Management of the ecological impacts of urban land and activities on waterways

Issues Paper: understanding the science

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Table of contents

Summary 1

Introduction 5

Scope **6**

Terminology **8**

Structure **8**

Navigation Map **9**

Section 1. Overview of pressures and impacts 10

1. Overview of the pressures introduced by urbanisation **10**

2. Overview of the impacts of urbanisation on waterways **12**

2.1. Hydrology 12

2.2. Hydraulic & geomorphology 15

2.3. Water quality 15

2.4. Biota 19

Section 2. Understanding waterway systems 20

1. Describing & characterising urbanisation impacts on waterways **20**

1.1. What is in our waterways? 20

1.2. Organising information on impacts 21

2. Assessing waterway (ecological) condition **23**

2.1. Defining waterway condition 23

2.2. Overview of waterway condition indicators 23

2.3. Differentiating condition, performance and service 28

3. Predicting waterway condition **29**

3.1. Conceptualising waterways – conceptual models 29

3.2. Mathematical modelling 31

3.3. Melbourne's predictive model of waterway condition 34

3.4. Other predictive models: using stream hydrology to predict waterway condition 38

Section 3. Mitigating the impacts of urbanisation 40

1. Degradation **40**

1.1. Limiting factors 40

1.2. Stormwater is the most limiting factor to ecological condition 41

1.3. Ecological condition and ecological potential 42

1.4. Management scales and connectivity 43

2. Protection **44**

2.1. Management of stormwater runoff for protection outcomes 45

3. Restoration **51**

3.1. Balancing short-term and long-term outcomes 51

3.2. Management of riparian areas 51

3.3. Catchment scale stormwater restoration experiments 53

3.4. Water quality issues 56

4. Informing waterway management strategies **58**

Appendices 60

Appendix 1: Examples of conceptual models **60**

Appendix 2: Melbourne University predictive modelling variables **63**

Appendix 3: Water quality graphs LSC **64**

Appendix 4: Melbourne predictive modelling maps **65**

References 67

Summary

Waterways are severely degraded by urbanisation. Further growth of our city represents a major risk to waterway health as there is strong evidence showing that continuation of current urbanisation practices, stormwater management practices in particular, will result in severe degradation across the region. Developing a good science-based understanding of the problem is an important and necessary step in the development of strategies to mitigate the impacts of urbanisation.

This report provides a summary of current and emerging science on the impacts of urbanisation on waterways and on the mitigation of these impacts. It aims to clearly articulate what we know of the issue, whilst recognising the complexity of waterway science.

The core findings and ideas developed in this report are summarised below.

Urban pressures on waterways result in ecological degradation

- Urbanisation imposes a range of pressures on waterways through direct modifications, water extraction (both surface water and groundwater), wastewater inputs, stormwater inputs, and the introduction of pest species. It triggers changes in the hydrology, hydraulic, geomorphological, water quality, and biota of waterways, which lead to significant degradation of ecological condition.
- Urban stormwater that is conventionally drained to waterways is the dominant urban pressure and the most limiting factor to good ecological condition. This means that the degradation caused by urban stormwater conventionally discharged to a stream overrides other causes of degradation. It is also well established that severe degradation occurs at very low levels of urbanisation due to stormwater.
- In natural conditions, about 80-95% of the rain that falls in the Melbourne region is evapotranspired back to the atmosphere and therefore does not enter receiving streams. Most of the remaining rainfall is infiltrated with less than 5% of rainfall reaching the stream as direct surface runoff.
- Where traditional stormwater management and drainage practices are used, urbanisation drastically changes the water quality and flow regime of streams. Most of the rainfall previously evapotranspirated becomes surface runoff which is directed to the stream through the drainage network. This means streams receive ‘pulses’ of polluted runoff nearly each time it rains. Urbanisation also generally results in lower stream baseflows due to reduced infiltration and recharge to groundwater throughout the catchment.

- It has been shown that it takes a very small amount of directly connected imperviousness (DCI, defined as the proportion of impervious surfaces directly connected to the stream through conventional drainage) to cause severe degradation of stream condition. Severe degradation is consistently observed where DCI exceeds about 2%, with decline starting at the lowest measureable levels of DCI.
- Building on current conceptual understanding of degradation, robust statistical models linking urban pressure and biota are available for the Melbourne region. These predictive models of waterway condition show that a significant decline will occur if the urban growth boundary is developed using conventional / current management approaches.

Understanding waterway systems: assessing ecological condition is central to the understanding of waterway impacts and therefore to mitigation strategies

- Being able to assess waterway condition and establish what healthy means and what degraded means is central to the understanding of waterway impacts. It builds on knowledge of what waterways are, how they function, what lives in them and how they are influenced by their landscape.
- While the concept of waterway condition is intuitively easy to grasp, it is more difficult to define in scientific and unambiguous terms. Just like our heath, there is no direct and definite ways to measure it. There is however a number of well-established indicator measures that can help us understand waterway condition, assess impacts, and investigate root causes.
- Macroinvertebrates assemblage composition indices, such as SIGNAL for the Melbourne region, provide a good integrative measure of waterway condition. Significant effort has been expanded to develop robust datasets and predictive models for the Melbourne region.
- Waterway condition / health issues are very similar to any health issues. We need methods for screening, and have general rules for maintaining health, but we also need detailed investigation of some issues to refine what needs to be done. Strategies can be set at a high level to some degree, but we need specific understanding of local waterway issues as well.
- Conceptual models are a useful tool to make sense of complex reality by extracting key concepts and parameters, and establishing causal relationships between them. Whilst numerous conceptual models showing the links between urban pressures and waterway impacts are readily available, they are most useful when adapted to respond to a specific question so further work is typically required when using existing models.

Mitigating the impacts of urbanisation: degradation, protection, and restoration scenarios

- The degradation trajectory in the scenario of urban growth with conventional / current stormwater management practices is quite clear: it will result in severe degradation of waterways across Melbourne.
- Protecting waterways from this degradation will require removing almost all of the additional stormwater runoff created through urbanisation.

- While it is necessary to remove excess stormwater to protect waterways, urbanisation may introduce a number of other pressures that also need to be addressed to achieve protection (e.g. piping of ephemeral and small streams, removal of riparian vegetation; sediment from building activities; and treated or diluted wastewater discharges). Achieving good waterway condition may also require addressing pressures pre-existing urbanisation, for example lack of riparian vegetation due to agricultural use.
- Restoration is both harder to implement in practice and more uncertain than avoiding degradation in the first place (protection). Removal of a disturbance does not necessarily mean the system can recover; and if it can, the response is unlikely to be linear or immediate.
- The initial results of the Little Stringybark Creek catchment restoration pilot that aims to restore stream's health by limiting stormwater inputs to waterways to levels close to natural are encouraging. These results show some stream response for water quality and hydrology following the implementation of stormwater control measures to harvest, infiltrate and evapotranspire runoff throughout the catchment.
- We have evidence that extensive reforestation of riparian areas can be effective in restoring stream health where condition is not limited by stormwater.
- Whilst addressing water quality alone (i.e. without addressing underlying drivers to degradation and limiting factors to ecological condition such as stormwater inputs) may not enable waterway restoration, actions targeting water quality specifically may still be justified. For example, water quality may have local and acute toxic impacts that are not tolerable, or there may be legislative requirements to meet specific pollutant concentrations targets for both ecological and public health purposes. Also, waterway condition may be improved, at least locally, through targeted management of pollution discharges.
- Scales and connectivity are important consideration when establishing management strategies. For example, some populations of platypus are at significant risk of severe decline due to inbreeding caused by lack of connectivity. Connectivity is also important for biota to access critical refuges or feeding patches, or to enable important re-colonisation processes.

Planning for waterways protection and restoration outcomes

- The notion of limiting factors is useful to defining why waterway condition is degraded. A hierarchy of limiting factors helps to plan actions to maximise the likelihood of success in restoring condition.
- The ecology of a waterway can be conceptualised as one of a number of services/functions provided by waterways. While this paper focuses on ecology, it is important to keep in mind that the management of these services needs to be integrated for optimal outcomes.
- Condition, performance and service are distinct concepts often used in asset management. While assessment of condition can be regarded as a purely technical question, assessment of performance and service is context dependent. It is for example influenced by legal requirements and mandate, and customers' expectations and willingness to pay. Developing a framework defining how condition, performance and service are assessed and used to drive action and is key to establishing a clear investment logic for management strategies.

- Planning for protection or restoration need to consider the multiple pressures influencing waterway condition, both existing and future pressures.
- Long term versus short term outcomes need to be considered in the development of a management strategy. Repeated investments focusing on the short term may not add up to meet long term goals.
- Making an informed decision means that best available knowledge of the issue, implications and consequences of available options are carefully considered. It is crucial to consider the implications of both doing X and not doing X. Not taking action or making informed decisions as an issue unfolds is a decision 'de facto' that selects one future pathway over others. Adaptive management approaches provide a mean to refine strategies and review decisions in light of evolving knowledge.

Introduction

By nature, waterways are deeply connected to our landscape. As a result, profound changes in the natural landscape such as urbanisation also lead to significant changes to waterway ecosystems.

This paper aims to provide a summary of current and emerging scientific knowledge on the impacts urban areas and activities have on waterways, and on the management approaches that can mitigate these impacts.

Melbourne Water manages a very large network of streams, some very close to natural state form and others highly modified. As streams are connected to all part of their catchment by the movement of water, changes in land use introduce significant pressures to waterways. The transformation of natural vegetated catchments into either cultivated land or urban area has significantly altered waterway ecological condition, with the latter change having the most drastic impacts.

It is now well established that severe degradation occurs at very low levels of urbanisation, with loss of most sensitive species observed where impervious areas conventionally drained exceed about 2% of the catchment area (and decline starting at even lower levels of imperviousness; Walsh & Webb, 2016).

With 4.3 million inhabitants, Melbourne is a large city, it is also quite spread spatially occupying over 10,000km^2 of land. Consequently a large proportion of our streams are currently significantly impacted by urban areas.

Melbourne is also the fastest growing city in Australia and recent projections indicate that 1.6 million additional dwellings could be required by 2051 (State of Victoria, 2014).

To support the projected population growth, it is estimated that the amount of hard surfaces across the region will increase by 43% by 2051 (Spatial Economics, 2014). Out of the additional 376km^2 of hard surfaces, residential growth in greenfield areas is projected to contribute 296km^2.

Many waterways are threatened by this expansion of urban areas. The graph below presents results from predictive modelling of the impacts of this urban growth on waterway condition to illustrate what is at stake. The modelling it is based on is covered in details later in the document (see page 34) and map-based representation of some of the results is provided in Appendix 4.

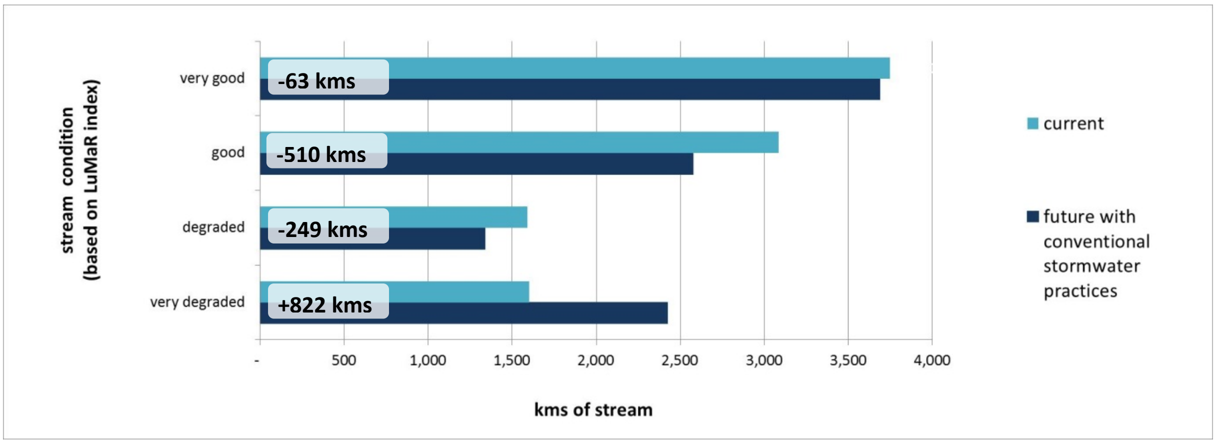

Figure 1. Evolution of stream condition estimated to 2030, shown as length of streams in each condition category (based on LUMAR macroinvertebrates assemblage index)

As a caretaker of river health, Melbourne Water is responsible for the development and implementation of waterway management strategies. At the core of such strategies' development is the evaluation of what the future could look like for waterways.

The projection of possible futures is shaped by a range of factors, including community values and political appetite for environmental protection, or the capacity to adopt and implement new technologies and management strategies. Importantly, it is also driven by our understanding of ecological responses to management strategies, which is the primary focus of this document.

Scope

Waterways have a number of functions and can be considered to provide a range of services as illustrated below. This paper focuses on the ecological component of waterways. However, management strategies need to consider all services provided and their interaction.

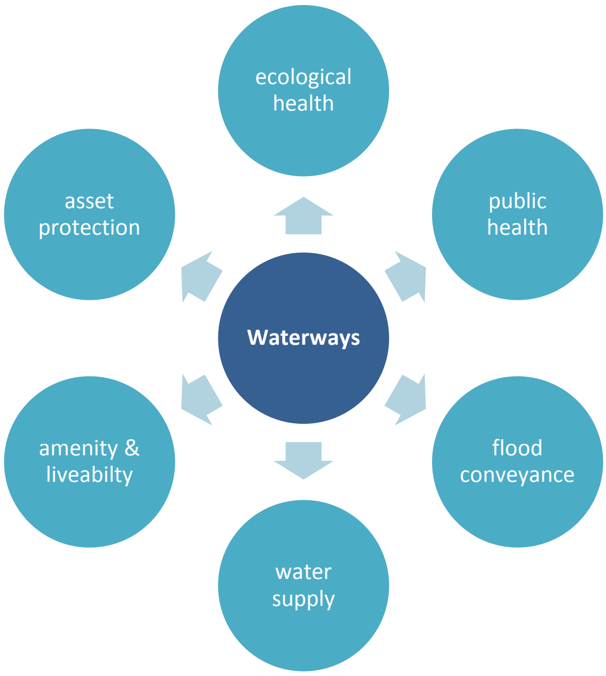

Figure 2. Some of the key waterways functions/services

This issues paper presents a review and synthesis of current knowledge (established and emerging) on waterway management focusing on the ecological impacts of urban areas. Its main purpose is to inform the scoping and development of Melbourne's strategy for waterway management, the Port Phillip and Westernport Regional Waterway Strategy. To this end, this paper addresses the following questions:

Q1. How do urban land use and activities impact waterway condition?

Q2. How can the impacts of urban land use and activities be mitigated?

These questions are very broad and the related literature is extensive. This paper does not aim to address them in an exhaustive manner, but instead focuses on synthetising key information and concepts that will support the development of future management approaches and strategies for Melbourne Water. Table 1 provide a snapshot of the scope of this paper.

Table 1. Scope snapshot

In – This paper does:	Out – This paper does not:
Focus on the impacts of **urban land use and activities** on waterways	
Review current understanding of key influences on waterway **ecological condition**	Review influences on **waterway amenity** (or other social values)
Review impacts in the context of waterway management objectives of protection and restoration	Review all existing ecological knowledge of waterways
Consider the influence of the impacts of cultivated land	Provide a detailed review of the impacts of cultivated land on waterways
Refer to the current Healthy Waterway Strategy (HWS) framework where possible (including the focal values)	Limit itself to the current HWS framework
Summarise current and emerging knowledge and outline knowledge gaps	Undertake new studies
Rely on the expertise of MW research partners	Undertake an exhaustive and systematic international literature review

Terminology

In this paper, we will refer to:

- **Urban areas** as any land that is used for residential, industrial, or commercial purposes. It covers our cities, but also townships and roads in rural areas;
- **Urbanisation** as the development of urban areas, in other terms a change of land use from cultivated or natural land use to urban land use;
- **Waterways** as perennially or ephemerally flowing waters, the terms of river, stream, and waterway are used interchangeably, this document also doesn't specifically focus on wetlands, lakes and estuaries, however the concepts covered also generally apply to these ecosystems;
- **Impacts** as changes outside of natural variability.

It is also worth noting that the term **ecological** is used in its broadest sense to include hydrological, hydraulic, geomorphic, physicochemical, and biological aspects of streams ecosystems, in line with the working definition adopted by Palmer et al. (2005).

Structure

The paper is structured in three main sections with supporting appendices. The contents of the sections can be summarised thus:

- The first section provides an overview of the pressures associated with urbanisation and their impacts on waterway condition.
- The second section discusses key concepts relating to the impacts of urbanisation, including how waterway condition can be assessed and predicted.
- The final section considers mitigation strategies, and reframes knowledge to inform the development of management strategies.

This document is especially relevant for planners and managers needing a scientific overview of the impacts of urbanisation on waterways to inform the design and review of waterway management strategies.

Navigation Map

Urbanisation significantly alters waterway ecological condition, changing the **hydrology, hydraulic, geomorphology, water quality** of waterways (p.12-18), and ultimately their **biota (p.19)**.

For more insights on the **ways in which biota is impacted** by urbanisation, also see tables on p.14 & p.24, p.42-44 (scales & connectivity), p.51-52 (riparian areas), p.38-39 (quantified relationships).

Robust **statistical models linking urban pressure and biota** are available **for the Melbourne region**. These predictive models show a **significant decline in waterway condition** in the future if conventional/current stormwater practices continue to be implemented in new urban developments.

For details on how these models have been developed and how they can be used to assess waterway condition under different management scenarios, see p.34-38 (and appendix 2, p.63).

For examples of results outputs, see p.6 and appendix 4 (p.65-66).

Decline in waterway condition due to stormwater inputs is observed at the lowest measurable levels of **DCI, directly connected imperviousness** (defined p.36). **Stormwater** is **the most limiting factor** to the ecological condition of waterways in that the degradation it causes overrides other causes of degradation. See p.41-42 (also p.34-35)

Other limiting factors can be categorised into: **direct modifications**, **water extraction**, **wastewater** inputs, and introduction of **pest species,** p.10-11 (also p.42-44, p.36-37, p.56-58).

SIGNAL (and more recently LUMAR) is a **good indicator of waterway ecological condition** in the Melbourne region. It is a **macroinvertebrate assemblage composition** index for which long-term and quality data is available. See p.27-28.

For a **broader overview** of **waterway condition assessment** and **indicators used,** see p.23-26.

The **Little Stringybark Creek** project is a **stormwater management** initiative **aiming to restore waterway condition.** Stormwater control measures have been implemented throughout the catchment in order to return a natural water quality and flow regime.

An **overview of this restoration research project** together with **initial water quality** and **hydrological results** is presented p.53-55.

Stormwater control measures such as raingardens and tanks can be **modelled in MUSIC** to assess their **treatment performance.**

Refer to p.47-48 for information on the **stormwater standards necessary to protect waterways** and the **different metrics** used to assess performance.

Understanding the hierarchy of **limiting factors** to the ecological condition of a waterway system (p.40) is important to plan effective actions for ecological outcomes. It also supports the assessment of **ecological potentia**l (p.42) and the **consideration of both short-term and long-term outcomes** in investment decisions (p.51).

The **water quality changes** caused by urbanisation are described as part of the **overview of impact section** p.15-18 (also see p.41).

Drivers and approaches for the **management of water quality** are discussed p.56-58 (also see p.47).

The selection of **adequate scales for management objectives and actions** is an important question for management strategies that is closely related to the issue of connectivity. See p.42-44 (also p.26).

Riparian areas have important functions in supporting ecological integrity of waterways (see), their role and management is discussed p.51-52 (also see p.36-37).

Section 1. Overview of pressures and impacts

This section provides an overview of the pressures introduced by urbanisation and their impacts on waterway condition, and is presented as an introduction to subsequent discussions on means to assess impacts and development of mitigation strategies.

1. Overview of the pressures introduced by urbanisation

Changes in both the stream catchment and the areas immediately adjacent to or within the stream impact its ecological condition in varied and complex ways. At a high-level, the main pressures introduced by urbanisation can be grouped into the following main sources (listed in no particular order):

a) Direct modification of channel, banks and riparian zone (including dams and modification of connection to floodplain)

The most visible changes generally associated with urbanisation are direct physical modifications of waterways as well as their riparian zone and their floodplain. Flood mitigation and land management have often been implemented in the form of varying levels of bank reinforcement or channelisation, vegetation removal and disconnection from floodplain. Construction of various structures across the stream profile (e.g. weirs, dams, culverts) is another type of modification to waterway form that significantly affects sediment transport as well as movement of biota and in turn population viability.

b) Water extraction

Water supply needs associated with urbanisation put great pressures on waterways. Water is extracted (as surface water or groundwater) to meet water demand. In addition to the resulting hydrological changes, direct modifications of the waterway (dams, weirs) are implemented to control water levels and allow diversion.

In the Melbourne region, most of the water supplied to the city is extracted far upstream of it, so the impacts of urbanisation also start far upstream. Impacts also range beyond the city as a large amount of its water supply is provided by rivers that do not flow into Melbourne.

c) Wastewater inputs

Most of the water supplied is collected as wastewater, and most of that transferred to either the Western Treatment Plant or the Eastern Treatment Plant where it is treated before being discharged to the Port Philip Bay and Bass Straight. While most of Melbourne treated sewage is discharged (subject to regulations) directly to the marine environment, waterways also receive discharges (also subject to regulations) from:

- Smaller Treatment Plants (18 across Melbourne Water's area)
- Sanitary Sewer Overflows (SSOs)

Importantly waterways also receive wastewater discharges through stormwater drains collecting sewage (dry-weather flow from illegal connections or leaky sewers).

All these discharges can have very damaging impacts on water quality and aquatic life. The impact may be quite localised for smaller treatment plants and even marginally beneficial from a flow perspective (Walsh & Webb, 2016). However, given the spatial extent of the drainage system linking all parts of the catchment to a receiving stream, the issue of wastewater pollution discharge from stormwater drains has widespread impacts on waterways. It is important to remember that stormwater drains do not only discharge stormwater, as illustrated in Figure 3 below.

d) Stormwater runoff inputs to waterway

The changes in rainfall-runoff behaviour associated with the development of urban areas where conventional drainage practices are adopted (representing most urban areas) completely shift catchment and stream hydrology. Typically, peak flows are greatly increased as the waterway receives runoff each time it rains though the drainage network, and stream baseflows are greatly diminished due to reduced infiltration and recharge to groundwater. The traditional drainage approach also introduces significant alteration of water quality as pollutants deposited on hard surfaces are transported with runoff to the receiving waters. These pollutants come from varied catchment sources, ranging from natural atmospheric deposition to ill-controlled industrial activities, as further detailed in the section on restoration (see page 56).

