements are linked to urban planning through Clause 56.07 of the Victoria Planning Provisions gazetted in 2006. Clause 56.07 states that BPEM targets must be met within all new residential subdivisions of undeveloped lands. These statutory obligations are also referenced in the State Environment Protection Policy (Waters of Victoria) where the BPEM is an incorporated document to this instrument. Recent changes to the Victoria Planning Provisions also applied the BPEM requirements to apartment developments (Clauses 55.07 and 58.03).

Since the introduction of BPEM, the scientific community’s understanding of the science of stormwater quality, flow and methods of treatment has grown, alongside the understanding of what the community values about our waterways and bays. In 2013 / 14 DesignFlow undertook a review of BPEM, including the supporting science and modelling, to recommend new BPEM targets.

The Victorian Government has recently made a series of commitments to improve stormwater management which includes both reviewing the coverage of the Victoria Planning Provisions and updating the BPEM.

This report aims to review science that has been undertaken since 2013/14 that could influence future policy and regulation in relation to stormwater management. The report builds on the work from 2013/14 with the outcomes used to inform the development of stormwater management options and a cost benefit analysis (undertaken in parallel with this project).

Pollutant	Receiving water objective:	Current best practice performance objective:
Post construction phase:		
Suspended solids (SS)	comply with SEPP (e.g. not exceed the 90th percentile of 80 mg/L) (1)	80% retention of the typical urban annual load
Total phosphorus (TP)	comply with SEPP (e.g. base flow concentration not to exceed 0.08 mg/L) (2)	45% retention of the typical urban annual load
Total nitrogen (TN)	comply with SEPP (e.g. base flow concentration not to exceed 0.9 mg/L) (2)	45% retention of the typical urban annual load
Litter	comply with SEPP (e.g. No litter in waterways) (1)	70% reduction of typical urban annual load (3)
Flows	Maintain flows at pre-urbanisation levels	Maintain discharges for the 1.5 year ARI at pre-development levels
Construction phase:		
Suspended solids	comply with SEPP	Effective treatment of 90% of daily run-off events (e.g. <4 months ARI). Effective treatment equates to a 50%ile SS concentration of 50 mg/L.
Litter	comply with SEPP (e.g. No litter in waterways) (1)	Prevent litter from entering the stormwater system.
Other pollutants	comply with SEPP	Limit the application, generation and migration of toxic substances to the maximum extent practicable

1 An example using SEPP (Waters of Victoria 1988), general surface waters segment.
2 SEPP Schedule F7—Yarra Catchment—urban waterways for the Yarra River main stream.
3 Litter is defined as anthropogenic material larger than five millimetres.

Figure 1. BPEM Targets (CSIRO, 1999)

Scope of the literature review

This Review of Stormwater Science is a review of the scientific literature supporting the management of stormwater in Victoria focussing on scientific literature produced since 2013/14. This review refers to pre-2014 literature where supporting context is required.

The review focuses on the topics and questions summarised in the Research Topics section below. The outcomes of this report will support a science and policy review of the BPEM, including the metrics to measure stormwater impact, the land uses to which the BPEM applies and the suitability of our current approaches to ensuring that these impacts are managed to protect waterway values.

This review focuses on urban development and increases in catchment imperviousness as the primary and most threatening process. We acknowledge that many of the pollutants and parameters discussed here could also enter the stormwater system through poor industrial practice, leaking sewers or poor waste management. These ‘point’ sources are likely to require different management approaches, such as site management regulation, education and enforcement, which should be considered separately than an overall BPEM objective for development.

Objectives

The objectives of this technical report are to:

- Update and ensure currency of scientific knowledge around urban stormwater, including flows; pollutants, treatment measures for these pollutants; and the appropriateness of the stormwater management requirements in the current BPEM.
- Provide information that will inform the development of stormwater management tools and regulatory options to assist consultations with key government stakeholders.

In delivering these objectives this project has:

- Developed four research topics
- Reviewed relevant scientific documentation, focussing on outcomes produced since 2013/14, to address those questions
- Provided recommendations based on the outcomes of that scientific research.

Research Topics

Research topics were developed in consultation with EPA Victoria to guide the literature review. Each chapter of the report addresses one research topic. While there is naturally overlap between research topics, the document is structured to establish waterway and bay values and objectives, investigate our understanding of the impacts of stormwater (through the headings of flow and quality) before discussing the objectives of stormwater treatment assets and their measured performance.

Research topic	Guiding questions
Values and place-based objectives	What social, cultural, or environmental indicators best reflect our objectives in protecting receiving environments? What do 'place-based' objectives look like and how can they be applied?
Flow	What flow and geomorphology metrics (and targets) are important indicators for receiving environment health? What impact is climate change having on urban catchment hydrology and water quality and how might this influence our development of best practice targets?
Quality	Are the current targets proposed in the BPEM sufficient to protect waterway health and public health? Should additional water quality metrics be included within the BPEM and if so, what targets need to be set?
Stormwater management objectives and performance of urban stormwater management and treatment measures	How is WSUD being applied and how effectively is this contributing to achieving the BPEM objectives? How effective are WSUD measures at removing 'existing' and emerging pollutants? What impact does WSUD have on catchment hydrology (flow and peak flowrates)? How is WSUD affected by climate change? What other management options or approaches are open to EPA to meet their objectives?

Foundation documents

The project focuses on developments of the scientific understanding since 2013/14. The review begins by considering ‘Foundation Documents’, being the key documents that underpinned the 2013/14 review. The aim of reviewing these documents is to understand the basis upon which the previous review was based. These documents are:

- State Environment Protection Policy (SEPP) – Waters (DELWP, 2018) and the corresponding Policy Impact Assessment (DELWP, 2017a)
- Urban Stormwater BPEM Standards Paper (Design Flow, 2013b, 2013a, 2014)
- Management of the ecological impacts of urban land and activities on waterways (Urrutiaguer et al., 2016)
- Stormwater knowledge synthesis report (EPA, 2017)
- Healthy waterways strategy draft (Melbourne Water, 2018).

State Environment Protection Policy (Water of Victoria) (EPA, 2003)

The State Environment Protection Policy (SEPP) sets a ‘statutory framework for the protection of the uses and values of Victoria’s fresh and marine water environments. With regard to relevance for this literature review, the SEPP defines the uses and values of Victoria’s waters. Associated environmental quality indicators and objectives assist in providing an understanding as to when those values are being protected and to provide a guide as to what is required to protect them. Uses and values are collectively referred to as ‘beneficial uses’ that include:

- Aquatic ecosystems
- Water based recreation
- Cultural and spiritual values
- Water for agriculture and irrigation
- Water for aquaculture
- Water for industrial and commercial use
- Water for human consumption
- Agriculture and irrigation
- Fish, crustacea & molluscs for human consumption.

Indicators adopted to gauge the protection of beneficial uses within rivers and streams include nutrients (phosphorus and nitrogen), turbidity, salinity, pH, dissolved oxygen, toxicants (in water and sediments) and biological indicators.

Urban Stormwater BPEM Standards Paper (Design Flow, 2013b, 2013a, 2014)

The aim of these papers was to develop suitable environmental stormwater discharge standards for Victoria across two phases of work:

- Phase A: Identifying (selecting) metrics that were important for waterway health and that had sufficient and clear data to understand how treatment trains perform against those metrics, and
- Phase B: Determining numeric targets for each metric taking into account performance, cost, liveability and administrative requirements.

The outcome of the analysis was a recommendation for modified pollution reduction targets for total suspended solids (85%), total phosphorus (50%) and total nitrogen (50%).

In addition, a flow reduction target of 25% of mean annual runoff (via means such as harvesting, infiltration and / or evapotranspiration) was proposed, with accompanying baseflow contribution and stream stability targets. There were also construction phase targets including sediment removal via ‘sediment retention systems’. It was recommended that these targets be applied to all land uses. Other pollutants were considered however targets were not recommended for these for the following reasons:

- *Heavy metals (lead, copper and zinc)*: no targets because estimated reductions in metals are correlated with reductions in total nitrogen loads
- *E.Coli*: there was “no defendable method for estimating E.Coli concentrations in Victorian baseflow” and “no defendable method for estimating E.Coli reduction in wetlands”.
- *Litter*: A standard was not proposed as it was argued that litter would be removed while meeting the new standards for other (finer) pollutants.

The analysis then identified treatment trains and costs to meet proposed targets. Cost curves illustrated points of diminishing return that balanced pollution reduction targets against cost. It was estimated that meeting the targets in a greenfield residential development would cost approximately $4,000/lot.

An addendum to the Urban Stormwater BPEM Standards Paper was released in September of 2013 that summarised the outcomes of a ‘Technical Reference Committee’ workshop. This ‘Phase C’ work examined:

- the maximum practical total runoff volume reduction that can be achieved for typical scenarios
- to identify the most suitable baseflow contribution standard
- to resolve whether to include numerical standards for metal and E.coli, and
- to resolve the most suitable stream stability standard.

Key outcomes from this addendum included:

- The link between metals and other pollutants was reaffirmed.
- A ‘two tier’ flow regime standard was proposed to better protect intact, high value waterways. This in turn requires classification of waterway condition, with some parameters suggested.
- A baseflow contribution of 10% of mean annual rainfall was recommended.
- Two flow regime reductions were also recommended with 25% reduction found to be achievable in urbanised areas. A 60% reduction was assessed as being the highest removal percentage feasible in typical development scenarios in Melbourne.
- Stream erosion index (SEI) was found to be a suitable metric for stream stability.

The cost of meeting these requirements was also assessed concluding that ‘the cost of meeting the new standards is considerably higher than the cost of meeting the existing ones’.

Management of the ecological impacts of urban land and activities on waterways (Urrutiaguer et al., 2016)

Urrutiaguer et al., (2016) provided a summary of current and emerging science on the impacts of urbanisation on waterways and on the mitigation of these impacts. The outcomes of that review are briefly summarised below.

Urban pressures: Urbanisation imposes a range of pressures on waterways through stormwater, wastewater, extractions amongst other things. Under natural conditions, approximately 80-95% of the rain that falls in the Melbourne region is evapotranspired back to the atmosphere, never reaching a waterway. Urban stormwater that is drained to waterways is identified as the dominant urban pressure on waterways and the key limiting factor to good ecological condition (Fletcher, et al., 2011). Degradation of waterways can occur at very low levels of urbanisation with studies suggesting it takes a very small percentage (about 2%) of directly connected imperviousness (DCI) to cause severe degradation of stream condition (Walsh, et al., 2005; Walsh & Kunapo, 2009; Walsh & Webb, 2016).

Understanding waterway systems: Assessing waterway condition and establishing what 'healthy' and 'degraded' means is central to the understanding of waterway impacts. Macroinvertebrate assemblage composition indices such as SIGNAL (for the Melbourne region) are noted as providing good integrative measure of waterway condition. DCI is the strongest predictive model of SIGNAL (Burns et al., 2015).

Mitigating the impacts of urbanisation: Stormwater was seen to be the limiting factor to river health in urban areas noting that 'waterways cannot be in good ecological condition where significant urban stormwater inputs are permitted to occur (Fletcher, et al., 2011'). Protecting waterways from degradation (due to urbanisation) will require removing 'almost all of the additional stormwater runoff created through urbanisation'. It is assumed this means retaining pre-European values.

It was also noted that urbanisation introduces pressures other than stormwater including piping of ephemeral and small streams, removal of riparian vegetation; sediment from building activities; and treated or diluted wastewater discharges.

Stormwater Knowledge Synthesis Report (EPA, 2014)

EPA produced a document to 'collate and analyse the current available knowledge on urban stormwater in Victoria'. The document refers to stakeholder perceptions and scientific literature to summarise the key impacts on waterway health. While the key outcomes are referenced in the literature review below, the paper highlights some knowledge gaps including:

1. **Land Use Type and Stormwater Pollution**: There is an inadequate understanding of the relative contribution of different land use types on the pollution of urban stormwater
2. **Better Mapping of Water Quality Data and Industry / Traffic**: A gap was identified in the use of GIS analysis to understand the relationship between water quality (including heavy metals) and levels of traffic and presence of industry.
3. **Refinement of our Understanding of Impacted Areas and Key Contaminants**: this gap seems to refer specifically to sediment, and the use of sediment monitoring sites to draw a link between contaminants and impacted sites (i.e. waterways).
4. **Understanding Risk in Rural Victoria**: This gap is broadly stated as the need to better understand the risk to waterways of stormwater in rural Victoria.
5. **Understanding the sources and risks of high levels of bacterial contamination at the Bay beaches and lower Yarra River**: there is limited information on the source of bacteria that enters Melbourne's beaches and bays after rain, noting that 'human faecal indicators in the lower Yarra implicates leakage or discharges from the sewerage system'.
6. **Use of SEPP and other Policy instruments to control stormwater impacts**: This gap highlights the need to adequately or better address contaminants of concern (including heavy metals, hydrocarbons and pathogens), changes in hydrology (or flow) and the impact of construction sites.
7. **Relative amounts of contaminants arising from various sources**: While we broadly understand the source of contaminants, there are gaps in understanding around the specific pollutant contribution of certain activities and land uses, as well as their behavior and fate.
8. **Effectiveness of current techniques or WSUD and ways of dealing with urban stormwater**: there is a gap in our understanding of the effectiveness of WSUD and the ability of WSUD practices to 'preserve or restore the ecological health of an urban waterway'.

Improving Stormwater Management Advisory Committee (DEWLP, 2018)

In 2018 the Victorian Government convened the Improving Stormwater Management Advisory Committee with the aim of "(providing) advice to the Minister for Planning and the Minister for Water on how to improve stormwater management and strengthen the links between planning and urban water management."

The Committee is due to report to the Minister for Planning in October 2018 and was asked to consider land use types that are not currently subject to stormwater management requirements, whether they should be and how this could be achieved. The group was also asked to provide advice about strengthening links between stormwater management and the planning and development system.

The key issues that were highlighted include opportunities to:

- extend the coverage of stormwater planning requirements (to land use types not currently covered, including commercial and industrial)
- provide broader benefits (i.e. improved amenity)
- deliver a 'place based' approach (i.e. to respond to local conditions and receiving environments)
- link water management and urban planning (particularly in examples of urban consolidation)
- improve compliance and implementation (particularly with regard to ensuring that Councils can adequately maintain those assets)
- support stormwater management in the public realm.

Further it is noted that the current BPEM standards were largely designed to protect Port Phillip Bay and are unlikely to protect the ecological condition of more natural waterways (or Western Port Bay and Gippsland Lakes) into the future.

Stormwater as an issue

The underlying premise of stormwater management is that condition of our urban waterways and bays does not meet community expectations, and stormwater is the primary cause of concern. The reality is that these concerns are not new. The stormwater pollution framework currently in place was designed in response to community demands in the 1970s and 1980s to improve the condition of Port Phillip Bay and waterways such as the Yarra River that flow to it.

Whilst significant improvements have been made, and Victoria's waterways rate highly compared to those in comparable global cities, the community demands further improvements. This was highlighted by the media coverage of beach closures following heavy rainfall over the 2016/17 summer (e.g. https://twitter.com/EPA_Victoria/status/822195142471852032).) Much of this impact was attributed to diffuse pollution throughout the Port Phillip Bay catchment.

Historical view - where have we come from?

Historically, Melbourne's beaches drained unsewered urban catchments. Beach closures and warnings were common. Mounting social activism and desire for change drove improvements in policy, practice and community education. Before the 1990s there were no environmental performance standards for stormwater. The turning point was the Port Phillip Bay Environmental Study in 1996, funded by Melbourne Water and delivered by the CSIRO, which suggested a 1000 tonne reduction in the annual nitrogen load discharged to the Bay. This landmark study quantified chemical and biological processes within the Bay, enabling practitioners to predict the impact of catchment changes on ecological function.

The release of the *SEPP (Waters of Victoria) Schedule F6 Waters of Port Phillip Bay* in 1997 required the development of a Port Phillip Bay Environmental Management Plan to provide a framework for the protection and enhancement of beneficial uses of the Bay. This included a requirement to develop a nutrient reduction plan to achieve the reduction of nitrogen loads identified in the Port Phillip Bay Environmental Study.

The Port Phillip Bay investigation provided a new and compelling reason to do something about stormwater pollution. Further detail about stormwater quality was provided by Duncan in 1999 with a statistical overview of urban stormwater quality drawing from approximately 500 sources. Importantly, Duncan's work provided an understanding of the 'broad scale behaviour of urban runoff quality, and its interactions with land use and other catchment characteristics'. In response, Melbourne Water, the EPA and Local Government collaborated to determine how diffuse source pollution could be better managed. What emerged was an agenda to clarify the roles of the EPA, Melbourne Water and Local Government along with environmental performance standards and best practice guidelines for urban stormwater. Councils were then empowered to determine how they would apply the standards through local stormwater management plans. The potential existed to formalise these management plans to demonstrate compliance with the SEPP (or similar).

This knowledge led to the BPEM targets in 1999, and MUSIC software developed in 2001, providing an invaluable decision support tool for stormwater practitioners.

Eventually these activities were adopted as a government policy initiative. The Stormwater Action Plan was funded to $22.5M, all councils developed a Stormwater Management Plan and since the Millennium drought these plans have evolved into IWM plans that broaden the scope of stormwater management.

Requirements for Integrated Water Management were subsequently included in the Victoria Planning Provisions referencing the environmental performance standards in the BPEM and were delivered along with extensive capacity building programs for Local Government and the ;land development industry. These planning controls have changed developer behaviour, mainstreaming the adoption of integrated water management in Victoria.