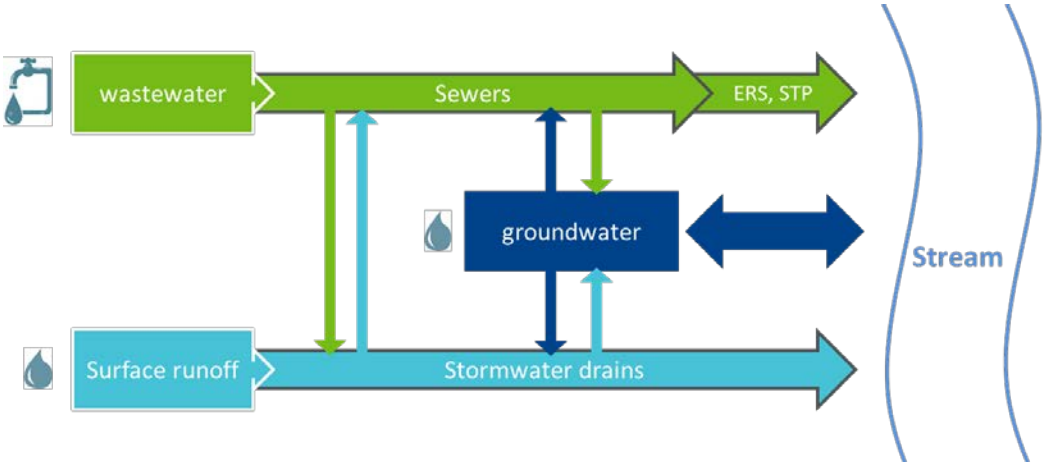

Figure 3. Cross-connected nature of sewers and stormwater drains. Stormwater drains not only discharge stormwater runoff that has collected pollutant deposited on hard surfaces, it also discharges wastewater from illegal sewer connections, leaky sewers or polluted groundwater.

e) Introduction of pest species

The release of exotic species can cause significant decrease in biodiversity through predation, competition for food or space for example. It can also result in significant degradation of habitat (e.g. rabbits grazing on riparian vegetation) which in turn affects biota.

While not fully understood, it is currently thought that systems already under stress are more vulnerable to invasion by pest species (Havel, et al., 2015). Modifications to land and water use reduce and modify fish habitat for the endemic species and create vacant niches for invasion by alien species (Rowe, et al., 2008). Local biota has evolved life histories that are competitive under natural conditions, so that the altered conditions resulting from urbanisation are more favourable to some of the introduced species (Bunn & Arthington, 2002), which may then outcompete native ones.

Introduction of pest species is thus a pressure introduced by human activities that is problematic when occurring in conjunction with alteration of natural conditions. The proliferation of pest species may be considered more as a symptom than a root cause of degradation.

2. Overview of the impacts of urbanisation on waterways

The structure adopted for this overview follows a simple conceptual framework based on a dominant cause-and-effect relationship between key functioning characteristics, as shown in the figure below adapted from Harman et al. (2012).

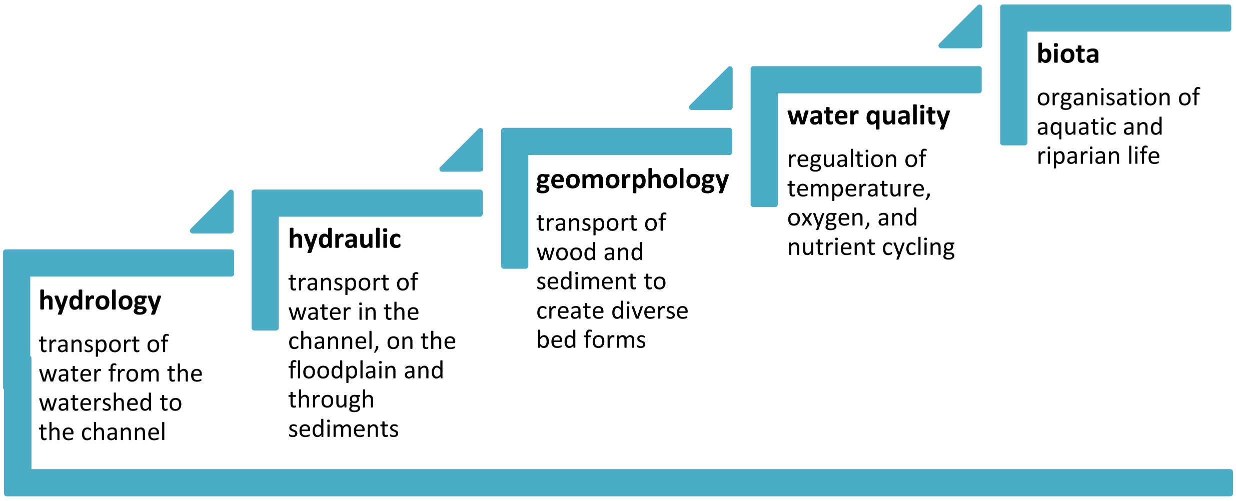

Figure 4. Stream key functioning characteristics, adapted from Harman et al. (2012).

While this structure highlights the dominant flow of cause-and-effect relationship, it should be noted that there are important feedback loops between these key functioning characteristics. For example, some fish and macroinvertebrates species have been shown to alter nutrient cycling and thus water quality (Beesley, et al., 2015 in review). In fact, the rich microbial communities in the hyporheic zone (an area of flow exchange between groundwater and surface water in the sediments below and alongside streams) are critical to nutrient processing and thus water quality. The biochemical nature of denitrification also shows that there is no hard boundaries between water quality and biota functions and similarly between the other functioning characteristics categories retained in this framework.

However, this broad-level pyramidal categorisation provides a starting point to think about how waterway functions that highlights flow on effects and points to the need to consider influences between supporting functions and biota.

2.1. Hydrology

Waterways are defined and shaped by their running water, and their hydrology is often described as the 'master variable' driving the diversity and vitality of river and floodplain ecosystems (Fletcher, et al., 2013; Poff, et al., 1997).

In a broad sense, hydrology is the science concerning the occurrence, circulation, and distribution, of water above and below ground both in time and space, or in other words the study of the water cycle. Stream hydrology focuses on how the rain falling on the watershed forms streams, and how the water behaves once it reaches a stream.

At a base level, hydrology is determined by catchment land use, catchment drainage characteristics (geology, topology, vegetation) and rainfall. As urbanisation significantly alters land use, it also alters the water cycle of a catchment and the resulting waterway hydrological regime.

In natural conditions, about 80-95% (for the Melbourne region) of rainfall is evapotranspired back to the atmosphere and therefore does not enter receiving streams (the exact amount depending on rainfall, vegetation cover, and catchment physiography;

Zhang, et al., 2001). Most of the remaining rainfall is infiltrated with less than 5% of rainfall reaching the stream as direct surface runoff. Infiltration of water is an important part of the water balance as it allows recharge of groundwater, which in turn provides baseflows to waterways.

Where traditional stormwater management and drainage practices are used, urbanisation drastically changes the water quality and flow regime of the stream as most of the rainfall previously evapotranspired is discharged to the river (see Figure 15 p.46). As impervious surfaces across all parts of the catchment are connected to the drainage system, streams receives 'pulses' of polluted runoff nearly each time it rains. The frequency of surface runoff discharge to the stream is increased 10-20 times (Fletcher, et al., 2007).

With a large increase in impervious cover, opportunity for infiltration and recharge of groundwater is also largely reduced. This has generally been shown to significantly reduce baseflow volumes and shift recharge patterns (Konrad & Booth, 2005).

Numerous metrics may be used to characterise a hydrograph and assess changes induced by non-natural pressures. Figure 5 shows key elements of a waterway hydrograph, noting that in the example provided we can observe a cease to flow period characteristic of an intermittent stream which typically would be a period of low flows for a perennial stream. Table 2 provides insight into their ecological relevance.

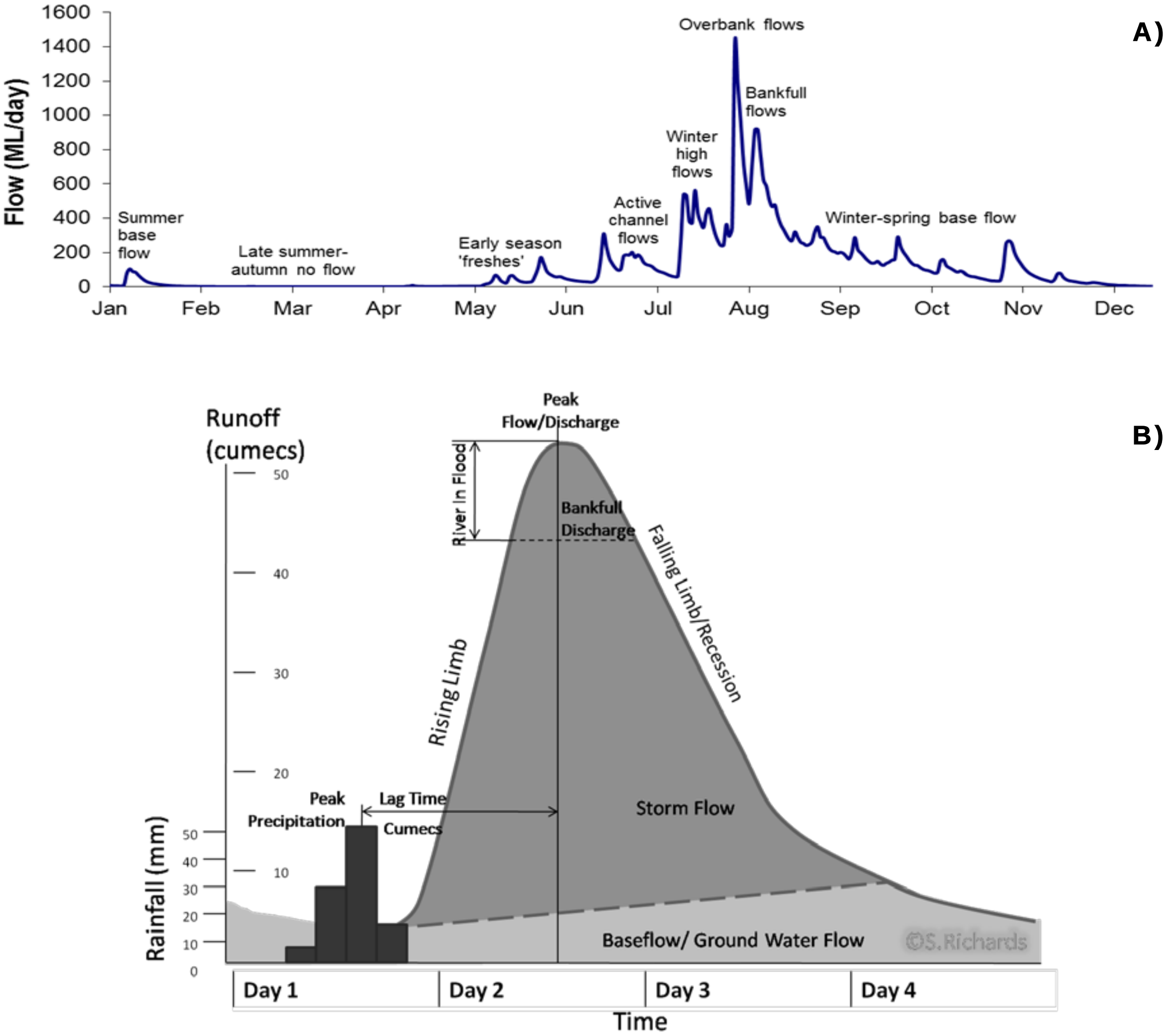

Figure 5. Typical hydrographs showing important flow components. A) annual hydrograph (reproduced from Green et al., 2010); B) storm hydrograph (reproduced from Richards, 2011).

Table 2. Ecological significance of hydrograph characteristics. Reproduced from Boulton et al. (2014).

Flow component	Ecological significance
Duration of zero flow	Duration of zero flow (cease-to-flow duration) affects water quality and persistence of aquatic biota in remaining pools, and influences establishment of terrestrial floodplain vegetation. Extended duration typically eradicates or reduces densities of aquatic species intolerant of drying. Viability of seeds and resting eggs of aquatic organisms declines over time. Changing the cease-to-flow duration alters the extent of isolation and drying of channel and floodplain wetlands and the composition of aquatic biota when flow resumes.
Interval since last flood peak	The interval since the last flood peak affects drying regimes of floodplain waterbodies and the establishment of most floodplain plants. Changes from natural patterns affect recruitment of biota with seasonal life-cycles (e.g. some native fishes).
Amplitude of the rising flood limb	The amplitude of the rising flood limb is related to pre-flood river level and size of flood. Big floods may facilitate breeding and recruitment of many river and floodplain species, and inundate large areas of floodplain, hydrologically reconnecting the mosaic of floodplain waterbodies. Changes to this amplitude affect the extent of nutrient release from floodplain sediments and the success of hatching of eggs or resting stages of aquatic animals and germination and growth of some floodplain plants.
Amplitude of the falling flood limb	The amplitude of the falling flood limb affects the degree of isolation of floodplain wetlands from the main channel. It influences fish recruitment (with cascading effects on invertebrates and waterbirds) and germination and growth of some floodplain plants. Changes to this amplitude typically alter the extent of inundation of littoral and floodplain habitat, and the immersion of sessile and sedentary biota.
Durations of rising and falling limbs	Durations of the rising and falling limbs of the flood pulse together influence inundation time of the floodplain (i.e. duration of period above the dashed line in Figure 9.5). Consequently, they affect the time for recolonization of floodplain waterbodies, growth of fishes, invertebrates and plants on the floodplain, changes in water quality, dissolved oxygen and temperature, and successional changes in the biota responding to flooding. Changing these durations alters the persistence and composition of floodplain assemblages.
Slopes of rising and falling limbs	Rates of change (slopes) of the rising and falling limbs of the flood pulse affect the responses by different groups of species to flooding. For example, steeply rising limbs may flush out lentic biota, whereas steeply falling limbs during drawdown may strand slow-moving animals, including juvenile fishes. Changes to these slopes affect survival and recruitment of many aquatic species, rates of erosion and deposition of sediments, and the speed of changes in water quality during flushing and drawdown in the main channel and floodplain waterbodies.
Magnitude of baseflows	Magnitude of baseflows influences water quality and defines the wetted habitat area available for biota. Urbanisation tends to reduce baseflows and therefore reduce the aquatic habitat available for invertebrates and fish (Poff et al. 2010).

2.2. Hydraulic & geomorphology

Hydraulics characterise how water is transported down the river channel, through sediments, and onto the floodplain. As such, it is driven by hydrology. It is also strongly influenced by channel form, and consequently by the geomorphological processes shaping the stream.

Geomorphology is commonly defined as the transport of debris (e.g., wood) and sediments, the dynamic processes of mobilisation of bed and bank sediments resulting in an equilibrium of erosion and deposition that shapes stream bed and banks. Erosion occurs when the stream capacity to mobilize sediment exceeds the rate of sediment supply, and deposition occurs when this balance is reversed.

Urbanisation is often accompanied by direct physical alteration of the waterway channel and its riparian area, typically to manage flooding or to gain developable land. Small ephemeral waterways may be buried as underground pipes, larger waterways may be disconnected from their floodplains and/or channelised.

Urbanisation also alters the direct sediment input to the stream from its catchment, and in particular reduces the supply coarse-grained sediment (Fletcher, et al., 2011).

The alteration in sediment input combined with the hydrological alterations disrupts the sediment transport process, and typically result in an increase of erosion.

Depending on the sediment composition of the stream, this may lead to channel incising or widening, together with a simplification of the channel form through loss of bars and benches for example (Vietz, et al., 2014; Vietz, et al., 2015).

Essentially, the increase of direct runoff to the stream caused by urbanisation increases the stream erosive power as flows capable of erosion occur more frequently and over longer periods. The reduction of catchment sediment input accelerates the erosion process as the sediment mobilised from bed and banks is not replenished.

This increase of erosion processes created by urbanisation often triggers management action aiming to stabilise the stream (e.g. rock beaching) in order to protect assets (e.g. roads, properties) but failing to address the increased erosion potential of the stream's flow, which only transfers the issue elsewhere.

2.3. Water quality

The two main sources of impacts on water quality are stormwater and wastewater inputs to waterways.

In addition to the hydrological disturbance created by conventional drainage, water quality is significantly impacted by runoff delivered through the drainage system. The water discharged contains a wide range of pollutants that are harmful to ecosystem health (e.g., some lead to depletion in oxygen which in turn can cause fish asphyxiation).

The changes in land use and drainage associated with urbanisation result in increased runoff generation, as well as increased mobilisation and transport processes of pollutants.

Whilst there has been significant progress in the treatment of wastewater before discharge to the environment over the last few decades, treatment plant discharges still impact receiving waters. A number of studies (e.g. Luo, et al., 2014; Michaela, et al., 2013) highlight that a range of pollutants are not removed by most treatment processes. This is the case, for example, for many antibiotics and other pharmaceutical products, and some pesticides.

Sewers may lack conveyance capacity during wet weather (as water infiltrates sewer pipes, see paragraph on urban karst on page 49), leading to discharge of sewage to receiving waters at Emergency Relief Structures (ERS).

Other reasons for lack of sewer capacity resulting in discharge to the environment include blockages, pumping station failures, simultaneous discharge from major industrial sites, and system growth where additional input from increased urbanisation exceeds system capacity.

The current legislation (State Environment Protection Policy) on sewerage management states that "losses of wastewater through sewer overflows, leakages and collapses need to be avoided to protect beneficial uses" and "sewerage infrastructure needs to contain flows associated with a 1-in-5-year rainfall event or a comparable design standard that avoids losses of wastewater" (State of Victoria, 2003).

Pollution may also occur as direct incidental discharge to receiving waters (e.g. incident involving truck carrying toxic substances, breach of old mining sites dams). It should be highlighted that the drainage network significantly increases the risk of waterway pollution. In the absence of drainage systems, the likelihood of a toxic spill reaching a stream is quite low, whereas once a catchment is conventionally drained, any spill on impervious surface will reach a stormwater drain and end up being discharged to the local receiving water.

The increased pollutant discharge associated with urbanisation affects not only water quality but also and importantly sediment quality. In fact many contaminants are present at much higher concentrations in sediments than in the water column and may be resuspended during high flow events (Wenger, et al., 2009) and increase toxicity.

The toxicity of a pollutant may not always be immediate. Some of the following can lead to lagged impacts (spatially and temporally):

- Chemical reactions
- Bioaccumulation
- Sediment movement and transport
- Cumulative effects of different pollutants

Table 3 provides a summary of key pollutants, their sources and their impact on biota. The word pollutant refers to any substance or physical agent introduced to our environment that may be harmful to living organisms (humans, plants and animals). Pollutants can be naturally occurring substances that are beneficial to life in natural circumstances (e.g. nitrogen is a much needed nutrient for plant growth) or man-made.

Table 3. Major types of pollutants

Pollutant	Source	Impact
Nitrogen & Phosphorus	Sewage treatment plant discharges; runoff from fertilised land and hard surfaces; industrial discharges; water softening compound in some detergents	The right balance of nitrogen and phosphorus is essential for maintaining natural biological communities and ecosystem functions in aquatic systems. They are limiting nutrients (nutrients which limit biological productivity), so additional supply increases aquatic plant growth. The resulting eutrophication, a process of nutrient enrichment that stimulates the growth of nuisance plants and cyanobacteria that can overtake other life forms (e.g. green algae blooms), can result in death of freshwater organisms (due to deoxygenation when the bloom dies).

Pollutant		Source	Impact
Inorganic nitrogen	Ammonia (NH_3) & ammonium (NH_4^+); Nitrates (NO_3^-) & nitrites (NO_2^-)	As above	Direct acute toxicity to freshwater organisms, for ammonia in particular. Toxicity has been most clearly recorded for fish with loss of equilibrium, hyper-excitability, increased respiratory activity and oxygen uptake, increased heart rate and at extreme levels convulsions, coma and death. Acidification of some ecological systems (with low acid-neutralizing capacity) causes a reduction in nutrient availability and increased solubility and toxicity of metals, and leads to loss of biodiversity due to biota toxicity.
Phosphate	Fertilisers	Agricultural and household gardens	Direct toxicity when in very high concentration
Hydrocarbons	Petroleum products	Road traffic deposition (rubber and fuel)	Creates black ooze (anaerobic sediments fuelled by carbon); induces cancers and mutations; is readily absorbed into fatty tissues; affects permeability of membranes and gills
Pesticides	Herbicides, fungicides, insecticides, rodenticides, fumigants	Weed spraying, building treatment, agriculture and residential gardens	Kills or impairs non-target species; bioaccumulates in predators; Acts as endocrine-disruptor: disrupts sex ratios, growth and reproduction in fishes and other organisms; interferes with endocrine function and disrupts food webs
Surfactants	e.g. surfactant detergents	Household and industrial uses; fuel additives	Surfactant detergents are implicated in decreasing the breeding ability of aquatic organisms. By lowering the surface tension of the water, surfactants make other organic chemicals such as pesticides and phenols are then much more easily absorbed by the fish.
Heavy metals	Mercury, cadmium, lead, chromium, zinc, arsenic	Involved in industrial processes (e.g. electroplating); present in consumer goods (rubber, paint pigment); used in pesticides	Toxic or poisonous at low concentrations; bioaccumulates (cannot be degraded or destroyed so accumulates in organisms and up food chains); strongly bounds to suspended solids; long-term issues. Examples: *Cadmium* - can be linked to increased blood pressure and effects on the myocardium in animals, may produce bone defects in both humans and animals. *Mercury* – toxic to both plants and animals, effects can be both lethal or sub-lethal (e.g. kidney damage, brain alteration, reduction

Pollutant		Source	Impact
			of sperm viability and embryogenesis, reduction in olfactory response, vision and respiration)
PCBs and other persistent organic pollutants	Heat transformer fluids, paint, pump fluid; insecticides	Industrial and DIY activities; agriculture	Disrupts hormonal processes; absorbed into fatty tissues; induces cancers and mutations; toxic to aquatic biota
Inorganic solvents	Acids, caustic agents, salts	Industrial effluents, household cleaners	Alters water chemistry and pH; toxic to biota
Micro-organisms	Virus, Bacteria, Protozoa, helminths and other parasites	Sewage, faeces from domestic animals and wildlife	Mostly a public health concern because of the potential transmission of diseases, but can also affect aquatic life

As shown in Table 3, pollutants are very varied in their chemical nature, their chemical and physical properties, their sources and their impacts. Below are some of the most commonly used characteristics pertinent to the understanding of impacts:

- **Naturally occurring/Man-made.** Synthetic compounds are very recent in evolutionary terms and there has been only limited opportunity for the evolution of protective mechanisms against their toxic effects (Walker, et al., 2001).
- **Persistence, Bioaccumulation and Bioavailability.** Persistent organic pollutants do not biodegrade or break down in the environment (or do extremely slowly), so that they may bioaccumulate. More broadly, bioavailability is the degree to which a compound can be taken up from the environment and is available to create a biological response.
- **Endocrine disruptor.** The endocrine system regulates the production of hormones of mammals, birds, fish, and many other types of living organisms. Hormones control or regulate many biological processes including development and reproduction. These hormones are naturally produced in extremely small quantities in the body, so introduction of man-made compounds which can disrupt the endocrine system (e.g. by mimicking a natural hormone) can occur at very low concentrations.
- **Dissolved/Particulate form and solubility.** Influences level of mobilisation at source, and transformation pathways.
- **Oxygen-demand.** An oxygen-demanding pollutant 'consumes' oxygen dissolved in the water, thus impacting primary production, and survival of aquatic life.
- **Organic/Inorganic.** Refers to the carbon-based nature of the chemical. Inorganic pollutants do not contain carbon, heavy metals are the most common class of inorganic pollutants. While organic and inorganic pollutants break down differently, they can both be very harmful.

2.4. Biota

Hydrology, hydraulic, geomorphology and water quality characteristics and processes direct the organisation of aquatic life. Overall it is well established that urbanisation has very negative impacts on biota because of the changes in these driving variables, as described above. Not all species respond in the same way to urbanisation, and some species are more tolerant than others (Danger & Walsh, 2008). However, while some very tolerant species may thrive, it is clear that urbanisation leads to significant loss in biodiversity (King, et al., 2010; Walsh, et al., 2005; Wenger, et al., 2009).

Urbanisation changes the abundance and composition of biota well beyond the variations that may occur naturally. Biota has evolved to be adapted to its natural habitat condition in very diverse ways resulting in very varied life forms and survival strategies. Aquatic species have evolved life history strategies primarily in direct response to the natural flow regimes (Bunn & Arthington, 2002), and the dispersal or reproduction of certain species is for example triggered by specific flow events. For some species it is the timing of rising flows that is determinant for spawning or migration, for other species, it might be the water level. Table 2 in section above provides an overview of the ways in which biota is impacted by changes in stream flows.

Waterway ecosystems are also less resilient to change once degraded. For example, while introduced species can be a problem in themselves, it seems that degraded systems are much more vulnerable to their introduction than natural systems (Dudgeon, et al., 2006).

Further information on how biota is impacted by urbanisation is discussed throughout the document.

Section 2. Understanding waterway systems

This section outlines concepts central to the analysis of urbanisation impacts on waterways, notably how waterway condition can be assessed and predicted.

While there may be intrinsic value in understanding how waterways function and how they are altered by urbanisation, from a natural resource management perspective, the value of this knowledge resides in its contribution to building our understanding of protection and restoration practices.

Protection and restoration are terms widely used in environmental science and management. For the purpose of this paper, we define waterway protection and restoration as follows:

- **Waterway protection** means ensuring that the waterway (ecological) condition does not decline.
- **Waterway restoration** is a little harder to define; it is about returning functions, form, and processes that are characteristic of healthy streams and support biota. It does not mean returning the stream to its pristine state before human impact (because such an outcome is likely not possible). Restoration means returning waterway condition to a specified desired level.

The distinction is important as associated actions rely on different parts of waterway management science. Waterway protection is about managing future pressures, and avoiding known degradation trajectories. Waterway restoration aims to 'reverse' degradation trajectories by addressing existing pressures and then doing work to replace lost components of the waterway form, if required. It is thus a more uncertain process as these trajectories are mostly unknown.

1. Describing & characterising urbanisation impacts on waterways

The pressures outlined in section 1 introduce a complex cascading series of changes to the waterway ecosystem structure and processes. This section aims to provide information on knowledge and tools to analyse this complexity and characterise impacts.

1.1. What is in our waterways?

Description and characterisation of urbanisation impacts on waterways builds on knowledge of what they are, how they function, and what live in them.

At a basic level a waterway is a dynamic ecological system that can be defined by its water, biota and energy fluxes as shown in the diagram below. The aim of this diagram is to provide a simple conceptualisation of a waterway system to help thinking about impacts, rather than any precise categorisation. As illustrated in the diagram, it is also worth keeping in mind that waterways are open systems shaped by their surrounding landscape.

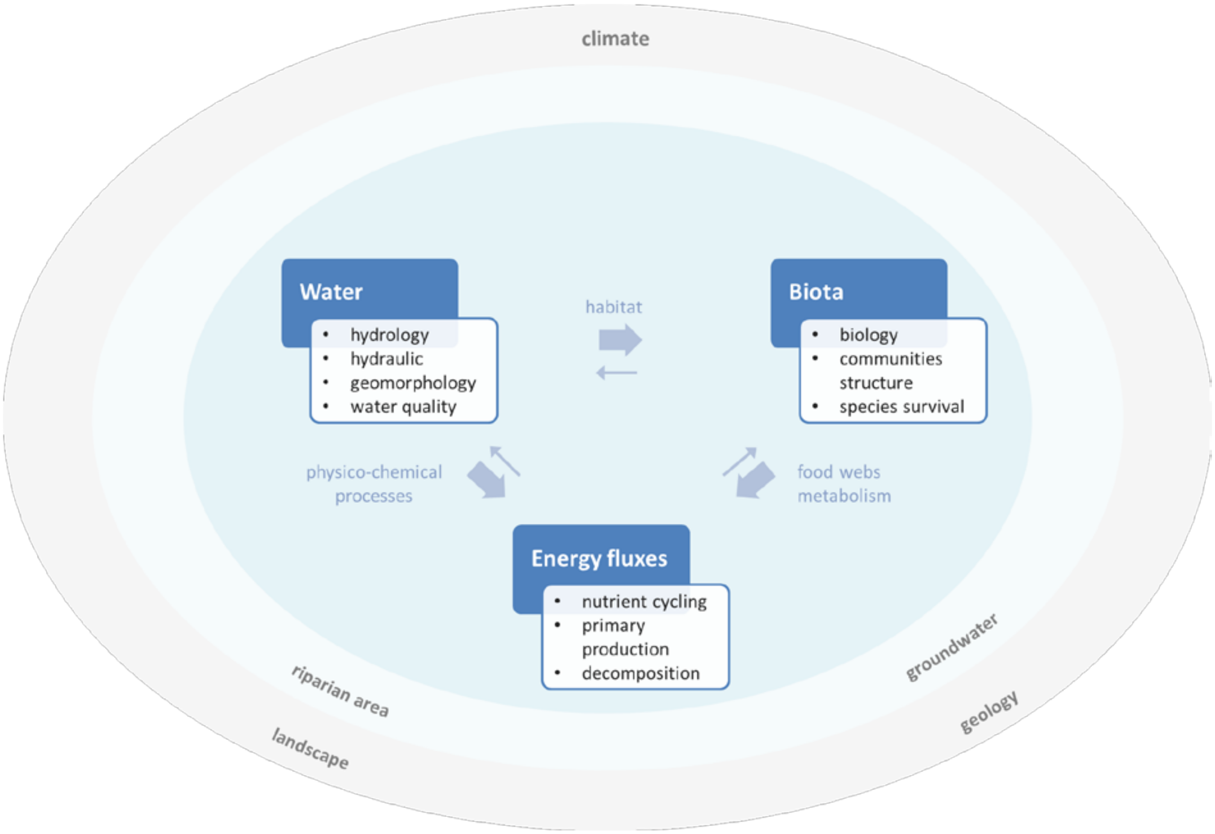

Figure 6. What is in a waterway? Simple conceptual representation of key elements of a stream and their interactions.

1.2. Organising information on impacts

The pressures introduced by urbanisation are multiple in nature, location and timescale.

While it is clear that waterways are significantly altered by the pressure introduced when a catchment is urbanised, the nature and mechanisms of this alteration are multifaceted and complex.

Consequently, any description of waterway impacts can seldom be complete and holistic despite the vast amount of information we have on pressures, impacts, and causal relationships between the two. However this information can be organised, and classified to help us understand and manage this complexity.

Table 4 shows different approaches to organising information and highlights their respective merits. These approaches can be and often are combined.

In addition, changes can be described adopting a chronological order, outlining how changes occur over time, or a causal order, outlining the cascade of cause and effects.

While these different ways of describing and characterising waterway impacts can all be useful, it is important to understand their focus to use them adequately depending on the objectives of the analysis.

Table 4. Categorisation types to organise information on waterways

Categorisation	Example	Advantage (best use)
By pressure	Stormwater inputs Wastewater inputs Direct alteration of physical form Riparian vegetation quality and quantity Introduced pest species Water extraction	Provides line of sight to management actions.
By stressor	Wenger et al. (2009) propose the following categorisation of stressors: - Hydrologic alterations - Geomorphologic alterations - Piping and filling of channels - Increased T°C and light - Increased toxicants - Dissolved O_2 - Increased ionic concentrations - Increased available nutrients - Altered terrestrial inputs - Increased barriers to movement	Helps understand system responses through the characterisation of key drivers of waterway condition. Useful for diagnosis of issues.
By ecosystem process impacted	Nutrient cycling Primary production Respiration Decomposition Sediment transport (deposition and erosion)	Helps understand the mechanisms of ecosystem responses.
By biota impacted	Species abundance and distribution Assemblages composition	Useful in defining outcomes. Supports the design of actions supporting species identified as important in terms of ecosystem functioning or community value. With knowledge of the species involved, distributions and assemblage composition can also help to understand the mechanisms of ecosystem responses. Useful indicators of general condition as biota integrate the multiple stressors and drivers of stream condition.
By system	Complete stream system / river basin Segment system (typically bounded by tributaries junctions) Reach system (typically defined by breaks in stream slope)* Pool/Riffle system Microhabitat system	Level of specificity in describing impacts and identifying issues increases with system scale.

By area	e.g. planning project boundaries, area assessed as threatening to receiving waters (industrial estate), organisational responsibility (council, water authority)	Useful to understand influence of the project considered.

* A length or section of stream / river usually refer to a relatively uniform section with regard to the hydrology, physical form, water quality and aquatic life (Healthy Waterways Strategy definition). Also see Figure 14 and associated discussion on scales and connectivity p.43.

2. Assessing waterway (ecological) condition

The assessment of waterway condition is a prerequisite to both waterway protection and restoration. Any waterway management strategy and activity starts with an assessment of current ecological status as it aims to influence it.

2.1. Defining waterway condition

Waterway condition is the state of a waterway and is intuitively an easy concept to grasp. It is however more difficult to define in scientific terms.

As discussed, waterways are dynamic systems with complex ecological functions and processes, characteristics, and diverse biota. While a number of indicators have been established to assess waterway condition, it remains an evolving science.

In essence, a waterway's condition can only be defined in reference to a baseline or benchmark, usually its 'pristine' or 'natural' state (i.e. before disruption introduced by human settlement) but sometimes a more subjective state such as 'best possible' (the approach adopted in the European Framework Directive for heavily modified rivers).

Condition assessment aims to establish how far from the chosen benchmark the waterway is; classifications can then be established to rate condition from very good to very degraded in comparison to the chosen benchmark.

The list of waterway condition indicators is virtually endless, it is thus critical to understand what they measure and how they can be used.

2.2. Overview of waterway condition indicators

Waterways are dynamic systems that are shaped by their environment (climate, geology, regional landscape, catchment physiography and vegetation…) which is naturally changing so there are natural variations in waterway attributes. The assessment of human impacts on waterway condition is about identifying changes that cannot be attributed to natural variation.

Waterway condition indicators are measurable attributes that provide an indication of what the ecological condition is likely to be.

Physical indicators such as nutrient and oxygen concentrations, temperature, and flow have long been used as indicators in waterway condition assessment. However, biotic indicators are generally recognised as the primary indicators of ecological condition (Karr & Chu, 1999; Walsh & Webb, 2014).

In an ideal world, we would have an in-depth knowledge of the species, population, and community of the waterway of concern in natural conditions, and have enough time and resources to undertake a complete inventory of biota that could then be compared to the natural reference. This is however highly unrealistic on both counts so that we need surrogate ways to assess condition, and consequently the development of suitable indicators is an on-going field of research. To be useful and representative, biotic indicators need to be:

1. Pertinent to the local context (the waterway assessed needs to be a known or potential habitat for the biota selected);
2. Sensitive to disturbance; and
3. Consistent in response across the sites assessed.

While assessment of biota provides information on waterway condition, it does not necessarily provide much information about the causes and mechanisms of the observed degradation where there is no empirical validation of a pressure-impact relationship for the biota selected. It is therefore important to complement biological assessment with an assessment of key waterway attributes as environmental condition variables.

Pressure-impact relationships also rarely fully explain the variability observed, so even when they exist, additional information will be necessary to inform management strategies.

Additionally, there could be significant time-lags in the biotic response to pressure, and other indicators may be able to provide earlier warning of degradation to better guide management actions.

Typical indicators

Indicators may be selected and used to help assess the magnitude of change of a waterway attribute that has been shown to be important to waterway ecological condition. They may also be more directly linked to a specific impact on biota. Table 5 shows indicators commonly used in the assessment of waterway condition. The last column aims to provide some insights of ecological relevance. It should be noted that these indicators are not independent, and as such there are many linkages between their ecological effects.

Table 5. Overview of waterway condition elements used to derive indicators.

Water	Hydrology	Rainfall runoff	Key characteristic of hydrological response.
		Groundwater exchange	As above
		High flow events (magnitude, duration and frequency)	Affects floodplain connectivity, washout of aquatic life.
		Low flow events (magnitude, timing, duration and frequency)	Low flows occur the majority of the year in natural conditions, they are important to maintaining water quality conditions supporting aquatic life. They also key to the establishment of a wide range of plants.
		Duration & timing (seasonality) of zero flow	Affects connectivity and species migration, water quality and persistence of aquatic biota in remaining pools, and influences the establishment of terrestrial floodplain vegetation.
		Rate of change	Rate of change in flows affects survival and recruitment of many aquatic species. For example, steep flow rises may flush out pools biota, and steep flow recession may strand slow-moving or juvenile animals.

	Hydraulics	Floodplain connectivity	Important to floodplain ecosystem functioning, floodplains have an important role in treating water during storms, they are an important source of food, key to reproduction of some aquatic species.
		Flow dynamics (velocity, shear stress)	Affects species ability to move.
	Geomorphology	Bed and bank mobilisation	Drives erosion and deposition, shapes habitat, washout or drown out of species attached to substrate.
		Bed form diversity	A diverse and complex bed form, as shown by the presence of bars and benches, of pools and riffles, or of large wood debris in particular provides the varied habitat required to support aquatic biodiversity.
		Bedload sediment (composition and depth)	Important habitat feature. Mobile coarse-grained bedload sediments support foraging and refuge for macroinvertebrates and fish, and are also important for nutrient retention, metabolism and temperature (as summarised by Vietz et al. (2014).
	Water quality	Temperature, DO, conductivity, pH, turbidity	Strongly influence stream metabolism, and may affect direct survival of biota.
		Nutrients	As above
		Toxicants	Affects direct survival of biota.
Energy fluxes	Stream metabolism	Daily changes in oxygen concentration	Stream metabolism reflects the interplay of photosynthesis and respiration, providing the food resources and energy underpinning most aquatic food-webs.
	Primary Production / Photosynthesis	Algal growth and biomass	Algae are major primary producers in running waters, so their growth is a measure of the rate of primary production within a stream and is primarily limited by the availability of light and nutrients.
	Respiration		See stream metabolism
	Decomposition	Leaf breakdown	See stream metabolism
	Nutrient cycling	Evolution of Nitrogen, Phosphorus and Carbon (forms, isotopes signature, transformation rates)	Essential to life, also see stream metabolism and primary production. Also important to receiving waters (e.g. bay, lakes, wetlands).
Biota	Flora	Algae (e.g. diatoms), floating plants, submerged plants, and emergent plants	Important source of food, key to nutrient cycling, provide habitat.
	Fauna and other life forms	Bacteria, fungi, viruses, invertebrates (insects, crustaceans, molluscs, and worms), vertebrates (fish, amphibians, reptiles, birds, mammals, rodents, marsupials)	Invertebrates are an important link in the food web between the producers (leaves, algae) and higher consumers such as fish.

Integrative indices (combining several indicators to form composite indices) and the ISC

Benchmarking waterway condition can be a useful starting point for developing management strategies as a first filter to identify issues but also in terms of communication and engagement. Indices combining a number of indicators are sometimes established to benchmark waterway condition. This is the case of the Index of Stream Condition (ISC) used to benchmark 29,000 km of major streams across Victoria, which is summarised in Figure 7.

The ISC has been designed to provide a 'snapshot' of condition across the State at a point in time (Third Index of Stream Condition report) rather than to assess trends, and to support broad management strategies for the state rather than specific reach interventions (Ladson, et al., 1999).

When using benchmark/report cards, it is important to understand the spatial and temporal scale of the data input, the data collection methods, and the method of inference used. Data collection procedures are designed to be cost effective and suitable for provision of information at the scale chosen for the benchmarking report.

While the ISC can be a useful index in itself, it is generally thought that the ISC State report card has limited value for supporting management planning for the Melbourne region. The two main issues are the limited number of monitoring points compared to the scale of the potential management actions and the focus on main stems to the exclusion of smaller streams.

Hydrology	Physical Form	Streamside zone	Water Quality	Aquatic Life
Hydrology refers to the amount of water that is within the river channel at a particular point in time at a particular location. A minimum of 15 years of monthly flow data is used.	Physical form takes into account the river bank condition as well as instream habitat (logs or 'snags') and major barriers to fish migration, such as dams and artificial weirs.	Streamside zone measures characteristics of the woody vegetation within 40 metres of the river's edge.	Water quality is the quality of water in the river.	Aquatic life is based on the number and type of aquatic macroinvertebrates found within the river.
• Low flows • High flows • Zero flows • Seasonality • Variability	• Bank condition • Artificial barriers • Instream woody habitat	• Width • Fragmentation • Overhang • Cover of trees and shrubs • Structure • Large Trees • Weeds	• Total Phosphorus • Turbidity • Salinity (EC) • pH	• AUSRIVAS • SIGNAL • EPT • Number of Families

Figure 7. Summary of the Index of Stream Condition. Reproduced from DEPI (2013).

The South East Queensland Healthy Waterways report card is another benchmarking example used in Australia. While the approach is similar to the ISC, the presentation differs as the results are presented graphically (see Figure 8) and interactively so that the rating of each sub-index can be interrogated. This report card was first issued in 2000 presenting freshwater condition, the assessment methodology changed in 2015 (adding riparian vegetation and replacing nutrient cycling with pollutant loads) so that the overall rating cannot be directly compared. It now also provides estuarine condition, as well as an assessment of social and economic benefits provided by waterways and community motivation to take action.

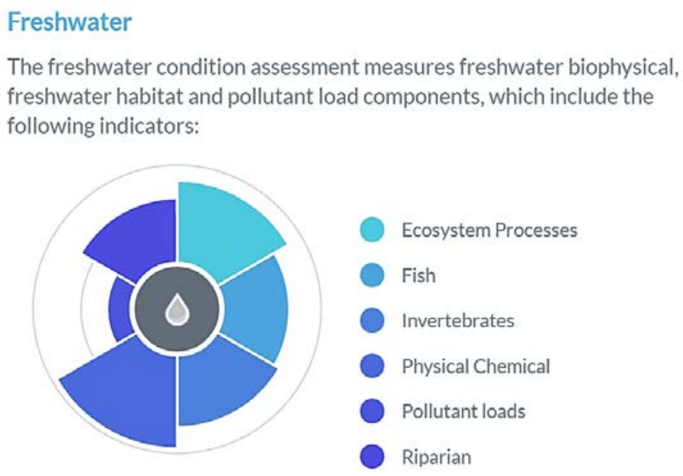

Figure 8. Example of report card results from the South East Queensland Healthy Waterways program. Reproduced from http://healthywaterways.org/reportcard.

Macroinvertbrates assemblage composition indicators and SIGNAL

Macroinvertebrate assemblage composition is accepted to be a robust indicator of waterway condition (Walsh, 2006; Walsh & Webb, 2013) and is well established as being sensitive to human disturbance, and provides a good integrative measure of ecological condition.

Macroinvertebrates are diverse, they mediate or reflect many ecological processes in standing and running waters, and vary in their tolerance to different impacts and disturbance (Boulton, et al., 2014).

The composition and diversity of macroinvertebrate assemblages is an excellent indicator of the ecological health and integrity of streams and rivers because of the high diversity, wide range of tolerances, and pivotal role in stream food-webs that macroinvertebrates have. This assertion is further strengthened for the assessment of the impacts of urban stormwater runoff due to the observed consistency of response by macroinvertebrates and other ecological indicators.

In the Melbourne region, macroinvertebrate assemblages present the additional advantage in terms of quantity and quality of data:

- Large series of long-term records (>9000 samples, across around 1000 sites) for the Melbourne region are available
- The dataset available is the most complete and consistent river health indicator dataset for the Melbourne region

In the Melbourne region the macroinvertebrates assemblage index most commonly used is SIGNAL. It was formulated to effectively detect the impacts of urbanisation and has been confirmed to be a sensitive indicator of stream health across Melbourne (Walsh, 2006; Webb & King, 2009).

While SIGNAL is a robust indicator of waterway condition, natural streams in the West tend to have lower SIGNAL score than natural streams in the East. This is an artefact of the way SIGNAL is calculated and the fact that higher discharge streams of the East of Melbourne tend have higher diversity in biota than lower discharge streams of the West. LUMAR, a variation of SIGNAL, has recently been developed by (Walsh & Webb, 2013) to enable better regional comparisons by ensuring a more uniform scoring across Melbourne streams in the absence of human impacts. This index is still being refined, and has not yet been published.

Using indicators

Condition indicators can provide different type and level of richness of information, have varied specificity and sensitivity, and can play different roles in developing mitigation actions and strategies.