Water industry practice has also changed. Melbourne Water includes the stormwater management standards in its Development Services Schemes and uses its separate head of power to mandate these standards in green field subdivisions. As a result, virtually all greenfield development uses these standards and Melbourne Water now has ~500 stormwater wetlands and at any one time will have ~20 under construction.

In parallel, the scientific body of knowledge has continued to grow. In 2004 Fletcher et al synthesised data across five key themes to provide the industry with a better understanding of stormwater characteristics (including quality and flow), impacts, treatment options and their effectiveness and costs. The work also identified gaps in data and recommendations for further work. In recent years, the role of pathogens and toxicants in impacting waterway values such as recreation has become more important, as we try to deliver liveable urban spaces. Publications such as the CRC for Water Sensitive Cities' stormwater blueprints (Wong et al, 2013) have synthesised contemporary research to reframe urban water from a harm into an opportunity for cities to create sustainable water sources to address scarcity issues, and as an urban design response to emerging issues such as the urban heat island effect, for instance, through wide spread use of green infrastructure.

Science updates since 2013/14

Values

SEPP (Waters of Victoria) defines the uses and values of Victoria's waters, collectively referring to them as 'beneficial uses'. The SEPP also defines the level of environmental quality required to protect these beneficial uses by setting environmental quality indicators and objectives. These objectives can be used by waterway managers to inform their management plans and monitoring programs to help protect these beneficial uses.

Rutherfurd (2000) suggests that the simplest measure of waterway value is in comparison to the condition of waterways prior to European contact. Rutherfurd's consideration of value also incorporates values beyond ecology to include intrinsic beauty, recreation (i.e. swimming and fishing) and geodiversity (or physical characteristics). Hobbs (2006) took an alternative view to consider the value of modified urbanised ecosystems. By recognising what he termed 'novel ecosystems' that had evolved through 'human agency', he recognised the intrinsic benefits that those environments provided.

In addition to the ecological values identified by Rutherfurd and Hobbs, the recognition of the social values associated with water has evolved. The ANZECC Guidelines (2000) recognised indigenous, cultural and spiritual values and the 2003 version of SEPP (Waters of Victoria) introduced a beneficial use for both Indigenous and non-Indigenous cultural and spiritual values.

Healthy Land and Water in South East Queensland (SEQ) were early adopters of a regional approach to establishing values, reporting on progress through catchment Report Cards that have been released since 2000. The Report Cards deliver 'Environmental condition' and 'Waterway benefits' ratings (Healthy Land and Water, 2017, 2018b, 2018a). In 2015 the Report Cards objectives were updated with the Environmental condition objectives expanded to include 'Restoring and maintaining key habitats (i.e. riparian vegetation)' and 'Reducing pollutant loads (sediment and nutrients) entering waterways' (Healthy Land and Water, 2017, 2018b, 2018a). It is notable that 'Waterway benefits' includes community values and satisfaction, access to water, economic benefits realised through recreation and the contribution of catchments to drinking water provision as values.

In Victoria the most well-recognised waterway values framework is the Healthy Waterways Strategy (Melbourne Water, 2013). The Healthy Waterways Strategy (HWS) strategy is designed to protect the environmental, economic and social values of Port Phillip Bay and the five catchments within Metropolitan Melbourne. In 2013 seven values: Birds, Fish, Frogs, Macroinvertebrates, Platypus, Vegetation and Amenity were defined to protect the values associated with Melbourne's waterways and bays.

The Draft Healthy Waterways Strategy (2018) provides an update on the 2013 strategy. It has added the social values "community connection" and "recreation" to the 2013 values framework to better reflect the "broad range of social values" derived from waterways and integrates the previously separate waterway management and stormwater management strategies for Port Phillip and Western Port bays to deliver a common suite of values and objectives. Jones et al (2016) supports this approach, suggesting that effective waterway management requires an appreciation of how people interact with these environments to tailor and build public support for management plans. This is critical as the approach to waterway (and bay) management will change depending upon the values being protected (Jeppe et al, 2017).

In the Draft Healthy Waterways Strategy (2018) economic values are detailed, highlighting the link between economic benefit and ecosystem services. The economic costs and benefits delivered by a waterway are listed as including:

- Urban water supply/storage
- Recreation and commercial tourism
- Natural water treatment and dilution/assimilation of waste
- Production from extractive uses
- Drainage and flood conveyance
- Increase in property values.

This is supported by economic research on community willingness to pay, for example research finds a positive willingness to pay to manage stormwater to improve waterway condition as well as providing a range of other benefits such as urban cooling (CRC for Water Sensitive Cities, 2014)

The Draft Healthy Waterways Strategy (2018) has also evolved to identify priority areas and targets for stormwater harvesting and infiltration, quantifying the link between flow reduction, integrated water management and the protection of values.

Discussion

In summary, since 2013, the definition of values associated with Melbourne's waterways has evolved to encompass social values reflecting the greater consideration and range of community interactions with waterways and the environment. Economic values are explicitly listed while the role of integrated water management approaches has been quantified and geographically prioritised. As such the values that stormwater management would seek to protect are well defined across Metropolitan Melbourne. It is less well define across regional Victoria.

One of the questions that this science review is seeking to investigate is how the protection of these values is translated to specific places and conditions. Therefore, what do 'place-based' objectives look like and how can they be applied?

Place-based objectives

What do 'place-based' objectives look like and how can they be applied?

There are a range of values that occur throughout the rivers, wetlands, estuaries and bays of Melbourne (Pettigrove, 2018). These values, social, economic and ecological, are not homogeneous across the landscape and therefore management approaches to protect those values and risks should not adopt a "one size fits all approach" (Jones, 2016). The Draft Healthy Waterways Strategy (Melbourne Water, 2018) can be considered 'place-based' as it is designed to protect values within Metropolitan Melbourne's five main waterway catchments: the Werribee, Maribyrnong, Yarra, Dandenong, and Western Port. The strategy sets targets for rivers, wetlands, and estuaries with 15 categories of waterways defined with objectives set for each against the strategy's key values: Birds, Fish, Frogs, Macroinvertebrates, Platypus, Vegetation, Amenity, Community connection and Recreation. In doing so the strategy aims to optimise ecological outcomes in response to local conditions and opportunities (Coleman et al 2018). The desired outcomes will flow through to the design of catchment specific stormwater treatment options to protect priority values within those catchments (Horne et al, 2017).

The Draft Healthy Waterways Strategy also identified priority areas to harvest stormwater (82.7 GL/year) and for infiltration (22.6 GL/year), linking place-based targets to integrated water management practices.

There are examples where place-based objectives have been successfully applied to protect identified values. Spromberg et al (2016) investigated the rising mortality rates of the iconic Coho salmon in the Pacific North West, finding that untreated highway runoff was "universally lethal". Pre-treatment of stormwater via biofiltration met the water quality objectives required and led to a change in planning policy. From India, Tare et al (2013) determined water quality and flow objectives to support the cultural objectives for the Kumbh spiritual festival on the Ganges River. In Metropolitan Melbourne, Duncan et al (2014) investigated place-based flow metrics to estimate the reductions in flow that would be required to protect ecological values within Kororoit Creek: an ephemeral, headwater stream representing an intact and unique ecosystem. The study concluded that protecting pre-urbanisation values would require reductions in total annual runoff volume in the order of 70-90%. These examples illustrate the potential to introduce objectives to protect defined values. There is additional complexity in setting objectives when there are potentially multiple objectives and values, as there are within the Draft Healthy Waterways Strategy (2018). The potential for compromising certain values is illustrated in the Tare (2013) example where meeting cultural objectives reduced the volume of water available for agriculture, compromising economic and social values. Even in the context of a wetland, Jeppe et al.(2017) reflected that if the objective is pollutant removal, then this may compromise the wetland's suitability as habitat to support other values (e.g. fish).

Another challenge is having sufficient data to reasonably set objectives. Pettigrove (2018) suggests that it is unclear which pollutants are impacting Melbourne's waterway values due to insufficient weight of evidence, emphasising that this understanding is necessary to make informed management decisions. Miller (2018) concluded that gaps in understanding of the hydro-ecology of native Australian species made place-based targets, that protected values across a range of fish species, almost impossible to define. Similarly, McCarthy (2017) concluded there is insufficient evidence to determine health-based targets to enhance or protect the social value of recreation (swimming) in Port Phillip Bay. This reflects the current state of data quality and coverage, limiting the application of fine-grained place-based objectives, but does not dismiss the principle as such.

Duncan et al (2014) also recognises that the nature of place-based objectives makes scaling metrics up or down challenging (i.e. metrics that are effective at the catchment scale are less effective at local scales and visa versa). Burns et al (2013), note the considerable uncertainty associated with scaling lot-scale interventions to impacts at the catchment scale. The question of scaleability concept posits that in meeting the requirements of the receiving waterway or lot, that the sum of inputs or objectives should also corresponds to what is required to protect values of the catchment as a whole (Stewardson and Guarino, 2018).