The term condition indicator is typically used regardless of the purpose. It is however beneficial to be clear on the purpose of the indicators used to develop strategies. They can be used to:

- Benchmark condition
- Identify problems and risks to manage
- Investigate cause(s) of problem
- Identify mechanisms of alteration
- Monitor effectiveness of management actions
- Set performance targets
- Specify outcomes
- Communicate outcomes

There are some practical challenges that need to be considered when using waterway condition data and information. Some of the main issues to take into account relate to:

- **Condition rating**. The threshold used for classification can be somewhat arbitrary and not necessary ecologically meaningful and may lead to issues in evaluating effectiveness of action. Classification boundaries may be established following ecological, statistical, or expert-based criteria.
- **Extrapolations** – spatial and temporal. Monitoring provides waterway condition data points, i.e. at specific locations and specific times, which are then used to infer condition in between data points.
- **Data acquisition**. Sampling methodology and standardisation, and data quality.

2.3. Differentiating condition, performance and service

While the fields of natural resource management and asset management use similar methods to inform investment strategies, the terminology used differ. The terminology of condition, performance and service commonly used in asset management may be useful when thinking about waterway management strategies.

In asset management, it is considered good practice to differentiate condition, performance and service as it helps in defining clear investment logic. They are also not necessarily directly linked, and when they are, the relationship is often not linear.

While assessment of condition can be regarded as a purely technical question, assessment of performance is dependent on the management context and relates to the asset management strategy adopted.

An asset assessed to be in bad condition could be performing well or badly depending on the function under consideration. For example, a waterway may be performing its flow conveyance function while being in poor ecological condition.

While condition and performance are fundamentally different concepts, condition indicators may be selected to set performance targets. The selection of performance indicators is informed by a range of evolving factors: legal requirements and mandate, customers' expectations of service and willingness to pay, organisational strategic plans, and identified drivers of management improvement (e.g. data collection performance indicator).

Ecological performance indicators may be set around functioning characteristics (e.g. hydrological indicators, such as peak flow), overall condition (e.g. integrative indices such as SIGNAL), specific species (e.g. platypus), and biodiversity (e.g. fish abundance and diversity). For example:

- Melbourne Water's current waterway strategy has adopted seven 'key values' as performance indicators: amenity, birds, fish, frogs, macroinvertebrates, platypus and vegetation.
- The Victorian State Environment Protection Policy (SEPP) sets both water quality and biological performance indicators.

Establishing how condition relates to performance is an important component underpinning the development of waterway management strategies and remains scientifically challenging. It relies on our conceptual models of waterways, this will be discussed in the following section (Predicting waterway condition).

Overall waterway management performance indicators will combine ecological indicators with other indicators covering the other functions (see Figure 2) of waterways such as amenity and conveyance. The overall performance of the asset as perceived by the user may be referred to as service. Melbourne Water's overall waterway service measure is for example a community waterway satisfaction survey index.

3. Predicting waterway condition

Predicting future waterway condition in response to specified actions is core to the development of waterway management strategies and actions. In order to secure funding, waterway managers need to be able to tangibly outline the benefits that will result from a proposed investment, and are thus looking for waterway condition models to support decisions.

3.1. Conceptualising waterways – conceptual models

Describing the impact of urbanisation on waterways, defining waterway condition and performance implicitly involve some conceptualisation of waterway ecosystems as well as urban pressures.

Conceptual models are a way to make sense of complex reality by extracting key concepts and parameters, and establishing causal relationships between them.

Developing a conceptual model is a more formal and structured way of describing and characterising the functioning of a system.

It is important to bear in mind that all conceptual models are a simplification of a complex reality designed to help us make sense of it. As illustrated in Figure 9, views of issues and/or decisions are influenced by individual and collective mental models that are often not made explicit and contain assumptions that are worth reviewing. Differences in mental models can lead to different conclusions on decisions and needs, which is important when considering stakeholder engagement.

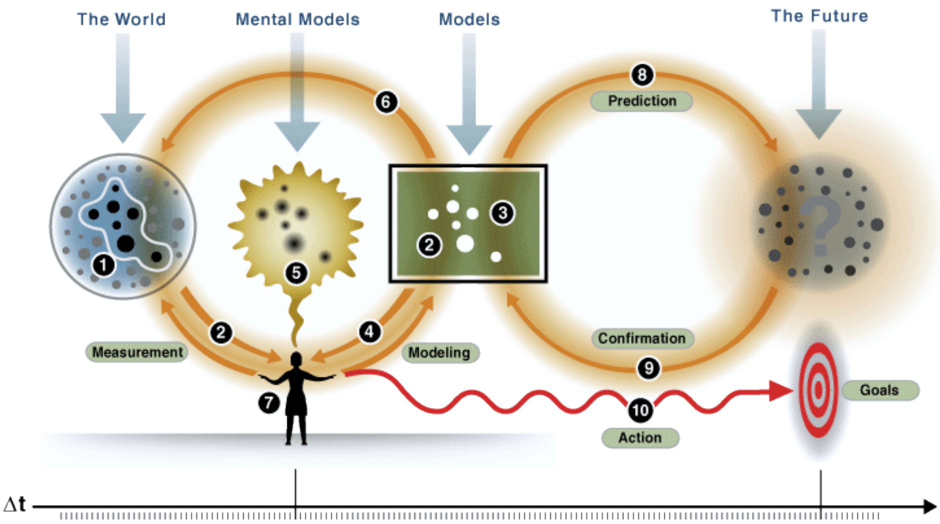

Figure 9. Models: making sense of a complex reality. Reproduced from http://www.idiagram.com/ideas/models.html

Figure 9 highlights some of the interactions between the modeller/decision maker, the real world and the model as an important context influencing its development and use. For example, models are developed that reflect and embed our understanding of the real world; they are then used to make predications which are validated against real world expectations. While this provides an input into a decision about which course of action to take, the modeller/decision maker plays an integral role in the overall decision making process. In particular, the outputs from the model are compared to the decision maker's mental models which reflect their own understanding of how the world works.

As waterways are complex, a wide range of conceptual models has been developed to help us understand what they involve, and how they function. They can be a very useful problem solving tool and are most useful when adapted to respond to a specific question (Fischenich, 2008). Just like any type of model, it is important to consider that these models were developed for a specific purpose, to help resolve specific questions and issues or to explain a particular aspect of a waterway ecosystem.

There is not one model that can capture all aspects of a waterway ecosystem; and it is not necessarily desirable either as such a model would not be usable in practice. The level of details and specificity of a conceptual model is mostly inversely proportional to the level to which the system is being described.

Some conceptual models aim to provide an overview of waterway functioning and responses to changes. Others focus on a specific component, such as a stressor or an ecosystem process. The list of categorisation parameters shown in Table 4 (p.22) is also relevant to describe the range of conceptual models that are developed for waterways.

An example of conceptual model representing key changes introduced by urbanisation with a focus on the impacts of stormwater is shown in Figure 10. Other examples are included in Appendix 1.

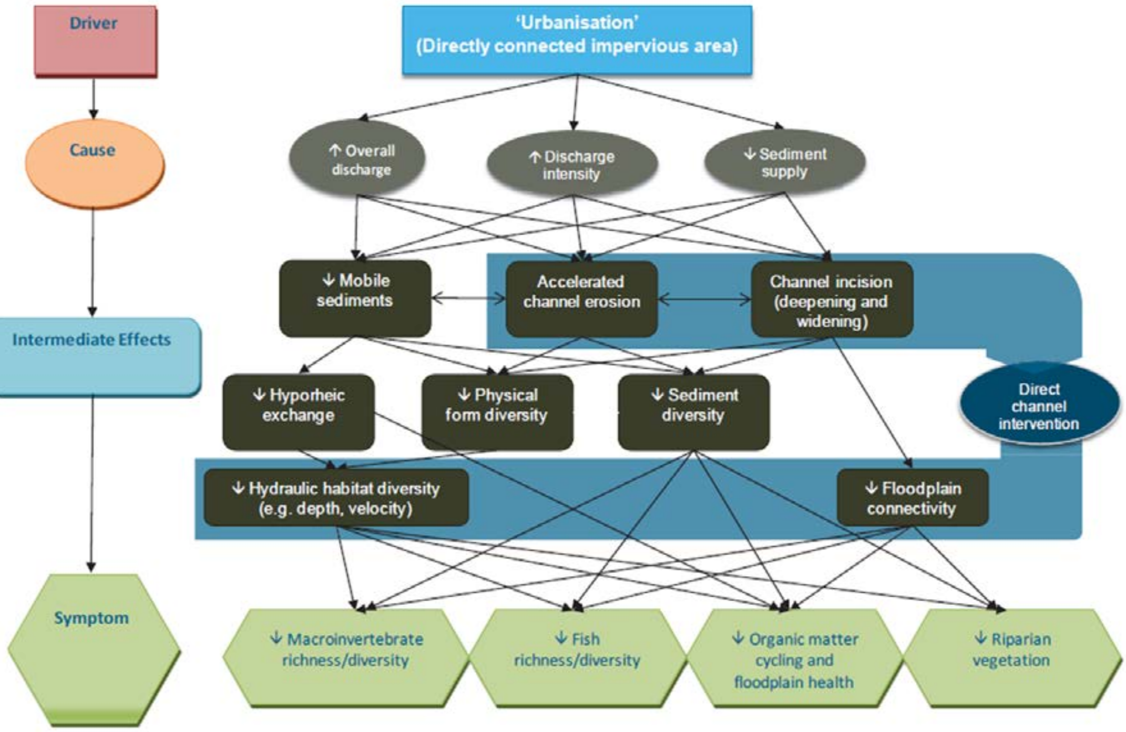

Figure 10. Example of conceptual model of the impacts of urbanisation on waterway condition. This conceptual model shows the cascading changes caused by land use change and stormwater drainage, linking directly connected imperviousness (see definition in Table 6 on p.36) to biota. Reproduced from Fletcher et al. (2011).

Each type of model has a role to play in supporting the development of waterway strategies, they should be seen as tools to analyse waterway functioning and management issues.

3.2. Mathematical modelling

Mathematical modelling aims to provide quantified relationships between variables selected to represent a system structure and/or functioning. As illustrated in Figure 11, it builds on conceptual models with the aim of providing quantitative predictions.

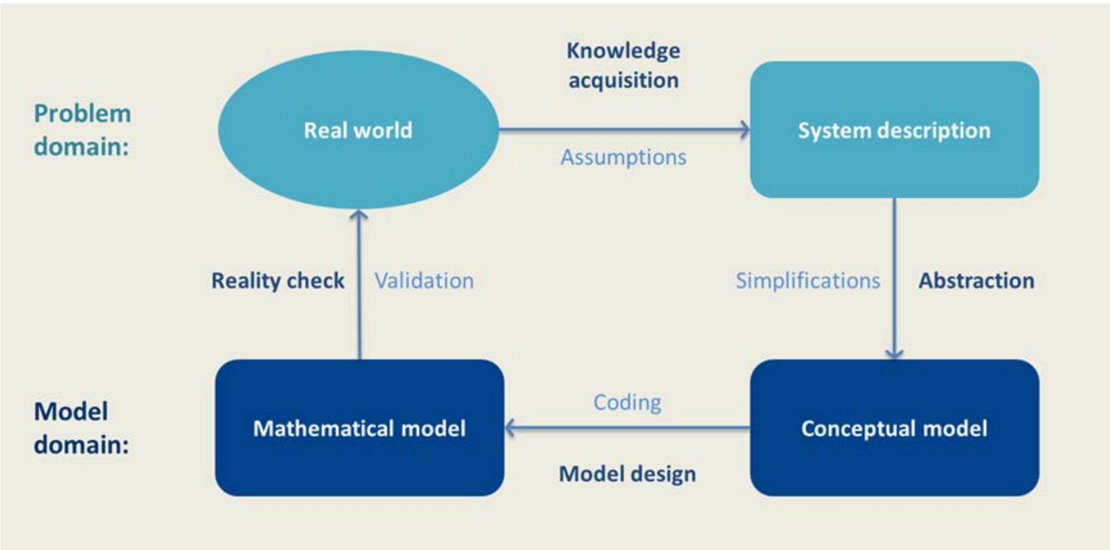

Figure 11. Key modelling stages and linkages. Reproduced from Kotiadis & Robison (2008).

At a high level, there are two significantly different types of mathematical models, statistical and mechanistic models:

- **Mechanistic model**. A hypothesized relationship between the variables in the data set where the nature of the relationship is specified in terms of the biological processes that are thought to have given rise to the data. The parameters in the mechanistic model all have biological definitions and so they can be measured independently of the data set referenced above.
- **Statistical (also called Phenomenological) model**. A hypothesized relationship between the variables in the data set, where the relationship seeks only to best describe the data.

When causes and effects are complex, mechanistic models can be difficult to develop. Statistical models present the advantage of providing a way to quantify cause and effects relationship without having to quantify each causal step. To be useful in decision-making though, statistical models need to combine understanding of causal relationships with the statistical analysis as correlations alone cannot show causations.

Figure 12 provides a high-level summary of our waterway condition modelling state of knowledge to support the discussion in this section.

We can generally predict the changes in waterway condition that will result from urbanisation. The relationship between urban land use and waterway condition is widely accepted, and the degradation pathways are broadly understood, with strong evidence that stormwater drainage networks are the dominant driver of degradation in modern cities such as Melbourne (Walsh et al. 2012) However, we are still lacking a detailed and comprehensive knowledge of the mechanisms of the degradation processes set by urbanisation (Wenger, et al., 2009) in that we rarely have quantified relationships of changes to support prescriptive management actions.

In addition restoration trajectories do not necessarily follow the degradation ones. This means that establishing accurate and quantified predictions of waterway's ecological response to actions remains challenging.

However, as illustrated in Figure 12, we have strong statistical models linking the impacts of urban stormwater runoff and forest cover with waterway condition for the Melbourne region, these models will be described in next section. We also have good mechanistic models for parts of waterway functioning:

- Hydrology - Rainfall-runoff models (e.g. MUSIC, SymHyd, SWMM)
- Hydraulic – Flood models (e.g. HecRas, Tuflow, Canoe)
- Geomorphology - sediment transport models (e.g. ISIS Sediment Transport) and erosion capacity mathematical analysis
- Water quality – pollutant transport and fate (e.g. Mike11, MUSIC, QUAL, Canoe)

As for any modelling, a key requirement is calibration. It is however not uncommon to be lacking flow data, and even more so the case for water quality. An important field of research in this area include the derivation of stream hydrology predictive models in ungauged catchments using physiographic attributes.

While we generally have a fair understanding of the impacts of changes of stream hydrology on stream biota, we are lacking quantified relationships between stream hydrology and biota. This question will be developed later in the document.

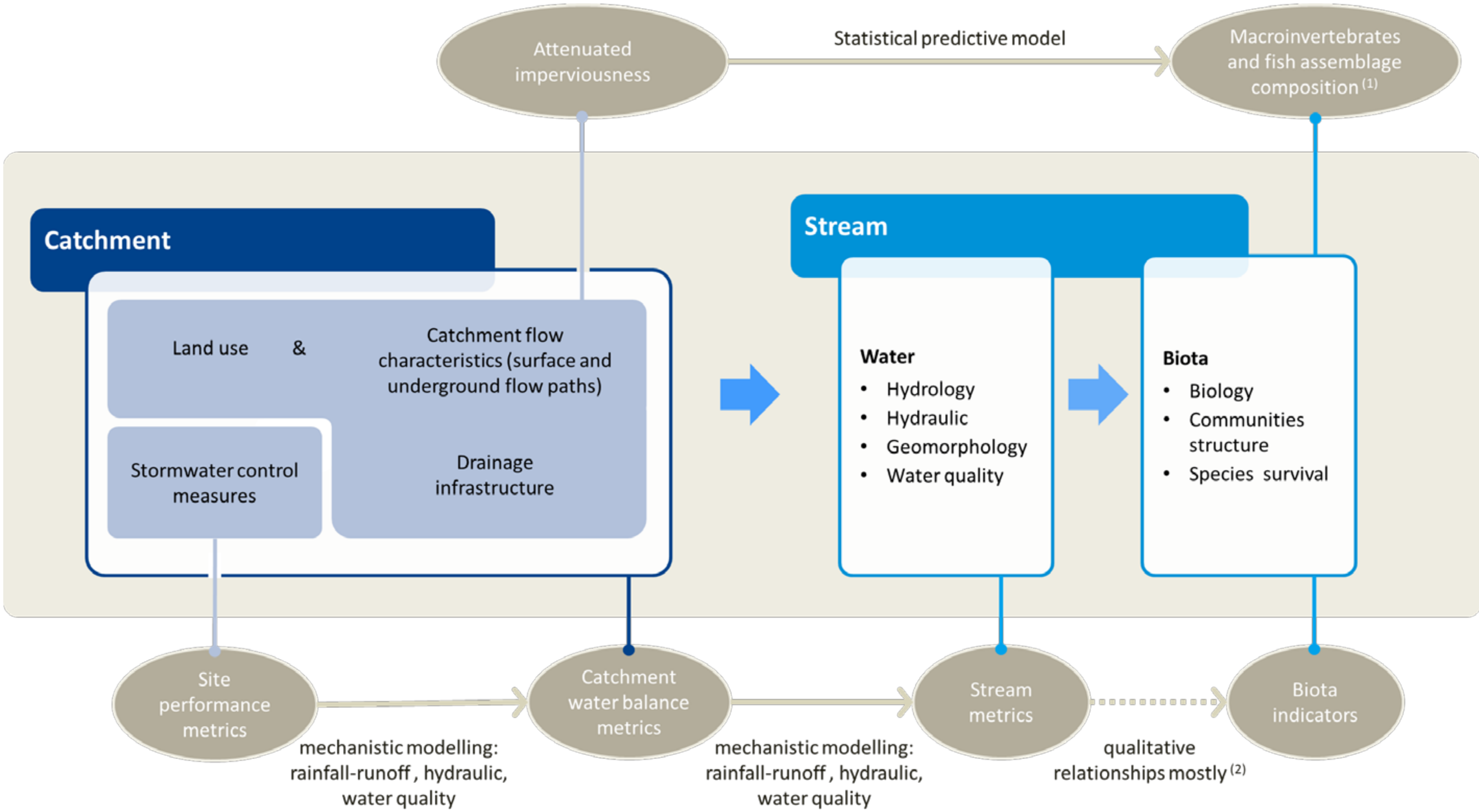

Figure 12. Conceptual framework of catchment pressures to impact on streams, showing key linkages and current knowledge.
(1) Attenuated Imperviousness has also been statistically linked to water quality and geomorphic metrics (see page 41), however these relationships have not yet been used to make predictions. (2) For further details, refer to p. 38 (Other predictive models: using stream hydrology to predict waterway condition) and p. 56 (Water quality issues)

3.3. Melbourne's predictive model of waterway condition

While we do not have mechanistic predictive models of the impacts of urbanisation on biota, we have a robust statistical model linking urban pressure and biota for the Melbourne region that builds on our conceptual understanding of urban degradation pathways.

Walsh and Webb (2013) developed a predictive model of stream macroinvertebrate assemblage composition as a function of land use, physiography and climate, based on a database of over 9000 macroinvertebrate samples collected over the last two decades. The approach taken was to quantify relationships between drivers of waterway condition as indicated by SIGNAL score and invertebrate distributions through statistical analysis.

Macroinvertebrate assemblage composition was selected as an indicator of waterway condition for this modelling as:

- It is well established as a sensitive indicator of stream condition (as explained in the section above on indicators)
- Large and long-term records for the Melbourne region are available
- The dataset available is the most complete and consistent condition indicator dataset for the Melbourne region

The modelling study consists of:

- Statistical analysis to establish optimal predictive variables of waterway condition as indicated by SIGNAL score.
- Development of distribution models of 60 macroinvertebrate families using the predictive variables established.
- Modelling of current state scenario. The model was first developed to make prediction about the current state, providing waterway condition in all reaches of the region rather than just at monitoring points.
- Modelling of future state scenarios. The model was then used to run a range of management scenarios using the predictive variable established in the first stage.

Predicting current condition

While human disturbance results in significant variation in ecological condition, some variation can also be explained by natural factors. As such, the model uses indicators of:

- Human disturbance (riparian forest cover, impervious cover connected to the drainage network), and
- Natural differences (elevation, catchment area, catchment geology / substrate type, mean annual discharge, antecedent flow).

These variables are used to predict a number of macroinvertebrates assemblage indicators of waterway condition:

- SIGNAL
- LUMAR (a variation of SIGNAL that is more homogeneous between the East and West of Melbourne, in development)
- 60 macroinvertebrate families

Figure 13 provides an overview of the model structure and the table in Appendix 2 provides more details on the indicators tested to establish the predictive model. The modelling approach is currently being extended to include other biotic indicators. A first cut of a fish model for 20 fish species has been developed (see progress reporting of project 1.6 of the Melbourne Waterway Research Practice partnership). Some initial results have also been produced for platypus. Both fish and platypus models present a likelihood of presence or absence.

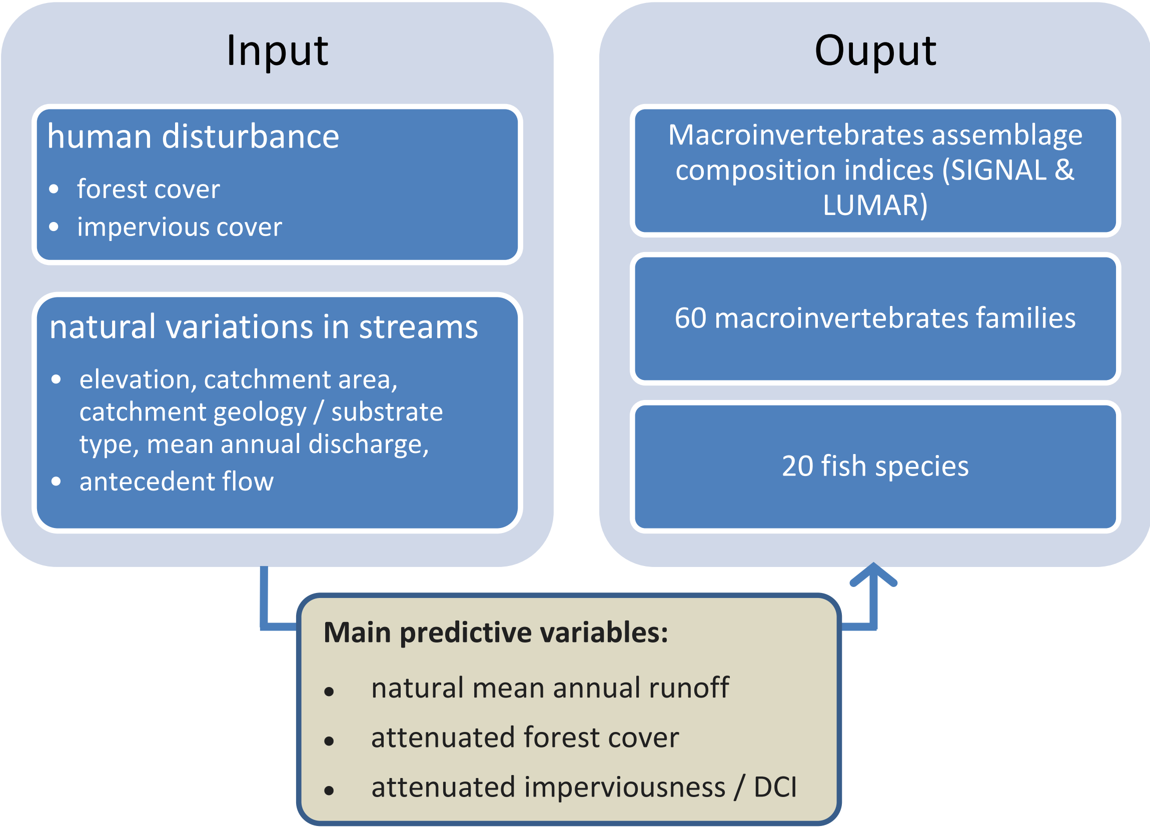

Figure 13. Overview of the waterway condition predictive model structure of Walsh and Webb (2013) and ongoing research by the Melbourne Waterway Research-Practice Partnership.

The macroinvertebrate modelling study establishes that the three main predictive variables are mean annual runoff (estimate of natural discharge), attenuated forest cover (AF) and attenuated imperviousness (AI) also commonly termed directly connected imperviousness (DCI). Definitions of AF and AI/DCI are provided in Table 6 below.

The best-fit model used for prediction of SIGNAL score is robust with an observed to predicted correlation of 0.85, with no evident bias among residuals. Together the three variables account for 89% of the explained variance, (57% for natural mean annual runoff, 16% for attenuated imperviousness, and 15% for attenuated forest).

A large decline in SIGNAL between 0 and about 3% DCI is predicted across the region.

Table 6. Definition of Attenuated Forest Cover (AF) and Attenuated Imperviousness (AI) / Directly Connected Imperviousness

Attenuated Imperviousness / Directly Connected Imperviousness	AI / DCI	The Attenuated Imperviousness of a stream is a weighted measure of the impervious cover of its catchment established by (Walsh & Kunapo, 2009). It also often referred to as Directly Connected Imperviousness (DCI) and defined as the proportion of impervious surfaces directly connected to the stream through conventional drainage. However, it is not a true mechanistic measure of impervious surfaces with direct piped connection to the stream, but a statistically determined estimate of those impervious surfaces that are likely to have the greatest influence on stream ecology (Urrutiaguer, et al., 2012).
Attenuated Forest Cover	AF	The Attenuated Forest Cover (AF) of a stream is a weighted measure of the forest cover of its catchment. It accounts for the decrease in influence of forest cover with distance from the stream both longitudinally and transversely.

The response to mean annual runoff is primarily a step function with a threshold of about 250mm, with lower SIGNAL scores predicted for the lower discharge streams. This points to a limitation of SIGNAL in that the maximum score observed in healthy streams varies across regions, and thus does not allow direct regional comparison, especially between the West (very dry) and East of Melbourne (wet). The thresholds of what can be considered good or very good ecological condition can however be adjusted to account for this, so this indicator remains valid and useful.

An analysis of variations by families led to the development of an alternate index, LUMAR, which is less influenced by physiographic and climatic variation across Melbourne's region (Walsh and Webb, 2013).

While DCI captures most of the pressure introduced by urbanisation, it does not explain 100% of variation in waterway condition. Further work is underway to explore potential refinements of the model:

- Refinement of in-stream temperature (will allow to better explore climate change scenarios, and management of riparian vegetation for shading)
- Refinement of hydrological predictors: flow permanence, flow stress (volume extraction, farm dams)
- Refinement of land use: forest cover quality (focusing on woody weeds), agricultural use refinement
- Refinement in drainage pathways and flow attenuation to inform delineation of stream and calculation of attenuated imperviousness

Predicting future condition

The models of Walsh and Webb (2013, 2016) build on the current knowledge of waterway degradation mechanism and stormwater management requirement for protection. The results of the models provide an assessment of the impacts of different stormwater and other management strategies on waterway condition. Walsh and Webb (2013) modelled the scenarios summarised in Table 7.

Table 7. Summary of stormwater management scenarios modelled for waterway condition prediction

Stormwater management scenario modelled		Model input variable: DCI
Name	**Description**	
A) Present	Present state	**DCI maintained at its 'current' level** based on the dataset acquired by Melbourne Water and established using 2006 aerial photography.
B) Future with '90%' objective in all new developments	Future state under a policy that would require all new development creating new impervious surfaces to adhere to a near natural flow regime	
C) Future with lower objectives in all new developments	Future state with continuation of the current stormwater management policy (current BPEM) or adoption of low requirements for flow regime ('25%' and WQ only objectives, as well as '60%' objective for ephemeral streams at least if not for all streams)	**DCI set to future TI**, total imperviousness estimated for 2030 as a result of projected urban growth(1).
D) Future with '90%' objective for all urban areas	Future state with adoption of a new stormwater management policy implementing a near natural flow and water quality regime stormwater standard. Assuming that this results in restoration of ecological condition, this is yet to be demonstrated (see notes on Little Stringybark pilot).	**DCI set at zero** to represent the management of stormwater to achieve near natural flow regime standard for both all new impervious surfaces generated by urban development and all existing impervious surfaces through urban renewal. Based on typical urban renewal rates, a full renewal could be expected over about 50 years.

(1) see Urrutiaguer et al. (2012) for a summary of the methodology used to establish this urban growth projection

Other management scenario modelled		Model input variable
Name	**Description**	
E) Rock riffles	Construction of rock riffles in simplified channels to increase in-stream complexity as an important characteristic of habitat.	Macroinvertebrates monitoring sample type (riffle or pool edge).
F) Riparian tree revegetation	Replant forest cover in riparian areas.	Attenuated forest cover – set to 20, 40 and 100m wide buffer.

Other management scenario modelled		Model input variable
Name	**Description**	
G) Climate change	Warmer climate: temperature increase.	Elevation as a surrogate of water temperature
	Drier climate: rainfall decrease (two scenarios)	Mean annual discharge. Input values were derived from stream data from: 1) A 4-year period where the mean annual discharge of the mouth of the Yarra River is 25% lower than the long-term mean value 2) The 4-year period prior to 2007 (50% reduction of mean annual discharge compared to long-term mean value)
	Drier and warmer	Combination of the two scenarios above
	Note this is a very simplified climate change scenario. Impacts are likely to be much more complex. However this enables an exploration of the impacts of increase in water temperature, and influence on management strategies.	

3.4. Other predictive models: using stream hydrology to predict waterway condition

The model described above provides results for a range of management strategies. It is important to remember that at present the management strategies modelled can only be represented by the two human disturbance variable: DCI and forested cover, which are both land-use indicators of pressure.

The link between management actions and these variables is not direct as they are not true physical measures but statistical variables. Stormwater management measures are represented as a binary input where stormwater runoff is either fully disconnected or not at all as outlined in Table 7. This means that this model cannot be used to assess the impacts of gradual level of stormwater treatment.

As it is possible to model the impacts of stormwater strategies on hydrology, another route to quantify impacts on biota would be to link hydrological and biota measures (as shown in Figure 12).

A study by Burns et al. (2015) examined the possibility of building a predictive model similar to the one described above but using stream hydrology indicators as input variables instead of land-use variable to predict SIGNAL in the Melbourne region. The study explores the predictive capacity of models using both single and coupled hydrologic variables. It concludes that DCI is the strongest predictive model of SIGNAL, probably because it integrates both hydrological and water quality stressors. However, it also indicates that it may be possible to establish reasonably good models using just two hydrological variables (one representing ‘flashiness’, a good measure of stormwater runoff, and another representing baseflow). A model with these two metrics explains the majority of SIGNAL across Melbourne, but the proportion of variability unexplained by these two variables could be hypothesised to reflect water quality aspects which are not related to hydrology (eg. point-source pollution). This is a research area that the Melbourne Waterway Research Practice partnership aims to pursue.

A global 2010 literature review (Poff & Zimmerma, 2010) of ecological responses to altered flow regimes (due to dams and impoundments or water abstractions for a large portion of studies reviewed)found no support for a general and transferable relationship between flow alteration and ecological impact. They also conclude that flow alteration is associated with ecological change and that the risk of ecological change increases with increasing magnitude of flow alteration.

Our current state of knowledge may not be advanced enough to identify such as general relationship. It is however also as likely that a general relationship does not exist due to local specificities, or because other stressors need to be taken into account. It is indeed important to note that flow alteration is often associated with other changes affecting biota (e.g. degraded water quality).

Interestingly, environmental flows strategies rely on the development of quantitative relationship between flow measures and measures of outcomes for biota (fish in particular). While the relationships established may be valid, they are site specific based on local monitoring data and typically based on expert judgment rather than mathematical modelling. At present, these relationships are not developed or documented in a way that allows using them to be applied beyond the strategies for which they were developed.

Norris et al. (2012) highlighted that there is a vast amount of literature but little systematic organisation of the information contained in the studies published around cause and effect associations observed. A few initiatives around the world have started work aiming to address this knowledge synthesis gap. In Australia, the Eco Evidence database was developed by researchers and programmers at the eWater Cooperative Research Centre and can be searched on their website[1].

The concept and structure is interesting and could potentially be very useful to support decision-making, however as noted by Webb et al. (2015) in their paper providing a description of the database, it needs to be populated to a much greater degree to become an immediately useful resource for new reviews over a wide range of topic areas.

Recent work by Duncan et al. (2014) aimed to identify eco-hydrological indicators (i.e., hydrological indicators that have been shown to be important driving variable of ecology) as a mean to report the waterway condition outcomes of a range of stormwater management strategies.

Building on a previous literature review by Burns et al. (2010), they generally found that numerous studies in the literature outline the relevance of stream hydrology to stream biota and elect metrics for the purpose of their study. The evidence of the significance of the hydrologic metric is often restricted to a specific location, or a specific biotic indicator and missing a full statistical analysis of relative importance. Nonetheless, they make a short list of metrics that covers the ecologically important aspects of the flow regime and that have been shown to be significant explanatory variables for ecological condition (in at least one study / location). While this provides a work around way to link hydrology and ecological outcomes, the remaining issue is that it is difficult to characterise the ecological significance of a variation from natural level of most metrics.

[1] http://www.toolkit.net.au/Tools/Online/EE/Search/Default.aspx?NEW=1

Section 3. Mitigating the impacts of urbanisation

Strategies to mitigate the impacts of urbanisation on waterways (whether as restoration or protection) build on knowledge of the functioning of natural systems and their degradation. As outlined in the section above, understanding and characterising pressure – ecological responses relationships is core to this. Establishing the outcomes of mitigation actions often adds another level of complexity as mitigation activities can rarely remove the targeted pressure altogether.

This section outlines important notions relating to degradation which are most pertinent to inform mitigation strategies, before reviewing current and emerging knowledge of restoration and protection activities.

1. Degradation

Urbanisation introduces new pressures to waterways and sets multiple changes in chain reactions that unfold both spatially and temporally. For example, a new stormwater connection may not immediately threaten a population of fish or platypus, but it causes significant changes to water quality and flow regimes that degrades habitat and may eventually result in the disappearance of a fish or platypus population. Similarly, the impacts are also not limited to the location where the pressure occurs, stormwater inputs changes sedimentation and erosion process for example can spread both downstream and upstream of the discharge.

As outlined in the previous section, conceptual models typically map cause and effects relationships and are thus a useful tool to identify root causes of observed issues.

1.1. Limiting factors

Typically a number of pressures (e.g. stormwater inputs, riparian vegetation removal, disconnection from floodplain) combine to cause changes to the flow and water quality regime that becomes stressors (e.g. hydrologic alteration, pollution, disconnection from floodplain, and change in stream temperature) to the biota.

The concept of limiting factors is critical when assessing waterway management strategies and actions as it leads to not only establishing what actions are required to address pressures but also in what order they should be done to be most effective.

Limiting factors are defined as environmental influences that constrain the productivity of organisms, populations, or communities and thereby prevent them from achieving their full biological potential that could be realized under optimal conditions. Limiting factors can be single elements or a group of related factors.

Establishing the hierarchy of limiting factors to a stream condition allows actions to be planned to maximise the likelihood of success in terms of ecological improvement. For example, in a ‘peri-urban’ context, downstream of a small township where stormwater is conventionally drained and discharged, a waterway may go through some agricultural land where riparian vegetation has been removed. A management strategy needs to consider all the factors limiting waterway health, and address them in order of impacts. Urban stormwater runoff input has been shown to be the most likely limting factor to waterway health where it occurs, so in this case, addressing riparian vegetation alone will not be sufficient to improve ecological. However, once stormwater inputs are addressed, riparian vegetation is likely to become an effective strategy.

While cause and effect relationships are complex and often work in synergy, there are dominant pathways, and the categorization introduced in the first section (see Figure 4, p.12) can be helpful in thinking through dominant cause and effect relationships to identify root causes of dysfunction and the hierarchy of limiting factors to ecological condition.

1.2. Stormwater is the most limiting factor to ecological condition

Whilst other catchment and local-scale processes influence river health, waterways cannot be in good ecological condition where significant urban stormwater inputs are permitted to occur (Fletcher, et al., 2011). In other words, where stormwater is discharged to a stream, the degradation it causes overrides other causes of degradation.

Stormwater is thus the limiting factor to river health in many streams of the Melbourne Water region, and the stormwater drainage network is the primary pathway by which stormwater damages streams (Walsh & Kunapo, 2009; Wenger, et al., 2009).

Accordingly, the level of connection of impervious surfaces to the stormwater system, referred to as directly connected imperviousness (DCI) or attenuated imperviousness (AI), has been established as a measure of stormwater impacts on waterway.

Characterisation of stormwater impact on waterways using Directly Connected Imperviousness: a quantified pressure-condition relationship

A wide range of ecological indicators show a steep decline with even small inputs of urban stormwater runoff as measured by DCI (as summarised by Urrutiaguer et al., 2012, based on the research of waterway degradation drivers).

Decline in macroinvertebrate diversity (and many other ecological indicators) is observed at the lowest levels at which DCI has been confidently measured (<0.5%) with loss of most sensitive species observed in streams with >2-3% DCI (Walsh, et al., 2005; Walsh & Kunapo, 2009; Walsh & Webb, 2013). This steep decline in macroinvertebrate diversity (often indicated by a summary index such as SIGNAL score) is indicative of a severe loss of stream ecological and physical condition.

This trend in ecological condition decline is further supported by observations of ecologically significant changes to streams at similarly small values of DCI:

- Erosion and incision of stream channels that equate to a loss of associated habitat for stream animals and plants and threaten infrastructure such as bridges, paths and buildings (Vietz, et al., 2014). Such incision reduces the capacity of streams and their floodplains to prevent nitrogen from flowing downstream (Groffman, et al., 2003)
- Increases in concentration of many pollutants, both during dry and wet weather (Hatt, et al., 2004). Increases in nutrients such as nitrogen drive increased growth of algal and microbes in streams. The resulting daily oxygen slumps, and increases in toxic substances have direct negative effects on stream animals and plants.
- Increased growth of algae and shifts in algal species composition to those adapted to high nutrient conditions (Taylor, et al., 2004; Newall & Walsh,

2005); and shifts in the species composition of microbial communities that drive important denitrification processes (Perryman, et al., 2011).

- Loss of valued higher stream-dependent animals such as blackfish (Danger & Walsh, 2008) and platypus (Martin, et al., 2014).

The analysis undertaken as part of the predictive modelling described in the previous section builds on this understanding of degradation to further strengthen the conclusion that urban stormwater runoff is an overriding limiting factor to waterway ecological condition.

A recent analysis of macroinvertebrate data collected as part of the MW works monitoring program (Walsh, et al., in preparation)identified several reaches showing substantial declines in LUMAR caused by increased urbanisation in their catchments over the last decade. The three work sites that experienced the greatest growth in attenuated imperviousness (AI) during the study period (Jacksons Creek downstream of Gisborne; Werribee River at Werribee, downstream of Bacchus Marsh and Melton; and Plenty River downstream of Doreen) show a decline in scores as attenuated imperviousness increased to 1-2.5% respectively.

This provides temporal evidence of the degradation occurring with increase of stormwater runoff impacts as indicated by AI. This is an important finding as it supports the relationship between AI and waterway condition that has been established using spatial differentiation as a mean to explain evolution over time.

1.3. Ecological condition and ecological potential

The notion of ecological potential may be useful to establish long-term waterway management strategies. It is used in the European Waterway Framework Directive to specify objectives and can be defined as the best ecological status that can possibly be achieved for a modified waterway. It can be considered as a somewhat subjective concept, but it could be useful to explore possible futures and drive improvement.

For the same rating of poor overall ecological condition, two waterways might be subjected to different pressures, in nature and geographical extent, for which the cost and predicted effectiveness of mitigation measures is not equal.

Assessing strategies to manage emerging and future pressures not only needs to assess current condition, but also the ecological potential of the waterway. In some cases where a waterway is already degraded, the introduction of additional pressures may not result in further lowering of overall ecological condition. It could however significantly lower its ecological potential as the amount and extent of work required for restoration may be greatly increased. This may in effect ‘condemn’ a waterway to remain in poor ecological condition over the long-term. Whichever the decision is, it needs at least to be made consciously as the implications are long lasting. In this context, it is important to consider what future expectations and legislations may be to avoid generating strong public dissatisfaction and/or increasing regulatory compliance costs in the future. In other words, current business as usual drivers may not reflect those in the future and this potential change of circumstances needs to be actively considered and managed for rather than being allowed to arise by default (and without strategies in place to adapt to different future scenarios).

It should also be noted that while the overall condition may not seem to be affected, ecosystem processes that are critical to ecosystem functioning may be further impeded, and the likelihood of ecological restoration less certain.

1.4. Management scales and connectivity

As discussed in section 2.2 in relation to waterway condition assessment, the issue of scale needs careful consideration. Establishing the scale to which condition can be extrapolated based on discrete data points is crucial to deriving meaningful information. Ultimately, this issue of selecting an adequate scale also applies to defining management objectives.

As illustrated in Figure 14 below, a stream ecosystem can be conceptualised as a nested set of habitat subsystems, going from the stream system and its catchment as a whole to microhabitat systems such as the moss on a boulder. The smaller-scale systems develop within constraints set by the larger-scale systems of which they are part of, and stream biotic communities can be viewed as systems organized within this hierarchical habitat template (Frissell, et al., 1986). Consequently, waterway restoration and protection actions need to match the scale of the ecosystem organisation structure and processes impacted.

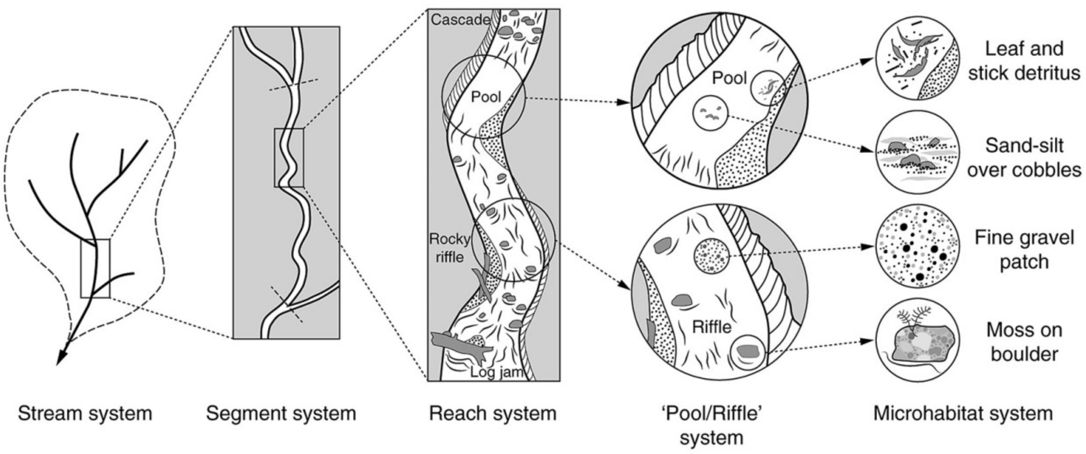

Figure 14. A stream ecosystem can be conceptualised as nested hierarchy of habitat subsystems. Conceptual model of stream habitat organisation developed by Frissell et al. (1986), figure reproduced from Boulton et al. (2014)

This concept of habitat systems also raises the issue of connectivity as the survival and success of a species often depend on its ability to move between habitat patches (Rudnick, et al., 2012). While a segment of waterway may be in good condition and showing a reasonably sized population (of platypus for example), study at the stream system level may reveal connectivity problems that ultimately threaten the survival of the population. Longitudinal barriers (such as culverts or dams) created by urbanisation can result in inaccessibility of critical refuges or feeding patches, inbreeding threatening the long-term viability of the population, or prevention of important re-colonisation processes that would occur naturally and provide resilience to biota. Indeed as summarised by Beesley et al. (2015 in review) the distribution of species across the landscape is not static, distributions expand when conditions are favourable and contract when they are not so that the long-term persistence of a species within a landscape is dependent on the presence of stronghold sites or 'refuges'.

The concept of nesting habitat described above focuses on the longitudinal dimension of streams. This concept also applies to the transversal dimension of stream habitat, and ultimately the two combine at the landscape scale. Transveral connectivity concerns primarily the natural connection of a stream to its riparian area and to its floodplain which both perform important ecosystem functions. Floodplains are vital to the processing of nutrients, and in the regulation of erosive flows. They also provide habitat, refuge, or breeding ground to many aquatic species.

Both transveral and longitudinal connectivity can be disrupted by direct physical modifications such as a culvert, a weir, or channel straightening. It can also occur as a result of the hydrological, geomorphological or water quality changes introduced by urbanisation. For example, a channel may become so incised that the stream can no longer overflow onto its floodplain (or at a much reduced frequency), or decreased baseflows may lower water level to the extent where refuge pools are not accessible. A segment of waterway in bad condition due to very high level of toxicant can also create a barrier separating and isolating populations.

Whilst less obvious, overland terrestrial connectivity is another important aspect of connectivity for freshwater streams as some species, frogs in particular but also platypus do travel overland to access different parts of the stream network or to move from stream habitat to inland habitat.