Discussion

Social, ecological and economic values are location specific and therefore strategies to protect those values or to address specific threatening processes are likely to require tailored responses. There are local and international examples where robust scientific approaches have led to the development of objectives that have successfully protected individual values, however there is greater complexity associated with the protection of multiple values.

The Draft Healthy Waterways Strategy (2018) sets place-based objectives for waterway values across the broader Melbourne Metropolitan area. Given this geographical focus, it would be up to local waterway managers (including Catchment Management Authorities) and local governments across Victoria to define the values they wish to protect. In doing they may be able to draw on and apply the outcomes of the Draft Healthy Waterways Strategy (2018) and the science that underpins it.

This is supported by Action 5.5 of the The Department of Environment, Land, Water and Planning's Water for Victoria document (2016) that includes Action 5.5. to "Improve stormwater management for greener environments" by "leading the development of local place-based targets for stormwater management".

The development of strategies to protect that range of values will respond to the value or values that the asset (or waterway) manager prioritises, for what purpose and at what cost. Lack of data and complexity of process is also noted as a potential barrier to objective setting in some cases.

Flow

What flow and geomorphology metrics (and targets) are important for receiving environment health?

The ecological health of waterways is generally known to be impacted by the hydrologic and water quality changes which occur due to urbanisation (McIntosh et al, 2013) which creates major changes to stream morphology and hydrology with the latter often cited as a primary stressor of urban stream ecosystems (Anim et al, 2017). In 2005 Walsh et al coined the term "Urban stream syndrome" to describe the observed ecological degradation of streams that drain urban catchments. The impacts of urban stream syndrome are wide ranging, with Walsh and Webb (2016) identifying urban stormwater as being likely to be a strong driver of macroinvertebrate species loss in streams.

The existing flow regulation within the BPEM states a requirement to 'maintain flows at pre-urbanisation levels' with a performance objective to maintain discharges for the 1.5-year ARI at pre-development levels.

While urbanisation is clearly associated with changes in hydrology, the changes are complex. In an extensive study in South East Queensland, McIntosh et al (2013) notes that while urbanisation is clearly associated with changes in hydrology, the impacts are complex and depend upon catchment characteristics (including size, slope, time of concentration and spatial hydrologic networks). Generally (but not always) the number of runoff events increase with urbanisation, the proportion of time under high flows tends to increase and time under low flows tends to decrease. McIntosh also proposed that hydrology on its own is not definitive with factors like temperature and construction phase water quality also important.

A number of studies have investigated flow metrics. Kennard et al, (2010) identified 120 potential flow metrics that describe ecologically relevant characteristics of the natural hydrologic regime with studies since then attempting to reduce the range to a more manageable number. Vietz et al. (2018) focussed on nine streamflow metrics (listed below) in applying the Urban Streamflow Impact Assessment (USIA) to understand the impacts on waterway values, and the setting of objectives to either retain or return those values:

1. Annual flow volume
2. Mean duration of zero flow periods
3. Total duration of zero flow periods
4. Baseflow index (ratio of baseflow to total flow volume)
5. Frequency of freshes (flows > 3 times median flow)
6. Total duration of freshes (flows > 3 times median flow)
7. Total duration of flows above channel erosion threshold
8. Frequency of floodplain engagement flows
9. Total duration of floodplain engagement flows

Data, tools and an expert panel were used to identify thresholds for each metric in response to the relevant values. Vietz presents the linkages between creek values and flow metrics. Their paper suggested that the metrics of 'mean annual flow volume' and 'time above the bed mobility threshold', were both associated with a high risk of losing values. The results suggest that for the Lowes Creek, Sydney case study, a 50% reduction in annual flow would be required to protect values, implying significant harvesting and reuse of stormwater. Vietz also identifies the reliance on expert opinion in negotiating metric thresholds as a shortcoming. This position supported by Stewardson et al (2017), suggesting that modelling of ecological responses has lagged behind that of hydrologic and hydraulic responses in environmental flows assessments, with expert opinion often used to predict likely ecological responses to specific changes in discharge and/or hydraulic habitat.

Despite recent work such as that set out in Vietz, the metrics adopted to analyse impact of stormwater on waterways has focussed on limited aspects of the flow regime, typically peak flows. This approach has the potential for perverse outcomes, such as large end-of catchment attempts at peak flow attenuation that don't mitigate the effects of urbanisation on stream geomorphology (Fletcher et al, 2014).

In response, Walsh et al (2016) proposed '5 principles for protecting stream ecology'. This approach includes the principle that the post development balance of evapotranspiration, stream flow, and infiltration should mimic the predevelopment balance an approach consistent with the natural flow regime. Along with Vietz et al (2018) and the work of Duncan et al (2014) discussed above, there is a consistent theme that reduction in total annual runoff volume is an important flow indicator.

There are obviously challenges to meeting high percentage reductions in mean annual flow particularly if this relies on stormwater harvesting, reuse and infiltration as there are significant space requirement associated with these approaches. Fletcher et al (2014), notes that stormwater harvesting is likely to be a critical element of an ecohydrological approach.

There are opportunities to restore pre-development catchment scale water fluxes (infiltration, evapotranspiration and runoff) via interventions at the land-parcel scale (Burns et al., 2013; Fletcher et al, 2013) ideally through a combination of rainwater harvesting and raingardens.

In Charlotte, North Carolina, Bell (2016) found that total imperviousness of a catchment was an effective management metric at the event scale that had driven uptake of WSUD. However, implementation of WSUD at the levels observed had not affected hydrology significantly at the watershed scale. In Australia more recently, the metric of effective imperviousness (EI) and directly connected imperviousness (DCI) have been used as an indicator of stream health. EI describes the proportion of a catchment made up of impervious areas that are directly connected to receiving waters via a constructed drainage system. EI provides a better prediction than Total imperviousness (TI) of changes in flow regime, water quality (Hatt et al., 2004) and geomorphic condition (Vietz et al., 2014).

Walsh et al., (2012) suggest that catchments with as little as 5–10% total imperviousness and conventional stormwater drainage are associated with poor in-stream ecological condition, reduced contributions to baseflows and increases in the frequency and magnitude of storm flows, while in similarly impervious catchments where there is informal drainage to forested hillslopes and no direct piped discharge to the stream, there is little hydrologic change and streams retain good ecological condition.

The focus on the nature of imperviousness (i.e. EI or DCI) may be an important step towards demonstrating the links between urban catchments and their streams.

A discussion on flows also requires consideration of the restoration of baseflows (Fletcher., 2014). The impacts of urbanisation on streams are mediated by alteration of land cover and subsurface drainage and understanding interactions of these two effects is critical (Walsh and Webb., 2016). Bonneau et al (2018) highlights the impact of urbanisation on groundwater flow, observing a relatively constant groundwater baseflow in forested catchments compared to distinct seasonal variations in urbanised catchments as groundwater responded to rainfall events. In summary Bonneau suggests that groundwater storages drain faster in the urbanised catchment, removing that constant baseflow that supports 'shallow slow water habitat' within urban streams.

Water sensitive urban design is applied to urban catchments to return them to a more natural flow regime. There are few existing monitoring studies provide early indications of the potential of stormwater control measures (SCMs) to deliver more natural flow regimes (Li et al, 2017). There remains a need for properly monitored studies that will assess the hydrologic effects of SCMs at the catchment scale. When discussing flow objectives, the Draft Healthy Waterways Strategy (HWS) (Melbourne Water., 2018) targets stormwater harvesting and infiltration as mechanisms to contribute to achieving those objectives, however there is a trade off in locating and paying for those systems.

The Little Stringybark Creek project (Walsh et al., 2012) aims to quantify the magnitude of this problem by comparing streamflow volumes from a range of undeveloped catchments in the Melbourne region with the volumes that would run off impervious surfaces in those catchments. The study estimates that for 1 Ha of impervious surface, the volume of excess stormwater is:

- 2.6–3.0 ML/y in catchments with mean annual rainfall of 400 mm rising to
- 5.1–7.8 ML/y in catchments with 1200 mm/year of rainfall.

Discussion

Flow is a critical threat to urban waterways and evidence to support this continues to grow. There are numerous potential indicators that can reflect the impact of flow on waterway values. Research has indicated that total annual runoff volume is a reasonable indicator when seeking to protect ecological values. Protecting or restoring values in an urbanised catchment may require something in the order of 50-90% reduction in flows, with stormwater harvesting, reuse and infiltration a key contributor to reaching such a target. This significant reduction would require suitable catchment conditions, sufficient demand for the harvested water and investment. There is limited information on whether lesser percentage reductions are suitable where protecting pre-development values is not the objective. There are also opportunities to contribute to flow reductions on the lot scale, via rainwater harvesting and infiltration.

Research continues into what the best metrics are to reflect the management of stormwater flow, with a range of potential options increasing the complexity. Importantly while flow management has been applied at a location scale, application at a catchment scale is more challenging.