A concept typically associated with connectivity is that of habitat corridors which can be defined as components of the landscape that facilitate the movement of organisms and processes between areas of intact habitat (Meiklejohn, et al., 2009). The term link or linkage is also used and sometimes preferred to emphasize functionality over structure. Whilst connectivity can be increased by creating or maintaining continuous corridors of habitat, it can also be increased by favourable habitat patterns (Bennett, 2003). The continuity of suitable habitat, the extent and length of gaps, the distance to be traversed, and the presence of alternative pathways or network properties are some of the main habitat patterns characteristics determinant to connectivity.

Connectivity is often discussed and described in relation to biota, it should be noted that connectivity also concern waterways processes such as nutrient cycling or sediment transport. Disconnection between a stream and its floodplain not only create a direct barrier to biota, it also hinders nutrient processing and natural flow attenuation.

The notion of connectivity highlights the importance to manage waterways as open systems connected to their landscape, in the way both pressures and impacts are considered. It provides another lens to analyse the impacts of urbanisation and inform mitigation measures. Practically, connectivity is an important consideration in the review of limiting factors to waterway condition, and in the selection of adequate scales for management objectives and actions. For example, whilst protecting a upper reach of waterway may be successful in the short-term, long-term success of some biotic species and thus potentially of the ecosystem as a whole may be limited by connectivity problems such as physical barriers further downstream, or lack of overland corridor with inland refuges. As highlighted by Taylor et al. (2006), connectivity needs to be considered as one of the many factors that influence the distribution and abundance of a species, and focusing on connectivity should not be done at the detriment of the management of habitat quality and extent.

2. Protection

Scientific evidence suggests that urban growth poses a threat to waterways across the region. We know that if new areas are developed implementing conventional and/or current practices, degradation will occur.

When a new development is built, a number of pressures that cause degradation of ecological condition may be introduced:

- Direct modifications
    - Piping of ephemeral and small streams
    - Permanent removal of riparian vegetation
    - Containment of channel
- Large discharge of sediment from building activities

- Treated wastewater discharge
- Stormwater discharge

To ensure a waterway is protected from degradation (and/or waterway health objectives are met), all these pressures need to be managed. From a perspective of knowledge about mitigation measures, treated wastewater discharge and stormwater discharges are the most complex to address. The other pressures may be difficult or costly to implement in practice but the required actions are quite easily specified.

While the models of Walsh & Webb (2013) do not account for all of these pressures, it clearly shows that urbanisation with the implementation of current stormwater management practices will result in significantly and wide-spread degradation of waterways.

Figure 17 illustrates the conceptual model proposed for assessing the waterway impact of different stormwater management strategies using this macroinvertebrate model.

2.1. Management of stormwater runoff for protection outcomes

Catchment hydrology

We have reasonable evidence that degradation can be prevented by maintaining a natural water quality and flow regime, the main arguments being that:

- Urban stormwater runoff is typically the most limiting factor to the ecological health of waterways, and the stormwater drainage network is the primary pathway by which stormwater damages streams (as detailed earlier).
- We have examples of streams with an urbanised catchment but no formal drainage that are in good condition. In the Melbourne region, the cases of Sassafras and Little Stringybark creeks in the east of Melbourne were used by Walsh et al. (2012) to illustrate this point. These creeks are situated in two neighbouring catchments with similar levels of urbanisation (about 10% of catchment covered by impervious surfaces): in the Sassafras catchment where no formal drainage exist (DCI~1%), the impact of impervious surface is attenuated and the creek is in good condition, whereas in the Little Stringybark catchment, the stream directly receives runoff from impervious surfaces through formal drainage (DCI~8%) and the stream is in poor condition. This illustrates well the importance of the drainage network as the driver of degradation. While these examples have been observed at low level of urbanisation compared to typical greenfield developments, there is conceptually no reason why this could not be replicated at higher densities.

Practically maintaining a natural water quality and flow regime means designing urban development so that most of the rain that falls is retained (through harvesting and/or evapotranspiration) and a small part of it is returned to baseflow (though infiltration or slow release of clean filtered water to the drainage system) as illustrated in Figure 15 below.

As outlined previously, under natural conditions about 80-95% of rainfall is evapotranspired back to the atmosphere and therefore does not enter receiving streams. Consequently, it is necessary to retain large volume of stormwater to match the natural water balance.

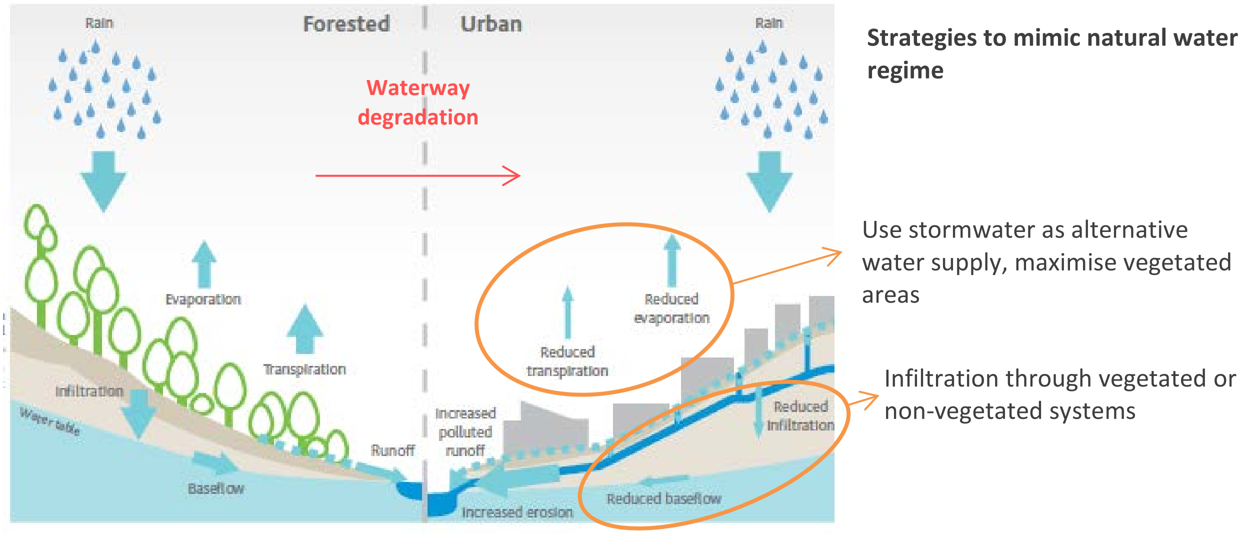

Figure 15. Comparison of the water balances of a forested catchment and an urban catchment (reproduced and adapted from (Melbourne Water, 2013) based on (Walsh, et al., 2004)

Retaining a natural water balance can be challenging in practice, in particular when water demand is low in comparison with the volume of water to retain. Understanding whether key ecological functions and processes could be protected when larger runoff volume than natural are discharged to waterways is thus an important question to address to inform the design of stormwater management strategies for waterway outcomes. Corresponding lines of investigation are shown on Figure 17 as a range of runoff volume reductions.

One of the research projects of the Melbourne Waterway Research Practice partnership between the University of Melbourne and Melbourne Water (Project 2.5) is exploring this question. This research aims in particular to establish what runoff volume reduction is necessary to maintain waterway hydrological and geomorphic characteristics key to their ecological integrity.

The approach adopted in this project is to investigate 2-3 case study catchments with the aim to generalise findings to provide practical guidance for developments in the Melbourne region. The first stage of the project examined the Kororoit Creek, an ephemeral creek in Melbourne's West, whose catchment will see significant urbanisation over the next few decades.

The results of Kororoit Creek catchment modelling (Duncan, et al., 2014) indicate that, at least for ephemeral streams, unless stormwater is managed to preserve the natural water balance, hydrologic and geomorphic characteristics key to ecological processes and functions will not be retained and the waterway will thus be significantly altered if not significantly degraded. In any case, the stream's ephemerality and the particular associated fauna and flora values will be lost.

The following phase of the investigation aims to examine a perennial stream. Whilst part of the Melbourne's water supply system and thus not marked for development, McMahons Creek, a tributary of the Yarra to the east of Warburton, was selected as representative of the hydrologic and physiographic conditions of development in catchments to the east of Melbourne. The higher rainfall experienced in this part of Melbourne will create a larger urban excess, however it was thought it may be possible to somewhat increase stream baseflows with some of the excess water, without significant ecological impacts. In which case, it would potentially be possible to retain the ecologically important hydrologic and geomorphic stream characteristics when applying a lesser reduction of runoff volume (in the range of 60-90%) by designing stormwater treatment so that the remaining ‘excess’ water is appropriately filtered (to ensure suitable water quality) and slowly released as a contribution to baseflow. The modelling however shows that whilst it is possible to maintain some of the metrics at their natural level with lower runoff volume reductions, it is not true for all seven metrics selected as important to the stream's ecological condition. The study shows that maintaining all metrics at their natural level can only be achieved by intercepting practically all the additional runoff generated by urbanisation.

In any case, it is worth noting that not all options meeting a lesser volume reduction will preserve important flow characteristics and would thus degrade waterways, so a lower volume reduction objective would need to be complemented or supplemented by a runoff frequency objective.

Specifying site performance metrics

Building on the understanding of the mechanics of stormwater impacts on waterways, it is recommended (see for example Burns et al., 2012; Walsh et al., 2014) that natural levels of 1) runoff frequency and 2) contribution to baseflows (through infiltration or slow filtered release) are adopted as targets for stormwater treatment performance to achieve for the protection of waterways.

Table 8. Near natural flow regime objectives (Walsh, et al., 2014)

Metric	Definition	Objective
Runoff frequency	Number of days of untreated runoff per year	Maximum of 1, 8 and 12 days for Mildura, Melbourne and Croydon respectively (can be regionalised)
Baseflow contribution	Volume of runoff contributing* to baseflows * Runoff is counted as contributing to baseflows if infiltrated or filtered and released at a maximum rate of 0.038, 0.028, 0.018 mm/h** for Mildura, Melbourne West and Melbourne East respectively	Baseflow contribution volume (as % of annual rainfall) within the following range: 1-2% for Mildura, 8-24% for Melbourne, and 15-36% for Croydon (can be regionalised)

** These values are intended to approximate high levels of baseflow in streams typical of each region. For Croydon, the target value equalled three times the median flow in nearby Olinda Creek (a primarily forested catchment).

For Melbourne and Mildura, this value was scaled to account for their lower rainfall. The objectives outlined in the table were established Mildura, Melbourne and Croydon rainfall to cover a range of rainfall representative of urban areas of Victoria.

These objectives a) limit how often untreated runoff flows directly to the stream, and b) restore lost baseflows with appropriate volumes of clean filtered water.

While at first glance these objectives may seem to only focus on flow, it should be noted that water quality objectives are integrated in their formulation by specifying the quality of the flows controlled (untreated, filtered). These objectives thus focus on both flow and water quality.

These are site-scale objectives that apply at the scale of the largest catchment or development area upstream of any waterway, i.e. before drainage pipe discharges to a receiving water. This includes natural drainage lines as they are small ephemeral streams. It is important as these small streams, sometimes referred to as headwaters, zero order or first order streams have their own ecological values and collectively have a higher biodiversity than all of the larger streams combined (Finn, et al., 2011).They also have an important role in retaining and treating runoff (Meyer and Wallace 2001; Doyle and Bernhardt 2011).

To make modelling easier, flow volume reduction is often used instead of flow frequency. The review of the current Best Practice Environment Management (BPEM), for example, proposed to use Total Runoff Volume (TRV) reduction together with a baseflow contribution objective, a geomorphic objective and water quality objectives.

Volume reduction has the advantage of being simple from a modelling perspective, easy to understand and easy to relate to water balance modelling. However, it is not a perfect surrogate as it not as directly linked to the ecological benefits (Walsh, et al., 2014) and using runoff frequency objectives provide a higher level of confidence in ecological outcomes than volume reduction objectives (and it can also be modelled in MUSIC).

Volume reduction is necessary to achieving waterway outcomes, but it is not sufficient as it does not address the way in which waterway are adversely impacted by stormwater runoff (that is frequent discharge of untreated runoff) when managed with a traditional drainage approach.

Fate of infiltrated water, a key knowledge gap

In natural conditions, most of the rainfall that is not evapotranspired is infiltrated, it seeps through the ground eventually reaching the saturated or phreatic groundwater zone (deep recharge) or may also move horizontally under the surface in the unsaturated or vadose zone (interflows). The resulting groundwater moves by gravity or pressure towards towards its discharge point, emerging to the surface as springs or baseflows (and interflows) to rivers, wetlands and other surface water bodies. Sub-surface flow paths range from less than a metre to thousands of kilometres, and travel time underground varies greatly depending on geological characteristics, but also climate, landform and vegetation, it may take a few weeks, to hundreds or even thousands of years (Boulton, et al., 2014; Crosbie, et al., 2010). The Port Phillip and Western Port Atlas (Southern Rural Water, July 2014) provides a good overview on groundwater in the Port Philip and Western Port region, covering on local characteristics as well as current management practices and issues.

As one of the key objectives identified for waterway protection outcomes is to mimic this natural process of recharging groundwater through infiltration of stormwater to maintain natural levels of baseflows, it is important to understand how stormwater control measures can achieve it. The resulting hydrology of stormwater control measures can be assessed using rainfall-runoff models such as MUSIC. Water entering a treatment system will evapotranspire, be directed to the stormwater drainage system (overflow or release after filtering), or be infiltrated. This water balance may appear fairly simple but has been shown to be quite problematic (Hamel, et al., 2013).

The main modelling uncertainty around this concerns the fate of infiltrated water from stormwater control measures, as illustrated in Figure 16, both individually and combined at the catchment level (effect may not be directly scalable).

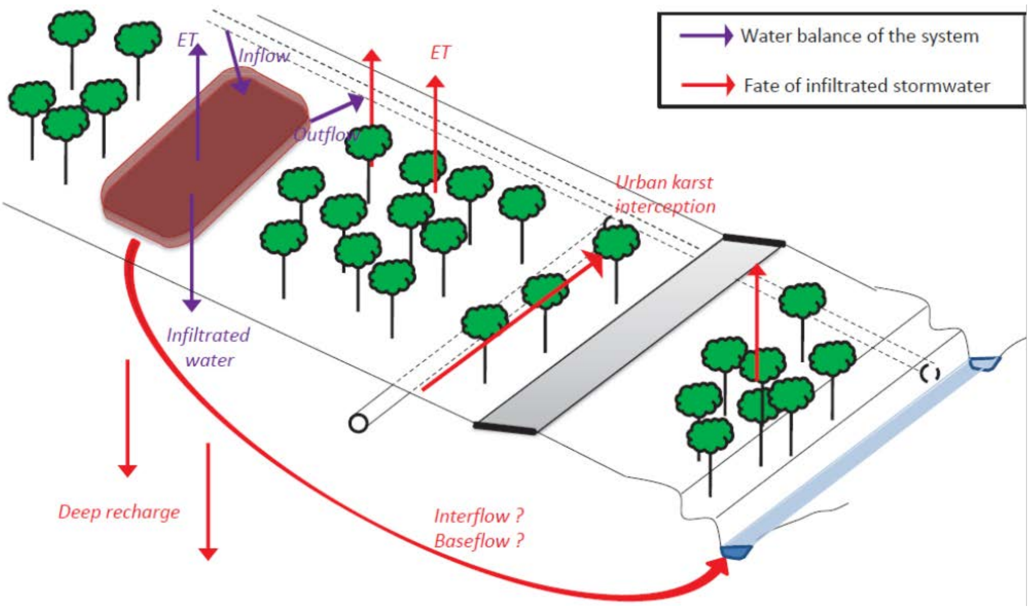

Figure 16. Pathways and fluxes for a vegetated infiltration system. Provided by Jeremie Bonneau as presented by Fletcher et al. (2015).

One key element of the current research on stormwater infiltration is the extensive investigation being conducted on a large infiltration biofilter in the Dobsons Creek catchment (Wicks Reserve). Early results show some unexpected behaviours that may be related to what is sometimes referred to as the 'urban karst' in the literature. This means that the underground infrastructure that services our cities acts as a karst or underground drainage network that complicate our ability to predict the fate of infiltrated water.

In the absence of more information, modelling studies have arbitrarily assumed a set proportion of the infiltrated water is recharging baseflows. Confidence in the results will be greatly improved by more knowledge in this area. This is one the research questions the Melbourne Water research partnership is focusing on.

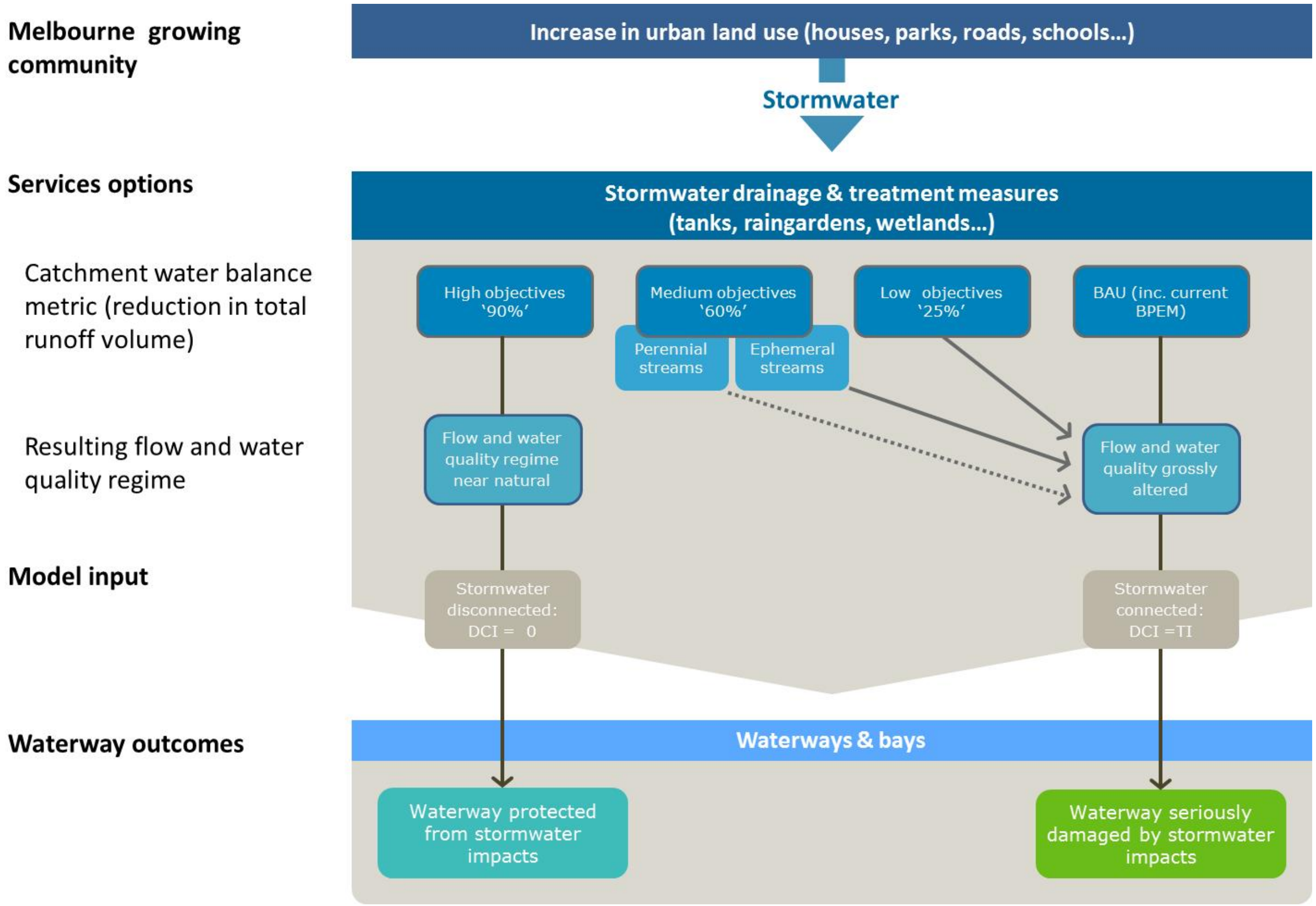

Figure 17. Conceptual framework of the outcomes of a range of stormwater strategies based on current knowledge.
This diagram shows the range of objectives considered in planning and policy investigations (for feasibility) and in research (to assess outcomes) as described above. The '90%' high objectives represent the replication of the natural water balance, the exact numerical value of the corresponding runoff reduction will vary depending on the location and development imperviousness (see p.47-48), it is about 90% for typical developments new developments in the West.

3. Restoration

There are more uncertainties in restoration than in protection, as removal of a disturbance does not necessarily mean the system can recover, and if it does, it is generally not clear to what degree and over what time period it would.

Degradation trajectories are typically non-linear, so it is highly unlikely that restoration trajectories will be linear.

While this section does not cover practical feasibility, it is worth highlighting that mitigating actions such as installation of stormwater control measures or revegetation are also more expensive and difficult in practice when done as retrofit works for restoration than when done when building a new development.

3.1. Balancing short-term and long-term outcomes

While it would be most effective to first address root causes of degradation for waterway condition outcomes, it may not always be feasible (due to practical or financial constraints) and it may take a very long time. This case is unfortunately quite common in very urbanised areas and poses the question of the value of investing in mitigating actions when root causes are not addressed. On the one hand, investing in these actions will be undermined by the unaddressed issue and as such can be considered as an ineffective use of resources. On the other hand, it could be argued that these actions are much needed to retain remaining ecological potential and amenity value, or even because inaction is unacceptable, especially since societal expectations and willingness to pay may change in the future allowing more investment to be made. In any case, this means that the investment plans for waterway management need to carefully consider both short-term and long-term outcomes and set corresponding objectives.

Restoration objectives may focus on reduction of a pressure (e.g. disconnection of impervious surfaces with urban renewal), removing a stressor (e.g. improving water quality), recovery of an individual species, linking isolated populations of the same species (e.g. platypus), recovery of environmental condition / functions and processes (e.g. tree revegetation for shading).

There can be significant lags in observing impacts on biota. Isolation of a species population is a good example of this; i.e., introduction of a physical barrier or severe degradation of a reach of waterways may isolate populations previously connected and make them too small for survival.

3.2. Management of riparian areas

In general terms, the riparian zone is the terrestrial area adjacent to the stream, it is influenced by the water in the stream and (or) has an influence on the aquatic system (Richardson & Moore, 2010). The physical boundaries defining the riparian area are somewhat blurry, as it is a transitional area providing a dynamic interface between the dry and the wet ecosystems.

Naturally vegetated riparian areas have important functions in supporting ecological integrity, such as filtration of water and regulation of energy fluxes through shading in particular. They also provide refuge, breeding, nursery and feeding habitat, and corridors for movement to many aquatic and terrestrial organisms. This is particularly important in the urban landscape where most of the natural vegetation and therefore most of the natural habitat has been removed and the remaining habitat is highly disconnected, and it may become even more critical with climate change (Capon, et al., 2013).

As shown in Figure 15, various elements and processes link waterways and riparian areas. As such, from a management perspective, they are typically considered together. Quality of riparian area vegetation is often used as a key indicator of waterway condition

Because riparian areas are transitional zones between the stream and its catchment, they can be considered as both a catchment influence and an intrinsic part of the waterway, as well as a natural asset with its own value.

This distinction is important in the development and evaluation of waterway strategies, especially in terms of being clear about outcomes and managing expectations. For example, improving riparian vegetation on a stream reach impacted by stormwater will not be effective in restoring instream ecological condition but, depending on the other pressures at play, may be effective in meeting other objectives such as improved amenity, or habitat refuge of targeted species (e.g. birds, frogs).

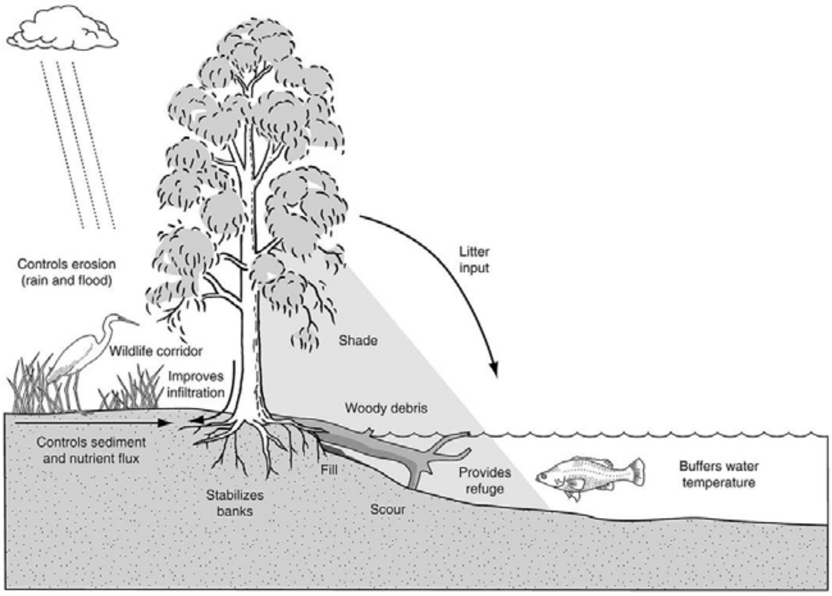

Figure 18: Elements and processes that link streams and riparian areas. Reproduced from Boulton et al. (2014; figure 10.8).

A recent analysis of trends in macroinvertebrates waterway condition data collected as part of the ISC monitoring program of MW works has provided some very useful insights into riparian vegetation management as it shows (Walsh, et al., in preparation):

- A substantial increase in the macroinvertebrate assemblage composition indices LUMAR (in development) in the few reaches that had enough upstream reafforestation (revegetation with trees) to substantially increase their attenuated forest cover (AF; increase by about 10% which typically requires forested buffers at least 20 m wide and expanding about 1km upstream), and
- No detectable effect on LUMAR from other management activities (primarily weed control and willow removal) without associated revegetation.

The relatively rapid (under 10 year) recovery response observed is encouraging as it shows that the restoration of macroinvertebrate fauna and the ecological condition that it indicates follows a restoration trajectory that is not greatly different from the degradation trajectory.

While this is very important evidence, the analysis would be strengthened by including more site(s) with high levels of revegetation. While only a small number of project sites have undergone revegetation extensive enough to see results, a few additional sites (e.g. reaches along the Tarago River) will be included once the post revegetation data is collected.

3.3. Catchment scale stormwater restoration experiments

The Little Stringybark Creek (LSC) and Dobsons Creek catchment initiatives both aim to restore the ecological condition of their local stream through the implementation of stormwater management systems that 'disconnect' the catchment impervious surfaces from the creek by treating, harvesting, infiltrating and evapo-transpiring stormwater runoff.

The Little Stringybark Creek initiative has been delivered by a research program in partnership between Melbourne University, Melbourne Water, Yarra Ranges Council and Monash University (Dept. of Civil Engineering and through the CRC for Water Sensitive Cities). The engagement of residents in the project has been led by Melbourne University. While implementation is not the focus of this document, it is worth highlighting that long-term partnership between institutions and community participation are essential components to a successful delivery (as detailed in Prosser et al., 2015; and Bos & Brown, 2015).

The Dobsons Creek initiative is a partnership between Melbourne Water, Knox City Council and Melbourne University. It has been delivered as an implementation pilot for Melbourne Water and accordingly the engagement of the residents has been led by Melbourne Water. While testing the ecology restoration remains a strong component of the project, the development of implementation model(s) for works required at the house scale is also an important component of it.

The Little Stringybark Creek catchment is situated in Mt Evelyn and covers about 420ha with about 740 properties draining to the stormwater system. At the start of the pilot, the total imperviousness was about 13% and the attenuated imperviousness about 9%.

In September 2015, nearly 300 stormwater control measures had been installed in the catchment on both private and public land treating a total of about 14ha of impervious area. This includes the provision of about 30ML/yr of alternative water supply (about half in private properties and half in public spaces).

Further work is being implemented and due for completion by mid-2016 to further reduce attenuated imperviousness (AI) down to a level where it is hypothesised restoration can occur.

Monitoring is set up on the main stem, as well as on the three main tributaries, as detailed in Table 9.

Table 9: Summary of monitoring sites

Monitoring sampling point	Catchment area (ha)	AI before (%)	Impervious area treated (ha) – Sept 15	Resulting AI – Sept 15
Whole catchment / Main stem				
Main sampling site	423 ha	9.40	14	6.0
Sub catchments / Tributaries				
Southern Tributary	95 ha	11.8	4.5	7.1
Northern Tributary	150 ha	5.8	3.5	3.4
Middle tributary	83 ha	21.6	3.6	17.2

A range of waterway condition indicators have been monitored with the aim of assessing whether a response to the works can be observed. The main stem has been intermittently sampled since 2001 with continuous data since 2009. Monitoring of the tributaries started in 2009. Table 10 provides a summary of the monitoring undertaken.

Table 10: Summary of the monitoring undertaken

	Indicators measured	Frequency
Hydrology	• Discharge (6 min)	Monthly
Water Quality	• Total & dissolved nutrients • Total suspended solids • Temperature • Electrical conductivity • Dissolved oxygen • pH	Events: (12-24/year) Regular: Fortnightly – Monthly
Biota and ecosystem structure and processes	• Macroinvertebrate community composition • Epilithic diatom community composition • Benthic algal biomass • Coarse particulate organic matter breakdown	Bi-annual

To ensure a robust analysis, the study also includes monitoring of two urban control streams (Brushy Creek and Ferny Creek) and three non-urban reference streams (Lyrebird Creek, Olinda Creek and Sassafrass Creek).

Recent analysis of water quality data shows a positive response to catchment intervention with a decrease observed for a range of variable (primarily in particulate nutrient) as summarised in Table 11 (Imberger, et al., November 2015). Key water quality graphs are shown in Appendix 3.

It is concluded that the water quality response observed can be clearly attributed to the stormwater control measures implemented in the catchment. It also highlights that a range of mechanisms could be responsible for this response. Increase of nutrient removal due to filtering and treatment by biofilters, groundwater dilution due to the increased infiltration from the biofilters, and increase in-stream processing due to an increase in macrophytes abundance, are all plausible possible explanations.

Imberger et al. (November 2015) indicated that this latter mechanism seems to be supported by the analysis of Total Phosphorus for the tributaries as it shows a greater decrease in concentration at the downstream catchment scale monitoring site than predicted by the sum of contributions from the three tributaries.

Similarly, a preliminary analysis of the hydrological data recently concluded that the stormwater control measures implemented in the catchment have reduced the size and frequency of polluted storm flows (Burns, et al., November 2015). The analysis identifies a decreasing trend in rainfall-runoff coefficient (see Figure 19) and attributes it to the effect of increased stormwater runoff storage in the catchment.

Table 11. Summary of water quality trends observed (↘ decrease / Ø no change / – not assessed)

Indicator	Baseflows	Events
TSS (Total Suspended Solids)	↘	↘
TN (Total Nitrogen)	↘	↘
TP (Total Phosphorus)	↘	↘
FRP (Filterable Reactive Phosphorus)	Ø	↘
NOx (Nitrogen Oxides)	↘	Ø
NH3 (Ammonia)	↘	Ø
EC (Electric Conductivity)	Ø	-
Temperature	Ø	-
pH	Ø	-
DO (Dissolved Oxygen)	Ø	-

Further analysis is currently being undertaken to assess the evolution of other flow metrics.

No change has been yet detected in the biota and ecosystem structure and processes indicators monitored. It is perhaps not that surprising at this stage as this water quality improvement trend is very recent and a lag in response between environmental condition and biological responses can be reasonably expected. Alternatively, other factors may be acting as limiters to improvement, such as a lack of recruitment, or changes to the channel form. Monitoring over the coming years will be critical to assessing this and providing guidance on whether instream works are then required to follow the mitigation of the catchment-scale impacts.

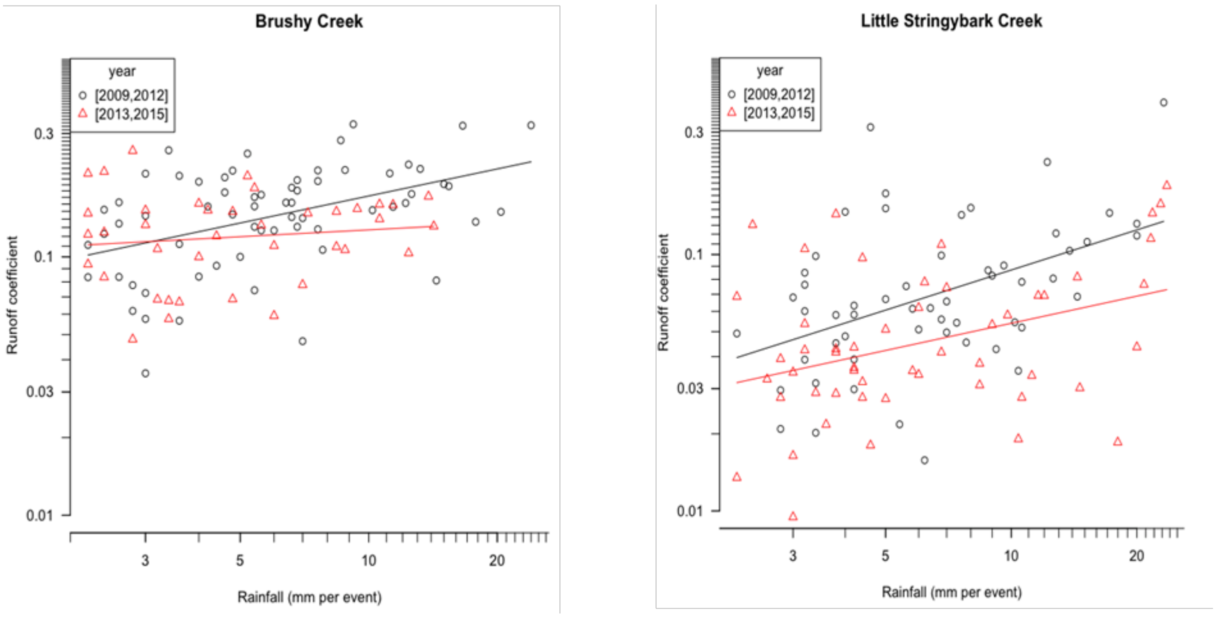

Figure 19. Rainfall–runoff coefficient for events for two periods representing before and after significant works implementation. At Brushy Creek (where no intervention works were undertaken), no change is detectable, while at Little Stringybark Creek (where some 300 stormwater control measures were constructed), the runoff coefficient has declined significantly. Reproduced from Burns et al. (November 2015).

3.4. Water quality issues

The management of water quality impact can be both done for restoration or protection outcomes. It is discussed in the restoration section of this document as it is a problem most prominent in established urban areas.

Whilst addressing water quality without addressing stormwater input as underlying drivers to degradation and limiting factor to ecological condition may not allow waterway restoration, it does not need to preclude actions targeting water quality specifically for various reasons. For example, water quality may have local and acute toxic impacts that are not tolerable, or there may be legislative requirements to meet specific pollutant concentrations targets for both ecological and public health purposes. Also, waterway condition may be improved, at least locally, through targeted management of pollution discharges. The improvement observed following work to increase water quality in some large heavily modified waterway such as the Thames, or closer to home the Yarra, is encouraging.

As described in the first section of this document, urbanisation result in an increase of pollutant discharge to waterways due to a combination of an increase generation of pollutant and an increase mobilisation and transport processes.

The term diffuse is often used to describe pollutants depositing on hard surfaces (e.g. nutrient from atmospheric deposition, hydrocarbons from road traffic) and picked by stormwater, in contrast with point source pollution. Diffuse refers to a widespread source and effects of pollution, where point source refers to a single and identifiable source of pollution. The terminology of hot spots is often associated with point source pollution to indicate a particularly high concentration of pollutants in the receiving environment.

Another categorisation of pollutant sources may help to differentiate the sources of pressure and guide action:

- Active direct discharge - where pollutants are knowingly and wilfully (or at least with a lack of due diligence) discharged to stormwater drains/receiving waters

(e.g. illegal industrial discharges, tipping of toxic substances to stormwater drains)

- Negligent discharge/passive diffuse - where infrastructure directly connects polluted flows to drains or receiving waters (stormwater runoff, but also sewer cross-connections, and contaminated groundwater)
- Active diffuse - where poor management practices result in elevated levels of pollution in runoff (lack of sediment control on building sites, lack of adequate stormwater runoff management measures on industrial sites)
- Legacy - where historic land use results in the pollution of drains and or receiving waters

Locating key sources of pollution is often the first step of pollution management programs. It is practically challenging and costly to undertake extensive monitoring and investigation to characterise and identify pollution sources, and it only suits a reactive or spatially targeted management of pollution. It would be thus useful to be able to relate pollutant concentrations to known catchment characteristics and numerous studies have tried to do so. Unfortunately using land use classifications as a predictor of pollutant concentrations has not been conclusive to date as the variation in pollutant concentrations observed between land use classes and within the same land use class is similar (Fletcher, et al., 2013).

It seems reasonable to expect a higher probability of finding high pollutant concentration in the runoff discharged downstream of an industrial area. However very different activities will occur within the same industrial land use class, and the standards of pollution and runoff control will also vary considerably. So it is perhaps not that surprising that land use alone hasn't been successfully established as a predictor of pollution. Other approaches have aimed to identify particularly polluting industries, for example the Compliance Strategy of the Victorian Environment Protection Authority recently prioritised the electroplating industry because of the environmental risks posed by the heavy metals and chemicals used, which can cause long term damage to aquatic ecosystem if released, even in very small amounts.

Analysis of land use and activities, combined with a review of long-term monitoring data trends may be used to identify high risk areas. In most cases, a monitoring investigation will be required to characterise the impacts of the pollution or identify its source.

While immediate death of aquatic life is the most drastic and clearest impact of pollution that can be observed, non-lethal impacts can also be very severe but are more complex to assess and not always well understood.

In a toxicity study, the end-point refers to the biological effect observed in the test conducted. Mortality, the most common test end-point, is measured to assess acute toxicity, typically measuring LC_{50}, the lethal concentration that kills 50% of test organisms in a given time. Biological end-points measured in chronic toxicity tests can be subdivided into three groups:

- Functions of life (include mortality, reproductive impairment, hatchability, immobilisation and inhibition of growth)
- Behavioural (include mobility, motility, burial rate, ventilation rates, swimming rate, responses to light and feeding rate)
- Biochemical (include inhibition of bioluminescence, induction and activity of a range of enzymes, changes in DNA and immune system dysfunction)

The approach adopted in the development of the ANZECC guidelines has been to only include toxicity data that measured 1) survival (including survival behaviour and immobilisation), 2) growth and 3) reproduction on the basis of these biological endpoints having the highest and most direct relevance for ecosystems (ANZECC, 2000).

The words acute and chronic are commonly used in toxicology, and can be slightly confusing as they can refer to both the nature of the exposure and of the impact of the toxicant studied. When relating to toxicity tests (as in paragraph above), it refers to the duration of exposure.

Detailed investigations are typically required to track the source of pollution, and to assess impacts on ecological condition. Monitoring and sampling methods critical to detecting aquatic pollution was traditionally based on chemistry analysis, it now includes biota analysis (ecological biomonitors, bioassays, mesocosm).

Bioassay is defined as the determination of the biological activity or potency of a substance by testing its effect on the growth of an organism. In the context of waterway ecology, it is used to assess the toxicity of pollutants of interest, and in particular to better understand the impacts of pollutants at sub-lethal levels.

It can be done 'in-situ', typically by placing a cage/net containing aquatic organisms in a waterway or drain of concern, or 'ex-situ' by taking water and/or sediments sampled in the location of concern to the lab and exposing aquatic organisms to it. In both cases, the aquatic organisms selected are closely monitored to assess their evolution in the altered environment.

4. Informing waterway management strategies

Overall we have a reasonable understanding of the impacts of urbanisation on waterways and of how to address them. There are degradation pathways and impacts common to all waterways in urbanised catchments that have been shown to be statistically significant.

While this paper may appear strongly focused on stormwater, it reflects the understanding that stormwater generally is the limiting factor to waterway condition in that waterways cannot be in good ecological condition where significant stormwater inputs occur.

This does not mean that a waterway will be in good condition once stormwater inputs are limited, other pressures such as water extraction upstream or point-source pollution inputs may limit waterway condition. This means that planning for restoration need to consider the multiple pressures influencing waterway condition.

It does mean however that urbanisation without effective mitigation of stormwater impacts will result in either direct waterway degradation or least significant decrease in any restoration potential. For example, in a greenfield development, a waterway may already be in degraded condition due to agricultural or water extraction impacts that could be addressed in the future. Unmitigated urbanisation will add a significant impact that will limit waterway condition.

In essence, general trends and analysis eclipse small local differences. They are useful to define bounds and high-level priorities for action. Local investigations are often needed in complement to refine both outcomes and solutions.

Cost, time and specificity demands of developing strategies need to be balanced to optimise the decision-making process in the knowledge that decisions are inevitably made with incomplete information. Addressing some of the remaining knowledge gaps or acquiring high levels of specificity in analysis may require an amount of time and resources that is not compatible with the timeframes of decision-making or of the issues to address. This is a question that is highly relevant in the case of greenfield developments in rapidly growing cities such as Melbourne.

Making an informed decision means that knowledge of the issue, implications and consequences of available options are carefully considered. It is crucial to consider the implications of both doing X and not doing X.

The precautionary principle is put forward in the State Environment Protection Policy as an underpinning policy principle, stating that:

(a) If there are threats of serious or irreversible environmental damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation.

(b) Decision making should be guided by-

    (i) A careful evaluation to avoid serious or irreversible damage to the environment wherever practicable; and

    (ii) An assessment of the risk-weighted consequences of various options

It can be argued that not taking action or making informed decisions as an issue unfolds is a decision 'de facto' for which responsibility will have to be assumed.

Appendix 1: Examples of conceptual models

Examples of conceptual models can be found at:

- http://www3.epa.gov/caddis/ssr_met_int.html
- http://healthywaterways.org/resources/documents/
- http://www.ozcoasts.gov.au/conceptual_mods/processes/nutrient.jsp

An example focused on hydrology as a major stressor

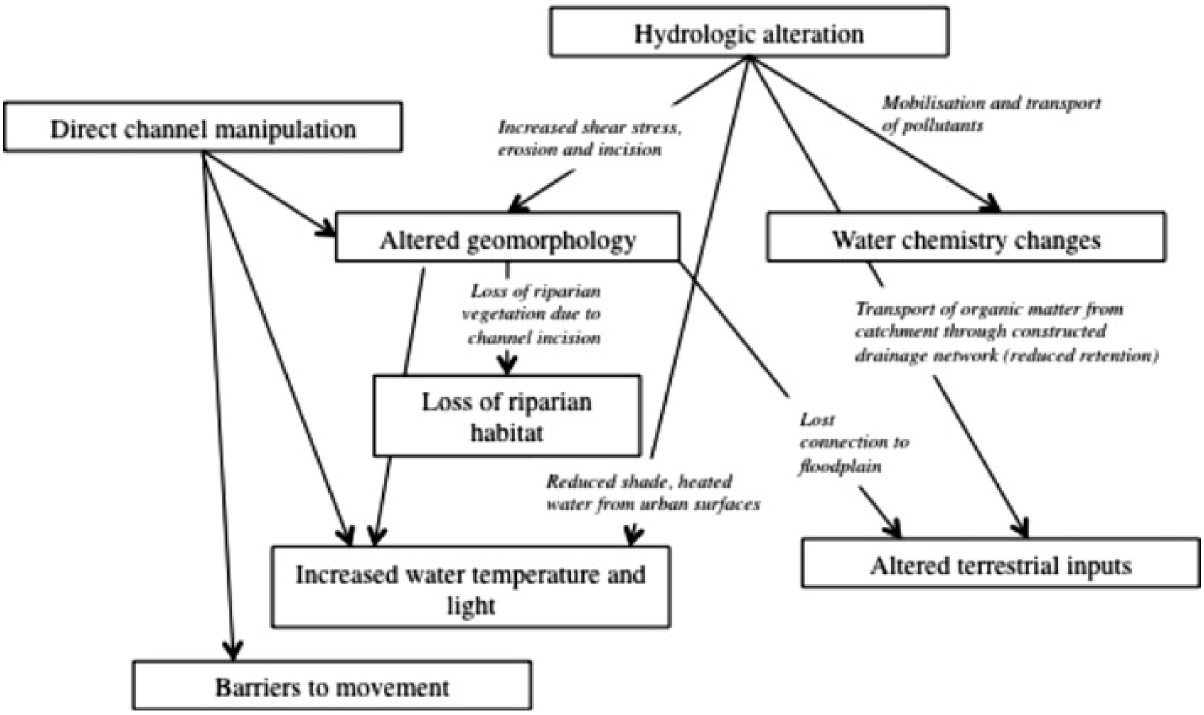

Figure 20. Reproduced from Fletcher et al. (2013). Illustration of some of the principal mechanisms by which urbanisation degrades aquatic ecosystems. The principal 'symptoms' of urbanisation Wenger et al. (2009) are presented in the boxes, the role of hydrology as a 'master variable' is illustrated with examples in italics to show the relationship between symptoms.