There is good scientific understanding of what is required to reduce flow; the retention of pervious areas, stormwater harvesting and infiltration, therefore management in the near term is likely to be driven by the cost effectiveness of these alternatives, while the scientific understanding of flow targets and objectives is refined. There is also a clear threshold of ~5% catchment imperviousness beyond which ecosystems are substantially damaged.

What remains unclear is the restoration pathway. Does removing excess flow in a highly impervious catchment (or modifying flow regimes) restore degraded ecosystems and is the benefit greater than the social and economic cost that this approach imposes? This suggests a two tier, place based approach, as advocated within the Healthy Waterways Strategy, to identify and retain intact, high value waterways using stringent flow-based targets while applying less stringent targets to highly urbanised and impervious catchments.

Stormwater quality

Are the current targets proposed in BPEM sufficient to protect waterway health and public health?

Current BPEM guidelines require a removal of TSS, TP, TN and litter from urban stormwater. Other planning guidelines and standards (e.g., Singapore, Queensland) also include TSS, TP and TN as key indicators to address in stormwater management strategies (Lim and Lu, 2016; Lucke et al., 2018). The removal of these constituents from stormwater is necessary for ecological protection and public health. Due to the association of microbial contaminants (Helen et al., 2016; Henry et al., 2015) and toxic contaminants to suspended matter in urban stormwater (Walaszek et al., 2018a), removal of the TSS enables removal of key toxic and microbial contaminants. In addition, fine sediments have been found to pose risks to aquatic biota in streams by smothering habitats and reducing light penetration (Aspray et al., 2017; Davies-Colley et al., 2014). Both phosphorus and nitrogen removal are necessary for guarding against eutrophication in receiving waters (Paerl et al., 2016, 2015; Yang and Lusk, 2018). In addition, litter (gross pollutants) in urban stormwater is often comprised of vegetated matter which can contribute nutrients to receiving waters (Alam et al., 2017). Indeed, street cleaning and the removal of gross pollutants from a catchment in North America was found to lead to reductions in total phosphorus by 84% and total nitrogen by 74% (Selbig, 2016).

As such, the current scientific literature appears to state that targeting reduction in suspended solids, gross pollutants and nutrients in receiving waters is important for protecting ecosystem health. The current BPEM removal targets from urban stormwater (of 80%, 45%, 45% and 70% for TSS, TP, TN and litter loads) were based on previous assessments around the reductions in nitrogen loads required to achieve outcomes in Port Phillip Bay (Port Phillip Bay Environmental Study (CSIRO, 1996)), but there is little evidence in the literature that these are sufficient for protecting stream and public health in urban waterways. Given that there is a significant amount of monitoring data from urban streams throughout Victoria, there is the opportunity to review this data to consider how these targets may be influencing the protection of urban waterways, but there is no literature that considers this. This would allow an analysis to determine if the BPEM objectives were sufficient in ensuring that the environmental quality objectives in the SEPP. For a sound assessment of the appropriateness of current BPEM objectives, a rigorous analysis of the existing data is needed. It is possible that the original load reduction targets were determined based on typical stormwater management technology load reduction performance at the time (Sage et al., 2015a), rather than a consideration of what is actually required to protect urban waterways.

Previous studies in other regions have found limited evidence of direct links between reduction in suspended solids and nutrient loads into waterways and improvements in stream health (as measured by biological community composition) (Lee and An, 2014). Furthermore, timing of the pollutant inputs and the impact of resuspended bed sediments in aquatic systems can significantly effect stream health (Davis and Koop, 2006; Visser et al., 2016). The focus on only reducing mean annual nutrient and sediment loads may therefore not account for the processes by which these contaminants impact urban waterways and suggests that the "blunt" lever of a percentage reduction in loads to facilitate actions that protect stream health needs to be reconsidered.

It is also important to note that current BPEM objectives target load reductions. There are examples of stormwater management objectives from other parts of the world (e.g., Singapore, Canada, New Zealand, France) where the urban stormwater quality objectives are composed of concentration targets (Lim and Lu, 2016; Sage et al., 2015a). Pollutant loads in streams can lead to ecological impairments, particularly in lentic systems (Sage et al., 2015a), in some lotic systems, pollutant concentrations can have stronger links to public health and ecological outcomes (Chambers et al., 2012; Zhao et al., 2018). Maret et al. (2010) identified stronger correlations between TN concentrations (compared to TN load) and eutrophication occurrence in agricultural streams in North America.

As such, it appears that there may be a need to consider including concentration objectives in stormwater management objectives, especially for lotic systems. According to Sage et al. (2015), whilst effluent concentration-based stormwater quality targets are rare but do exist in Auckland (New Zealand), Halifax and London (Canada) and Yonne (France). However, the authors of this study note that these strategies may be problematic as stormwater discharge is highly dependent on influent concentrations. As such, it may not be practical to design stormwater management strategies that can consistently meet a certain effluent concentration target. Furthermore, they note that if runoff volumes are not managed in the stormwater management tool or technology, the total loads entering receiving waters will may remain high regardless of whether concentration targets are met.

Should additional water quality parameters be included within BPEM?

In the scientific literature, a large number of studies have investigated water quality parameters not included in BPEM. These parameters include: heavy metals, pathogens, and trace organic contaminants (e.g., pharmaceuticals and personal care products (PPCPs), pesticides, hydrocarbons). Currently, BPEM assumes that the removal of TSS, TP, TN and gross pollutants will inherently lead to removal of additional compounds from stormwater (Sage et al., 2015a). In this section, the following questions will be addressed for each pollutant class:

- Do these pollutants pose a human health risk or environmental health risk?
- At what levels are these pollutants found in stormwater?
- What are the sources of these pollutants?
- Are there other water quality parameters that could act as surrogates for these pollutants?

A summary of the key findings relating to each of these groups of parameters is included below.

Heavy metals

Heavy metals are of concern due to their persistence in the environment and their potential toxicity to both aquatic organisms and humans (Egodawatta et al., 2013). Whilst data on heavy metal risks is available, these are generally in relation to the effect of individual metals on humans and/or the environment. It is important to take into account that risks can increase when humans and organisms are exposed to mixtures of metals through synergistic effects (Cobbina et al., 2015; Ma et al., 2016; Wu et al., 2016). As such, future studies assessing the impact of multiple metal mixtures on both humans and Victorian aquatic organisms are required for setting environmental and public health trigger values for heavy metals in water.

The most recent studies of heavy metal concentrations in Melbourne stormwater was conducted by the CRC for Water Sensitive Cities (Gernjak et al., 2016) and Allinson et al. (2017). In both studies, heavy metal concentrations in stormwater were analysed for urban stormwater collected in Melbourne, Victoria. The stormwater concentrations were collected between 2011 and 2012, and for most metals (Cu, Zn, Pb, Cr, Cd), maximum concentrations are higher than the Australian Drinking Water Guideline values (NHMRC, 2011) as well as the ANZECC/ARMCANZ trigger values for 95% ecosystem protection (ANZECC/ARMCANZ, 2000a).

The correlation between metals with each other or with sediments and nutrients is uncertain with variability in results suggesting the influence of individual site characteristics. Further investigation may be required to identify why correlations occur at some sites but not others. While conclusions regarding metals are limited by data, concentration-based objectives particularly for lotic systems with potential health concerns, should be considered.

Pathogens

Pathogens in stormwater are of concern to humans due to their potential to cause infectious and/or gastro-intestinal diseases (NRMMC–EPHC–NHMRC, 2009). They often come from human or animal waste and cross-contamination of stormwater with sewage (Jiang et al., 2015). Humans may come into contact with pathogens in stormwater when:

i. recreating in waterways where urban stormwater has been discharged, or
ii. harvesting stormwater for re-use.

Quantitative Microbial Risk Assessments (QMRA) are being used more frequently in recent studies to assess the risk that pathogens in stormwater poses to humans (de Man et al., 2014; Lim et al., 2015; Murphy et al., 2017; Sinclair et al., 2015; Soller et al., 2015). For example, Murphy et al., (2017) assessed the public health risks associated with Campylobacter spp. presence in stormwater.

The authors found that when stormwater was not treated, there was a risk of infection, which was above recommended health thresholds, when stormwater was harvested and reused for garden irrigation, toilet flushing or swimming. Whilst there are uncertainties associated with the QMRA method due to uncertainties in dose-response models (Lim et al., 2015; Murphy et al., 2017), this these methods could be used to help assess public health risks associated with pathogens in stormwater and are now commonly used in assessments of health impacts in drinking water supplies. The link between pathogens and other parameters (such as the current parameters in BPEM) is unclear, though as noted earlier, there is some evidence of correlations with suspended particulates and pathogens in some studies.

A review by Bichai and Ashbolt (2017) suggests that pathogen stormwater targets are uncommon, and to our knowledge do not exist. As highlighted in Murphy et al. (2017), and Schoen et al. (2017), the only pathogen guidelines for stormwater are in the context of stormwater harvesting and reuse.

As with metals, more work is needed to understand the specific risks concerning pathogens and the appropriate management approaches and targets to address those risks.

Trace organic contaminants (Polycyclic Aromatic Hydrocarbons (PAHs))

PAHs in urban stormwater are of concern due to the potential toxicity of these compounds to both aquatic organisms and humans (Gilbreath and McKee, 2015; McIntyre et al., 2016). The carcinogenic nature of these compounds has led to the inclusion of 16 PAHs (e.g., benzo anthracenes, benzopyrenes) on the list of priority pollutants monitored by the US EPA (Yan et al., 2004). McIntyre et al. (2015) found high levels of mortality of invertebrates and juvenile Coho Salmon when they were exposed to untreated highway runoff. Similarly Young et al. (2018) identified cardiovascular dysfunction and deformities in fish when exposed to urban runoff containing PAHs.

However, there is still a lack of understanding of the effect of PAHs in urban stormwater on Australian biota in receiving waters. Furthermore, a risk assessment of exposure of humans to stormwater contaminated with PAHs is still lacking.

Pharmaceuticals and Personal Care Products (PPCPs)

The effects of chronic exposure to low levels of PPCPs are not yet certain. Whilst predicted no effect concentrations have been developed for ecological effects (Fabbri and Franzellitti, 2016; López-Doval et al., 2017; You et al., 2015), these have been developed by conducting toxicity tests under controlled conditions. Questions remain about the toxicity of pharmaceuticals mixtures, and the effects on organisms in different environments (López-Doval et al., 2017).

The level of pharmaceuticals present in the environment are thought to be of little concern for human health (Cizmas et al., 2015). However, there are concerns about the potential increase in antibiotic resistant bacteria in the environment as a result of increased levels of antibiotics in the environment (Cizmas et al., 2015; Garner et al., 2017). More research is needed on the levels of these compounds in stormwater and the impact before they are incorporated in BPEM.

Pesticides/herbicides/insecticides/fungicides

Biocide concentrations in urban stormwater have not exceeded public health guidelines in the evidence we have reviewed. However, there are concerns about the effect of these biocides on aquatic organisms. Recent studies (Allinson et al., 2015; Carpenter et al., 2016; Jeppe et al., 2017) have shown that pesticides and herbicides found in urban stormwater can have toxic effects on aquatic biota. For example Carpenter et al. (2016) found that diversity of insects was lower in urban stream sites with high bifenthrin concentrations in sediments. Similarly, Allinson et al. (2015) found that all PSII herbicides (e.g., atrazine, simazine) pose a threat to primary producers in urban ponds and wetlands. Whilst there is a growing body of evidence about negative effects of biocides on aquatic ecosystems, more research is required to identify: (1) toxicity limits, (2) the effect of chronic, long-term exposure, (3) the effect of exposure to mixtures of biocides in the environment (Mokarizadeh et al., 2015).

The evidence of the link between biocides and other parameters is inconclusive although some studies suggest that stormwater infrastructure like raingardens can remove biocides. More research is needed on the levels of these compounds in stormwater and their impact before they are incorporated in BPEM.

Monitoring stormwater quality

Currently, stormwater quality is generally monitored using samples taken manually (grab samples) or samples taken using automated samplers. Whilst manual sampling can be cost effective, the advantage of automated samplers is that they can capture sudden or high flows that might not otherwise be sampled by humans due to timing or safety problems (McCarthy and Harmel, 2014). However automated samplers also have disadvantages including: the requirement for routine site visits to ensure the equipment is working, the costs associated with purchasing and installing an automated sampler, and uncertainties due to the location of the sampling intake, type of material used in the sampler and pumping capacity (McCarthy and Harmel, 2014).

There is a growing body of literature on high frequency passive sampling and environmental sensing of urban water quality. Passive samplers are able to detect time-weighted average levels of dissolved contaminants such as nutrients, metals and, trace organics (Almeida et al., 2016; Criquet et al., 2017; Joyce et al., 2015) in water. In these systems, contaminants are diffused onto the material in the passive sampler, until the material reaches equilibrium with the surrounding environment (Jeong et al., 2018). There are several of these devices on the market (e.g., Sorbicell, POCIS) (Novic et al., 2017). Whilst these devices can potentially capture the temporal variability in water quality in urban stormwater without needing a power supply, they require calibration prior to field deployment (Criquet et al., 2017). These samplers have been found to inadequately capture the particulate fraction of urban stormwater. Furthermore, it was found that concentrations in stormwater were overestimated because only flows above a threshold are measured by the passive sampler (Birch et al., 2011). For passive samplers, calibration in the field under different conditions to ensure that these passive samplers provide accurate concentrations is still needed (Almeida et al., 2016; Criquet et al., 2017; Hutchins et al., 2016).

In addition to passive samplers, environmental sensor networks are being developed for monitoring urban water systems. The sensors can be linked to wireless networks to provide real-time updates of water quality, which enable managers to respond quickly to sudden changes in water quality to minimise public health and ecological impacts of pollution events (Hutchins et al., 2016). Such systems have been implemented for the real-time monitoring of turbidity (Jones et al., 2017; Lambrou et al., 2014; Ng et al., 2015), nitrate (Jones et al., 2016; Miller et al., 2018; Pellerin et al., 2016), electrical conductivity (Krause et al., 2015), chlorophyll a (Hutchins et al., 2016), fluorescent Dissolved Organic Matter (Jones et al., 2017), dissolved oxygen (Jones et al., 2017) and pH (Jones et al., 2017).

In addition, studies have used real-time monitoring of climate and flow patterns to manage urban stormwater. For example, Xu et al. (2018) used real-time updates of rainfall to determine when to release water from rainwater tanks to reduce uncontrolled overflows of stormwater and this technology is now being used in Victoria, for instance in the Aquarevo development in south east Melbourne. Muschalla et al. (2014) used real-time monitoring and control of flow entering into stormwater retention basins to reduce overflow and bypasses. It is estimated that this resulted in a 60% greater removal rate of particulates from stormwater, compared with a base-case scenario with no real-time control (Muschalla et al., 2014).

Discussion

The literature since the previous review of BPEM suggests that removal of TSS, TP, TN and gross pollutants from urban stormwater is important, both to protect the health of receiving waters, and to protect public health. Whilst considering reductions in annual load of these pollutants are important, the literature suggests that as well as the annual load, the timing of loads, seasonality of loads and the concentrations of pollutants (especially in lotic systems) are also important for maintaining receiving water health and guarding against disease outbreaks. During this review we did not identify a study that has assessed the impact of the current BPEM targets on waterway and public health. A study by Zhao et al. (2018) paired a catchment approach to evaluate the impact of low impact development on pollution emissions from catchments and there have been studies that have predicted water quality in urban streams and in urban stormwater after the implementation of stormwater management tools (e.g., Hoghooghi et al. 2018). However, it appears that the modelled results have not yet been validated using measured data. A recent review by Eckhart et al. (2017) suggests that there is a lack of understanding of long-term performance, and long-term ecological impacts of stormwater treatment measures, in terms of water quality.

Whilst TSS, TP, TN and gross pollutants are important contaminants to remove from urban stormwater, there are other contaminants present in urban stormwater that can have significant public health and environmental health impacts including heavy metals, pathogens, PAHs, PPCPs, biocides, salts and other trace organic contaminants.

Whilst there is evidence that the removal of TSS, TP and TN also removes heavy metals in certain circumstances or conditions, there does not appear to not be a clear consensus in the recent literature on whether the removal of TSS, TP and TN from urban stormwater will lead to a concurrent removal in these additional toxicants.

This may be due to the fact that correlations between pollutants in urban stormwater and correlations between pollutant removal from urban stormwater are governed by site-specific or time-specific factors. These should be investigated further to gain a better understanding of under what contexts, the removal of TSS, TP and TN is likely to lead to removal of other stormwater contaminants.

It should also be noted that monitoring and modelling techniques are improving based on the evidence we have reviewed. Whilst there are still further technological improvements to be made on new monitoring techniques such as passive samplers and real-time environmental sensing, the implementation of these systems could lead to a shift in the way we monitor and understand stormwater quality. In addition, there is significant evidence that default pollutant concentrations used to assess current BPEM achievement do not reflect the last decade of monitoring data (including data funded by EPA and collected in Melbourne).

Stormwater management effectiveness

The current BPEM aims to protect waterway values primarily through a reduction in the loads of TSS, TP, TN and litter reaching Port Phillip Bay. Other receiving environments, like Western Port, have different ecologies (seagrass, mangrove and saltmarsh communities) and water quality risks (e.g. suspended sediment) and require different load reduction targets (EPA, 2001). The means to meet these load reduction targets is primarily achieved through the application of water sensitive urban design (WSUD), such as wetlands and biofiltration assets that are designed and modelled using the software tool MUSIC.

Pollution reduction

A review of the literature regarding the performance of WSUD assets has been divided into biofiltration and wetlands.