An example summarising how human actions disrupt the chemical, physical, and biological processes that influence stream biota.

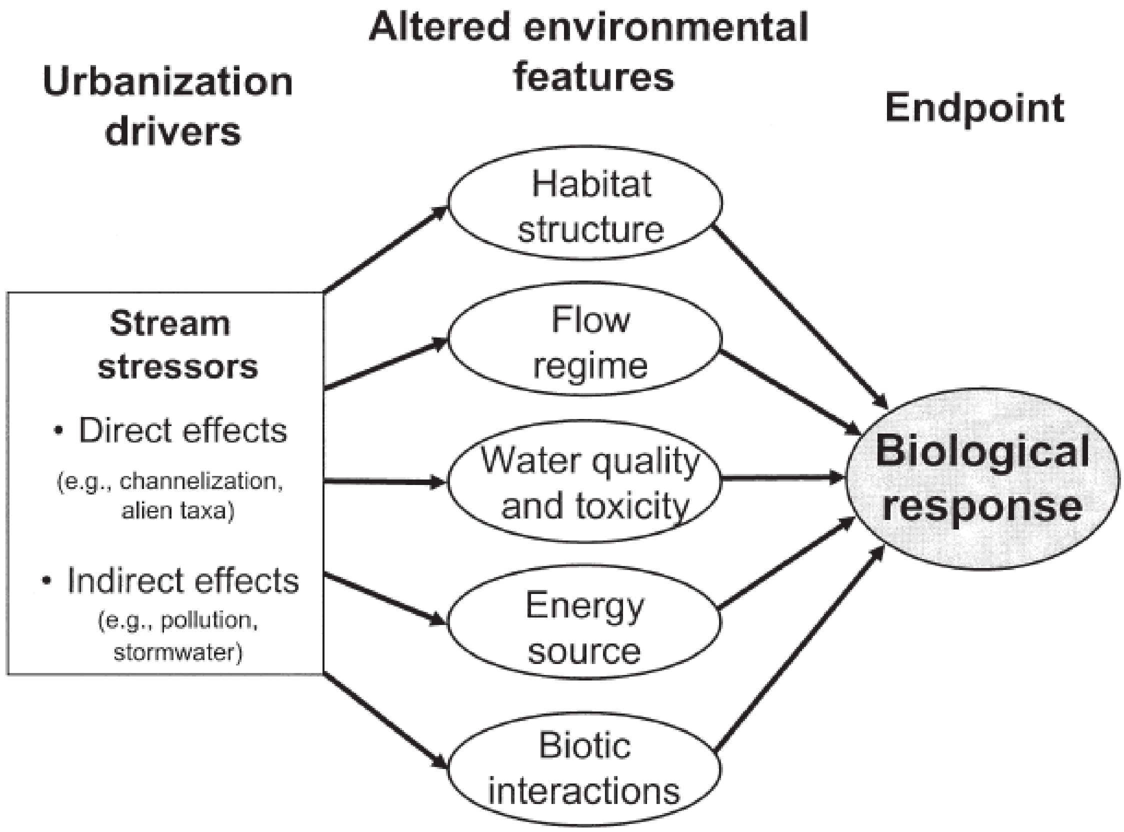

FIG. 1. Five environmental features that are affected by urban development and, in turn, affect biological conditions in urban streams (from Booth et al. 2004, reprinted with permission of the American Water Resources Association; modified from Karr 1991, Karr and Yoder 2004).

Figure 21. Perspectives on stream restoration. Reproduced from Booth (2005).

An example detailing the chain of effects of metals on waterway ecological condition.

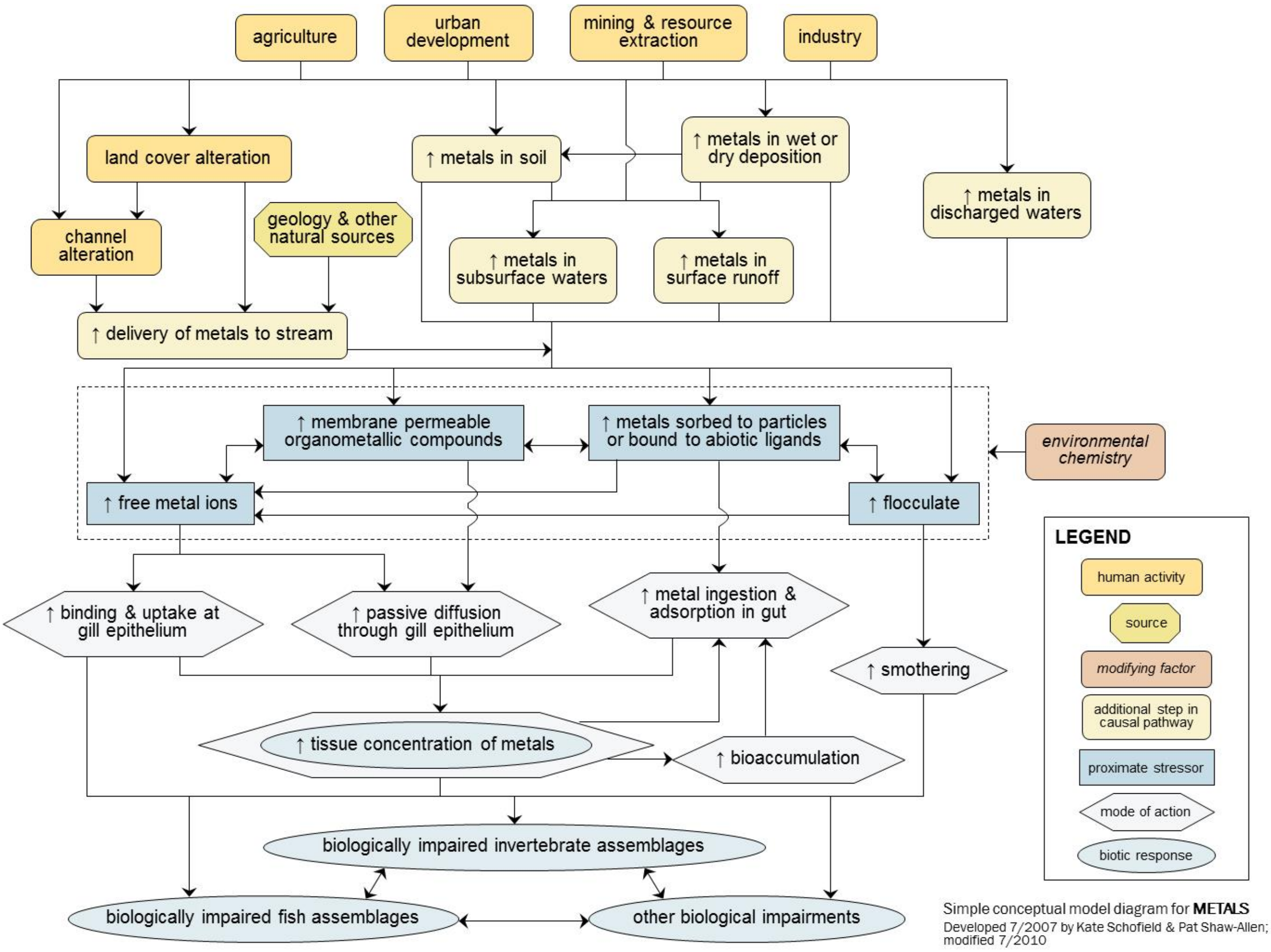

Figure 22. Conceptual model of the biotic impacts of metals. Reproduced from US EPA website CADDIS (http://www3.epa.gov/caddis/ssr_met4s.html).

Appendix 2: Melbourne University predictive modelling variables

Input Variables Tested				
Land use – human disturbance	**Land clearance**	**forest cover**	% forest cover of catchment, and a range of weighted variations	indicator of cleared land used for agriculture
		agricultural land cover	agricultural land type	indicator of cleared land used for agriculture Multiple agricultural classes didn't provide stronger prediction than a single class of cleared land
	Urbanisation	**impervious cover**	% impervious cover of catchment, and attenuated imperviousness	indicator of urbanisation
Stream typology – natural variation	**Physiographic variation** – likely to explain some variation of results between sites through effects on water chemistry and hydrology	**Elevation**	elevation	surrogate indicator for temperature change
		catchment area	catchment area	indicator of stream size, criteria for determining threshold of stream formation
		catchment geology (substrate type)	% of catchment area underlain by igneous rock (catign)	indicator of inorganic chemistry of stream waters (shown to be a good predictor of electrical conductivity across the region)
		mean annual discharge	estimate of mean annual discharge in the absence of human impacts	indicator of flow regime type (differentiating in particular drier western and lowland areas from wetter eastern and upland areas)
	Temporal hydrologic variation – likely to explain some variations of results between samples at the same site through effects on hydrology	**antecedent flow**	estimate of antecedent flow in the absence of human impacts, with a range of weighted variations	indicator of flow regime conditions (known to be an important driver of biotic structures and functions)

Appendix 3: Water quality graphs LSC

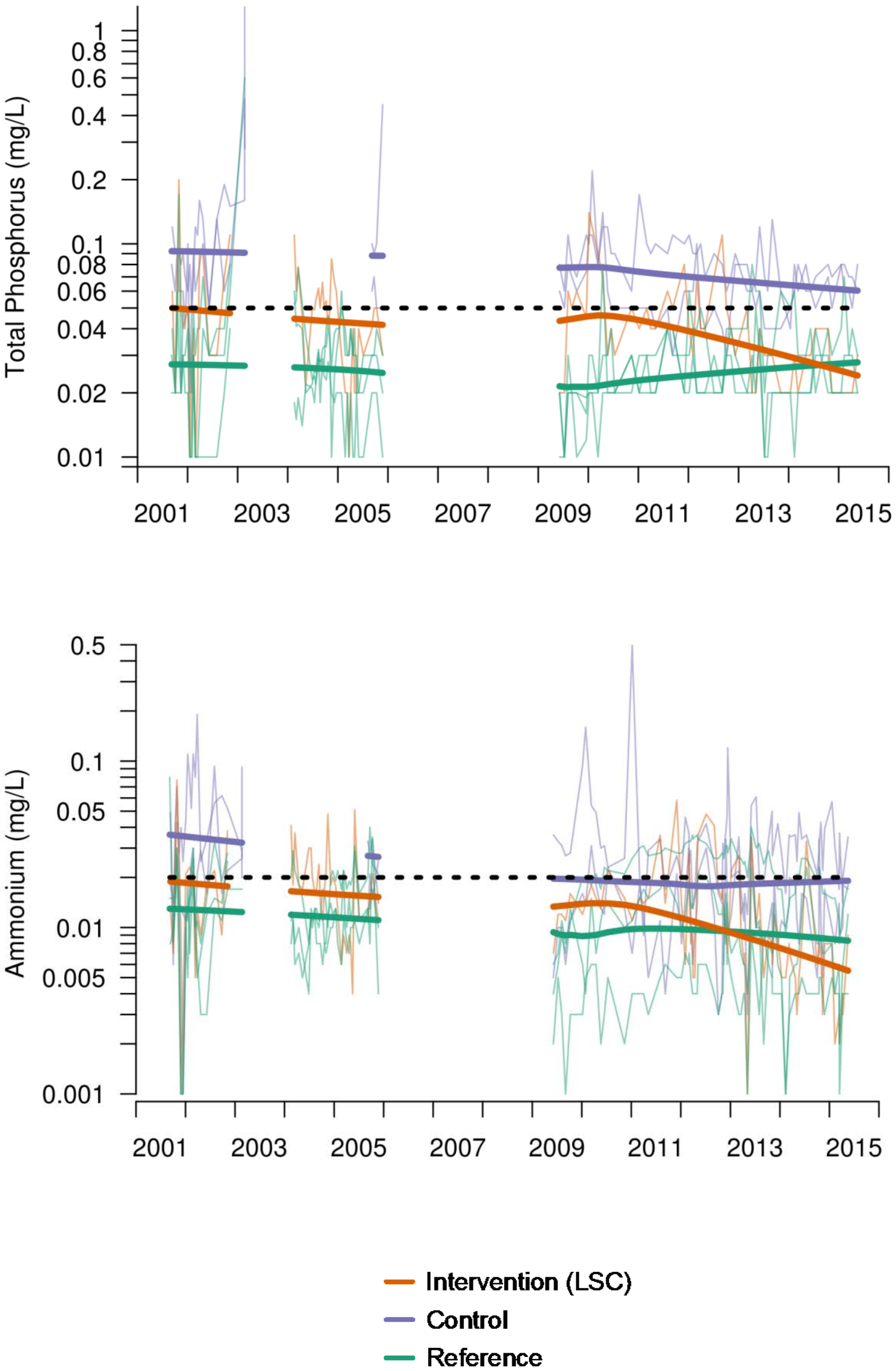

Figure 23. Evolution of concentrations in Total Phosphorus and Ammonium concentration between 2001 and 2015. Reproduced from Imberger et al. (November 2015)

Appendix 4: Melbourne predictive modelling maps

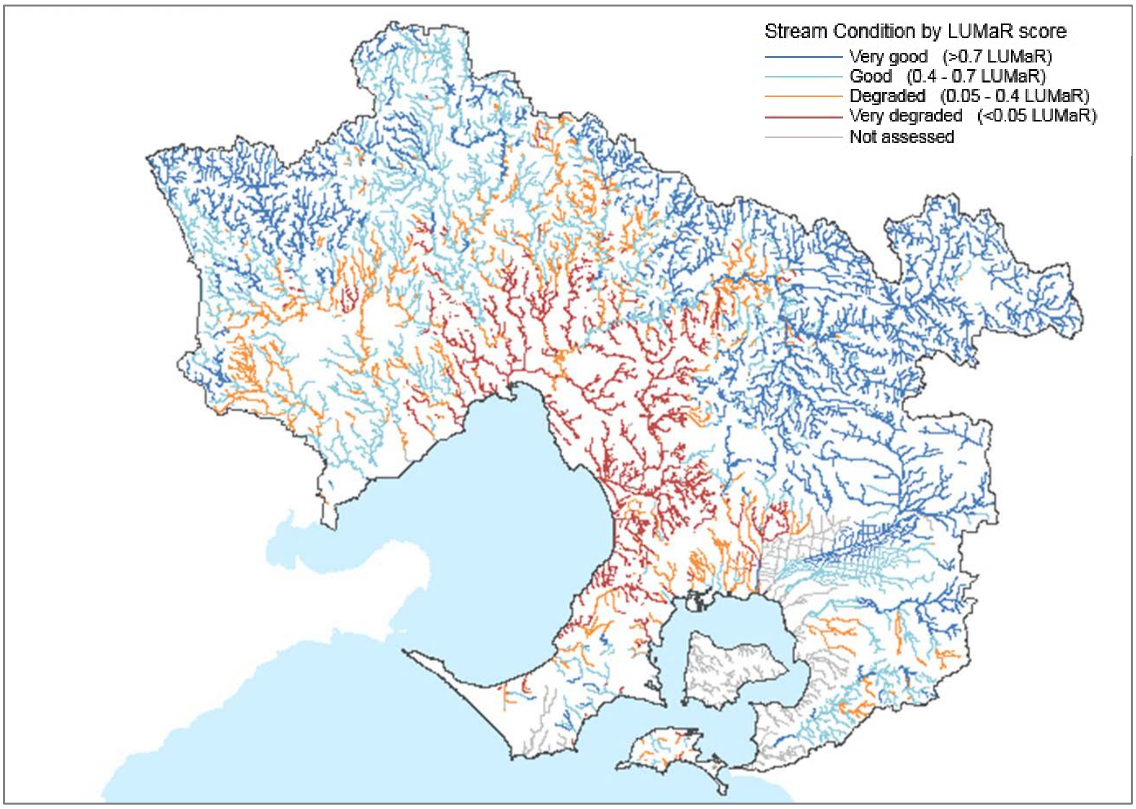

Figure 24. Map showing 'present' predicted stream condition for the Melbourne region, as indicated by the macroinvertebrate assemblage composition index LUMAR (based on 2006 aerial imagery). Scenario A) in Table 7.

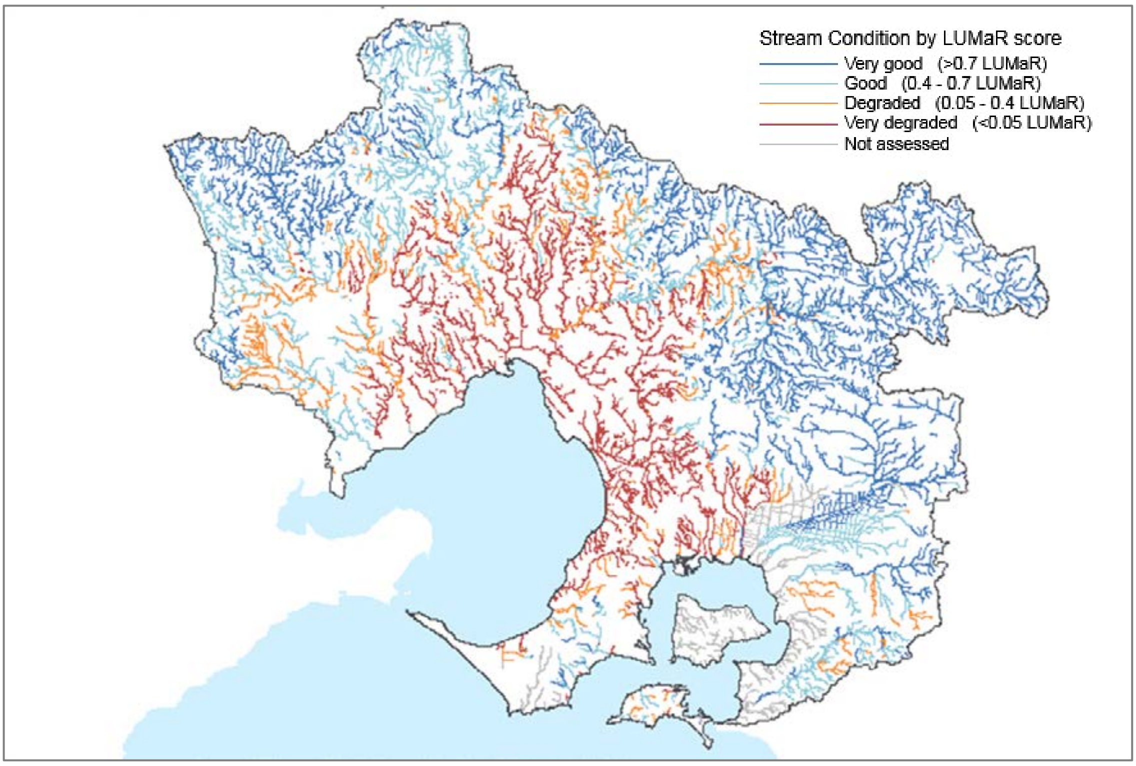

Figure 25. Map showing future predicted stream condition for the Melbourne region, as indicated by the macroinvertebrate assemblage composition index LUMAR, at 2030 with continuation of current stormwater practices in new developments. Scenario C) in Table 7.

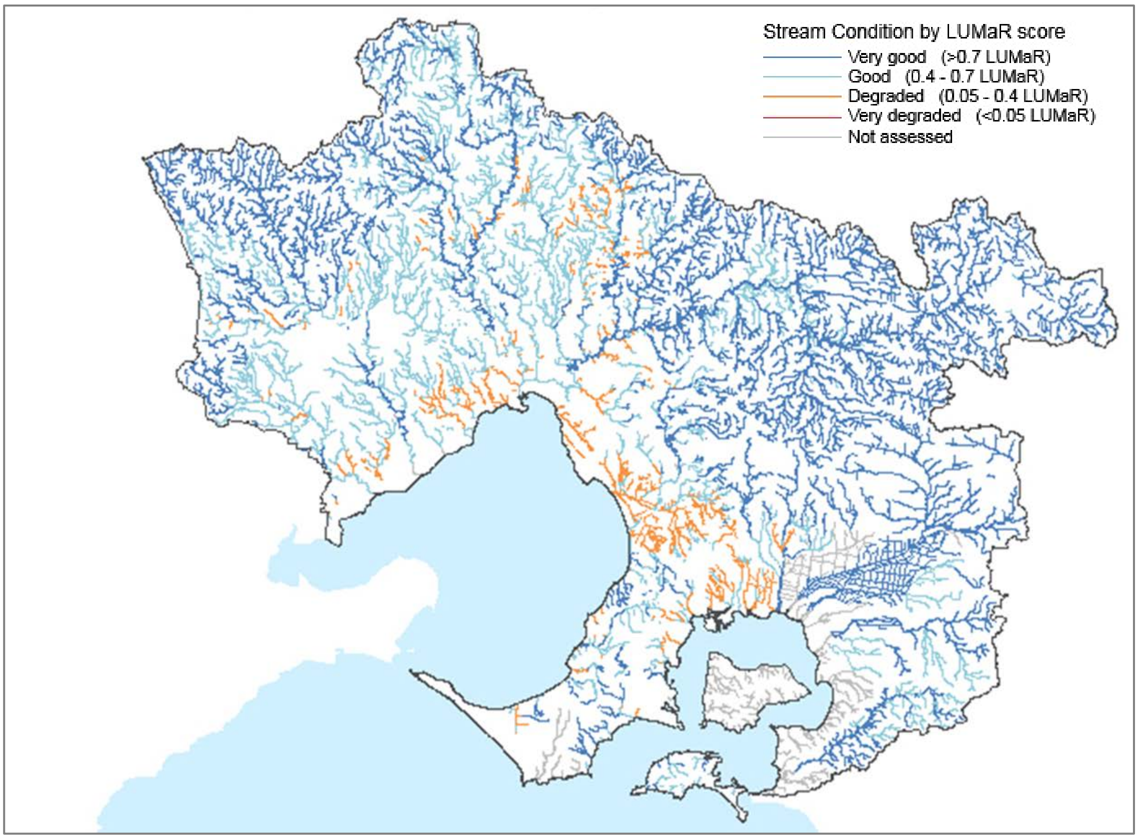

Figure 26. Map showing future predicted stream condition for the Melbourne region, as indicated by the macroinvertebrate assemblage composition index LUMAR, with adoption of a policy implementing a near natural flow and water quality stormwater standard for all urban areas (including retrofit of existing urban areas). Scenario D) in Table 7

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