Biofiltration: Biofiltration systems use the treatment capabilities of plants, microorganisms, and soil to mitigate the impacts of polluted stormwater. Analysis of the performance of biofiltration systems suggest treatment performance is variable, with nitrogen removal efficiencies ranging from a net increase in nitrogen to an up to 70% removal (Payne et al., 2014).

Hatt et al., (2009) concluded that pollutant removal in biofilters is closely correlated with the volume reduction across the biofilter due to evapotranspiration and/or infiltration, acknowledging that the extent of flow reduction was variable across sites. Parker, N., (2010) also found that pollutant load reduction could still be achieved via volume reduction, despite cases where pollutant concentrations exiting bioretention assets were higher than those entering.

Moore et al., (2017) summarises 246 studies published in 2016 addressing the characterisation and management of urban stormwater runoff. In that summary Moore highlighted experiments on 10-year-old biofiltration cells in Australia. They found the cells exported pollutants in tests where no pollutants were added, TP loads decreased for all tests and despite being close to roadways only minimal amounts of hydrocarbons and heavy metals were found within the media of these cells (Nichols and Lucke., 2016).

In terms of performance, biofilters are sensitive to plants species selection (Dietz., 2016) and nitrogen removal capability improves when internal water storage zones are included as part of bioretention cells design (Payne et al., 2014). Glaister, B.J., 2013 found that vegetation, a saturated zone and a novel metal-oxide rich filter media are integral to nitrogen removal, while Dagenais, D., (2018) found that bioretention performance is influenced by plant selection and factors such as root characteristics and growth rate, and this affects nutrient removal performance.

Biofilters or raingardens, have shown promising, yet variable, results in reducing pathogens (Chandrasena, G et al., 2017a). In a subsequent study by the same authors (Chandrasena, G et al., 2017b), the significant knowledge gaps in the capacity of stormwater biofilters to remove pathogens was recognised, including how this removal is impacted by biofilter design elements and operational conditions.

In summary, biofiltration performance in terms of concentration reduction is variable, with load reductions often driven through volumes loss. There are characteristics that are common to effective biofilters including suitable vegetation and water storage zones, making these, among other factors, critical for biofiltration design and application.

Wetlands: As with biofiltration units, in comparatively well-studied wetland systems the measures of nutrient plant uptake are debated (Payne et al., 2014). The effectiveness of WSUD in meeting BPEM targets was examined by Koch et al., (2014) who undertook a comprehensive synthesis of data to assess the variability in nitrogen (N) removal performance in urban stormwater ponds, wetlands, and swales. While wetlands showed high variability in NO_3 removal, this finding was largely driven by a single observation. Koch summarised that in the 19 examples reviewed (including constructed wetlands and wet swales), a 61% total nitrogen removal efficiency was observed. This study also noted that there is very little empirical information on the long-term effectiveness of using stormwater treatment assets (WSUD) to control excess nitrogen. In South East Queensland, Parker, N., (2010) found that pollutant load reductions in wetlands were attributable to reduced outflow concentrations.

Similarly, Moore et al., (2017) summarised 19 studies published on wetland performance in 2016 focused at least partially on their ability to sequester nutrients and metals across various temporal scales. Five studies examined water quality performance of wetlands between 4 and 20 years in age (Adyel et al., 2016; Al-Rubaei et al., 2016; Corstanje et al., 2016; Kadlec, 2016; Xu et al.,2016). Each study assessed phosphorus retention, which was found to achieve concentration reductions of between 60% and 77%.

A review of heavy metal uptake by wetland plants indicated that this process is highly variable and not well understood (Vyzmal and Brezinova, 2016), noting however that the relative fraction of the total metal load sequestered in plant shoots (as opposed to above ground tissue) ranged as high as 70%.

Studies also point to the importance of sedimentation as a pollution removal mechanism within wetlands while nutrient storage in plant biomass represents a relatively small proportion (5% to 34%) of total sequestration (Moore et al, 2017). Nichols et al. (2016) also investigated the performance of floating wetlands that act to slow passing flow enabling a greater proportion of sediments to settle out. While there was a high degree of variation, floating wetlands show potential at reducing TSS and TP.

In summary, whilst data is not conclusive, studies point to the reduction in concentration of TN and TP as a result of treatment via wetlands with sedimentation seen as an important element of the pollutant removal mechanism. Plant biomass is responsible for a relatively small amount of nutrient removal, while root systems are potentially effective at sequestering heavy metals.

Hydrologic performance

Understanding the hydrologic performance of water sensitive urban design (WSUD) assets is a complex and emerging field of research.

Individual assets

Early research by Hatt et al., (2009) illustrated that WSUD decreased peak flow rates and achieved long-term reductions in runoff. Performance however was highly site specific and dependent upon design, catchment, and climatic characteristics. Parker, N. (2010) concluded that constructed wetland, bioretention basin and bioretention swales reduced peak flow as well as runoff volume and frequency of flow. Palla, A and Gnecco, I (2015) modelled the effect of WSUD at an urban sub-catchment scale concluding that an effective impervious area of 5% is required to required to realise noticeable hydrologic benefits, including peak flow reduction, volume reduction and hydrograph delay.

Moore et al., (2017) identified two studies that focused solely on water quantity results including volume and peak reduction (Tang et al., 2016; Winston, Dorsey, and Hunt, 2016). Winston et al., (2016) in Ohio found that exfiltration rates were generally greater than the design values because of installed internal water storage zones. For 1-year rainfall intensities at these sites, peak flow was reduced by between 24% to 96%, with best performance occurring when the peak rainfall occurred before the centroid of the rainfall volume (i.e. where the peak arrived before 50% of the overall volume of the storm event).

Yau et al., (2017) also assessed the effect of ABC Waters Program when applied to a new precinct level development in Singapore. Features include bioretention lawns, raingardens, vegetated swales with modelling (using a 1D SWMM model) illustrating that WSUD is effective in reducing peak flow and runoff coefficient during storm events up to the 10-year design storm.

Catchment scale application

While these studies speak to the performance of individual assets, there is less conclusive evidence of WSUD assets meeting catchment scale objectives. Loperfido, J.V (2014) examined four catchments in the Chesapeake Bay watershed concluding that in urbanised catchments proportion of forest cover (or pervious area), was a more important driver of catchment scale hydrology than distributed WSUD in solving 'urban stream syndrome'. Bell et al (2016) concurred, finding from a meta-analysis of data across 16 catchments in North Carolina that WSUD did not significantly affect event hydrology *at the catchment scale* as total imperviousness remained the dominant predictor of event hydrologics metrics.

Walsh et al (2012) however suggest that in urbanised catchments dispersed urban stormwater retention measures can potentially protect urban stream ecosystems by mimicking the hydrologic effects of informal drainage if sufficient volumes of water are harvested and kept out of the stream. Walsh et al. (2015) and Li et al (2017) present results from the Little Stringybark Creek project (21.3 Ha of impervious roof and road surfaces) in outer Melbourne, concluding that stormwater control measures (SCMs) can significantly reduce streamflow volume and runoff coefficient at this scale.

In South Australia flow management is one of the primary drivers for WSUD uptake by councils, with WSUD implemented to control flooding and reduce peak flows. Myers et al. (2013) finds that a complete retrofit of every allotment in a catchment with detention, or street scale rain garden, was effective at maintaining peak flow rates at pre-infill development levels. Loperfido et al (2014) also concluded that distributed WSUD caused higher baseflows, lower maximum discharge and stream response, than centralised WSUD.

The location of WSUD in the catchment was also found to matter with at-source measures treating a larger range of pollutants at lower flowrates, while end of catchment treatments treat larger flows (Loperfido, J.V 2014)), In terms of managing catchment hydrology to protect receiving waterways, a combination of distributed and end of catchment measures is therefore needed.

Therefore, while the performance of WSUD systems within smaller catchments is relatively well researched, the evidence of catchment scale improvements is less well-known, with the Little Stringybark Creek project providing valuable data.

Integrated water management (IWM)

The harvesting of stormwater from the urbanised catchment along with WSUD, is also critical to reinstating a more natural hydrologic regime. The consideration of IWM options through retrofitting or as part of new developments continues to evolve, as does how these elements integrate with BPEM requirements. Rainwater and stormwater harvesting are two commonly applied IWM options.

Rainwater tanks*:* Rainwater tanks are proposed primarily to harvest roof water and reduce potable water demand. Households using rainwater for indoor and outdoor demands use approximately 42 kL/year at an energy rate of 1.8 kWh/kL (Moglia et al, 2014). The impact of rainwater tanks on hydrology was investigated by Burns et al, (2012) who concluded that the use of rainwater tanks alone cannot completely restore the natural retention capacity of typical land-parcels. Petrucci et al. (2012) indicated that retention tanks in a small urban catchment could influence flow during regular rainfall events, but not from large rainfall events. The on-going contribution of rainwater tanks to changed hydrology is perhaps debatable as Gardiner, 2010 suggested that landowners do not maintain their tanks.

Stormwater harvesting: Stormwater harvesting removes flow volumes from the catchment, typically for the purposes of open space irrigation, providing an alternative water source and contributing to waterway health objectives. As noted above, Melbourne Water (2018) has specified a target of 82.7 GL/year of stormwater harvesting to (generally) protect waterway values in the upper reaches of catchments. Duncan, H. (2014) supports this, suggesting that stormwater needs to be harvested at a point upstream of the smallest tributaries within the catchment for all these receiving waters to be protected.

Tang et al. (2013) went further and investigated the potential for stormwater reuse, and specifically indirect potable reuse of stormwater, by benchmarking stormwater samples from urban, residential and industrial sites across various Australian capital cities against samples from the entire water cycle, from sewage to drinking water. The study concluded that the baseline toxicity equivalent concentrations of the most polluted samples were similar to secondary treated effluent from wastewater treatment plants. It confirmed that road runoff is the potential source of contaminants and that high estrogenicity could be related to sewage overflow. A thorough understanding of stormwater quality is therefore essential to develop appropriate treatment facilities for potential reuse, or alternatively stormwater management should assume pathogen contamination and treat stormwater accordingly.

Asset condition

Melbourne Water undertook a comprehensive review of WSUD asset condition to understand the extent to which they are delivering their intended functions, the type of problems that exist and their causes (Melbourne Water, 2017). The audit divided assets into bioretention and tree pits, wetlands and aesthetic impact with the following summarised results:

- **Bioretention and tree pits**: 25% of these assets were found to be performing as designed with 25% failing and 50% underperforming. The main causes of underperforming or failing assets including blocked inlets, clogged filter media, incorrect levels and poor plant density.
- **Wetlands**: 13 wetlands were audited for treatment function and aesthetic condition. 20% were found to be performing well with 40% underperforming and 40% failed. Plant density was a significant cause of underperforming assets, often caused by water depths that are deeper than current design recommendations.
- **Aesthetics**: It was also found that about 50% of all assets audited are contributing to aesthetical improvements.

This audit concluded that while there are many examples of failing assets, design and construction has improved over time reflecting an industry that is maturing with the benefit of guidelines and specifications. Bioretention systems and tree pits constructed in the last five years are found to be well designed with no major construction issues. All wetlands constructed in the last four years had good plant cover with planted zones that were likely to have been designed with suitable water depths.

Payne et al., (2014) highlighted critical issues with wetland function including a firm basis for the beneficial role of plants, the inclusion of limited deep-water zones in wetlands of sufficient size, the need for careful design of wetland hydraulics including consistent features across the width of the wetland, and the importance of a relatively shallow water regime, both during vegetation establishment and on an ongoing basis.

Climate change and WSUD

For short-duration precipitation events, a global shift toward more intense individual storms and fewer weak storms is likely as temperatures increase (IPCC., 2013). This adverse impact on extreme rainfall intensities could increase the risk of flood at many locations (Engineers Australia., 2014). Further winter rainfall is projected to decline across much of southern Australia with the exception of Tasmania and the decline of rainfall in Southern Australia during the cool season remains a confident projection (Hope et al., 2015).

Climate change is impacting upon catchment hydrology and therefore the existing values that stormwater management aims to protect. Saft et al (2015) identified a significant shift in the rainfall-runoff relationship in ~46% of catchments studied following periods of prolonged, but temporary drought. Saft et al (2016) also noted that in catchments where the rainfall-runoff relationship has changed, predictive models consistently overestimated runoff, providing overly optimistic assessments of future water availability, with implications for catchment modelling approaches.

Several studies have investigated the impact of future climate change on urban stormwater quality by modelling the effect of future climate change scenarios on urban rainfall, runoff and pollutant export. These studies have been conducted for the east coast (Alamdari et al., 2017; Hathaway et al., 2014; Zahra et al., 2015), south-east (Ouyang et al., 2018) and west coast of North America (Tariq et al., 2017). The majority of these modelling studies have found that climate change will result in an increase in pollutant export from urban areas due to increases in flow. In particular, Hathaway et al. (2014) found increased frequency in untreated overflow from stormwater treatment basins (bioretention basins) under future climate change scenarios. Parker, N., (2010) concurs that nitrogen export from urban catchments is increasing as large storms become more frequent as a result of climate change.

It is expected that stormwater management objectives will have to be adjusted to take into account the increased stress that receiving waters will be experiencing due to future climate changes. For example, it is expected that increased temperatures and increased CO_2 concentrations in the atmosphere may result in increased frequencies of eutrophication in receiving waters, even without increasing nutrient exports from the catchment (Visser et al., 2016). To our knowledge, modelling studies that assess the impact of climate change on urban runoff has not been conducted for South-East Australian cities. This should be acknowledged as knowledge gap, with stormwater quality objectives defined based on current understanding and updated according to our understanding of climate change impacts in future. However, in undertaking these modelling studies, down-scaling of global circulation models (GCMs) can lead to significant uncertainties in climate projections, and these uncertainties will need to be taken into account in these modelling studies (Najafi and Hessami Kermani, 2017; Wang et al., 2017).

Offsets schemes

Melbourne Water operates a nitrogen offset scheme that allows developers who are unable to implement on-site WSUD controls to purchase an offset elsewhere in the catchment (www.melbournewater.com.au). In considering this approach, Croker et al (2016) suggest that offsets, as currently designed, target pollutant loads at catchment scale but often do not account for alterations to flow regimes that can cause local impacts. This approach enables stormwater management actions to be delivered at least cost.

There is also scope to attract funding for WSUD (or urban waterway rehabilitation) from broader offset schemes. Enhancing Our Dandenong Creek was a waterway improvement project negotiated between the EPA, the waterway manager and sewerage service provider in response to the failure to comply with environmental protection requirements. While not part of a formal offset process, it is an example of an approach to direct sewer upgrade funding to other amenity and pollution control activities that would have greater overall impact (Watkins, 2017). This approach takes a risk-based approach to water way protection and allows targeting of stormwater where it is the most harmful threatening process.`

Despite the fact that real-time monitoring and control by environmental sensors provides great promise in monitoring water quality dynamics and managing urban stormwater quality, further research in this field is required. First, we currently do not have sensors available to measure all pollutants of interest in urban stormwater (TSS, heavy metals, phosphorus, trace organic contaminants), and as such we rely on monitoring surrogates parameters, which can induce uncertainty in our understanding of the pollutant dynamics (McDonald et al., 2018; Wong and Kerkez, 2016). Secondly, further work is required to improve the power consumption of these sensors to reduce the need for frequent servicing and maintenance (Wong and Kerkez, 2016). Finally, refinement of currently used sensors is required to ensure high sensitivity and accuracy, whilst ensuring that fouling does not occur (Harmel et al., 2018; Pellerin et al., 2016).

Uncertainties in urban stormwater quality: It is important to acknowledge that collection of data on urban stormwater quality can have significant uncertainties. These can be a result of uncertainties due to discharge measurement uncertainties (especially during low flows), sample collection frequency (e.g. whether or not the first flush was capture) and location (e.g., location of automated sampler intake), sample preservation and storage and laboratory analysis (Harmel et al., 2018, 2016; McCarthy et al., 2008) (McCarthy and Harmel, 2014). For some constituents (e.g., TP, orthophosphate and *E. coli*), random uncertainty of up to 100% in concentrations has been detected in urban stormwater (Harmel et al., 2018). Further quantification of measurement uncertainties for other constituents (metals, organic contaminants) is needed. These uncertainty measures should be taken into account when setting targets and objectives for stormwater management.

Modelling urban stormwater quality: There are both deterministic and stochastic modelling for urban stormwater quality. Typically, stormwater quality models are comprised of empirical equations (e.g. modelling concentration as a function of runoff volumes) or processed based equations (for the movement of contaminants over surfaces and through pipes) (Daly et al., 2014). Key urban water quality models currently in use appear to still be models such as MUSIC, SWMM and Mike Urban (Wijesiri et al., 2016a). There are some concerns however that default stormwater pollutant generation algorithms in these models may become outdated with the implementation of source-control strategies (Lucke et al., 2018). For example, a study published in 2018 found that runoff concentrations in Queensland were significantly lower than what was previously reported and incorporated in MUSIC (Lucke et al., 2018).

Recently, there has been an increasing number of studies calling into question the validity of build-up wash-off models, especially at the catchment scale (Bonhomme and Petrucci, 2017). The urban stormwater quality that is simulated in build-up wash-off models have been found to have high levels of uncertainty (Sage et al., 2017). For example, Sage et al. (2015b) found that measured data of suspended solids build up could not be replicated by build-up models. Indeed Wijesriri et al. (2016b) also identified greater uncertainty in predictions of build-up processes compared to wash-off processes.

With increasing amounts of data available due to the development and implementation of environmental sensors, there is an opportunity for existing stormwater quality models to be validated and revised.

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Authorised and published by the Victorian Government, 1 Treasury Place, Melbourne

EPA0093