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Riparian Design Guidelines to Inform the Ecological Repair of Urban Waterways

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Riparian Design Guidelines to Inform the Ecological Repair of Urban Waterways
Protection and restoration of urban freshwater ecosystems: informing management and planning (Project B2.2/3)
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Executive summary

Riparian zones are strips of land that run adjacent to streams and rivers along their length, providing the interface between the terrestrial and aquatic environment. These strips of land can buffer the aquatic environment from disturbance in the catchment and they support an array of ecological processes that streams and rivers rely upon for healthy functioning. There is a strong incentive to manage and protect riparian land because disproportionally large benefits can be gained by repairing a relatively small tract of land, and because many restoration actions, such as revegetation, are simple and affordable. However, much of the evidence linking riparian integrity to instream health has arisen from agricultural landscapes, particularly in Australia. There remains debate as to whether such benefits can be attained in urban landscapes; however, managers are forging ahead repairing urban riparian zones. While we wait for the science to catch up, guidance is needed today. These guidelines are designed to meet this need by synthesising what is broadly known about riparian zones, and applying it to an urban context. Specifically, we identify 10 ecological processes performed by riparian zones, how these processes are stressed by urbanisation, and how they can be repaired. To assist managers in their decision-making process, we present a management framework that provides guidance on which on-ground actions can be prioritised given the natural and urban setting of the restoration site. *We stress that these guidelines are designed to assist site-based restoration.* Managers wanting to undertake landscape-scale protection and restoration of urban waterways are encouraged to use other resources.

Introduction

Riparian zones: what are they and why are they important?

Riparian zones are linear systems that run the length of streams and rivers, supporting diverse biological communities (Naiman and and Decamps 1997, Naiman et al. 2008). These strips of land are comprised of vegetation (trees, shrubs, grasses and herbs), soils and topography that regulate instream ecological processes, such as the movement of animals and propagules, as well as water and nutrients (Gregory et al. 1991, Naiman et al. 2005). As the riparian zone acts as the interface between terrestrial and aquatic systems, it often contains important gradients in environmental and community processes (Naiman and and Decamps 1997, Naiman et al. 2005). These strong environmental gradients tend to support higher diversity of plants and animals than the surrounding landscapes and are hotspots of interactions between plants, animals, soil, water, microbes, biogeochemical reactions and people (Ward et al. 2001, Tockner and Stanford 2002, Ward et al. 2002, Naiman et al. 2005, Sabo et al. 2005).

A healthy, functioning riparian zone is important to the ecological integrity of waterways because it influences an array of ecological processes. For example, riparian vegetation shades stream water regulating light and temperature, and can provide a source of food (carbon) for stream biota (Vannote et al. 1980, Gregory et al. 1991). Bankside vegetation, if deep-rooted, stabilizes the stream channel, controlling channel shape and its propensity to wander across the floodplain (Gregory et al. 1991, Rutherfurd et al. 1999). Riparian forests often play an important role in providing instream habitat of large wood, i.e., snags (Lyons et al. 2000). Riparian plants and soils on the floodplain also trap sediment and filter nutrients and other water-borne pollutants as they move from the catchment to the stream in surface or sub-surface flows (Dosskey et al. 2010). Lastly, vegetated riparian land provides habitat in its own right - supporting a diversity of plants and animals, and creating a shaded-microclimate corridor that facilitates the movement of terrestrial and semi-aquatic animals along the river network (Gregory et al. 1991).

From a human perspective, a healthy, functioning riparian zone is valuable because the ecological processes it provides support the delivery of numerous services. For example, riparian floodplain land can absorb high river flows and prevent flooding. Similarly, the filtration of catchment-sourced nutrients by floodplain vegetation, soils and microbes enables riparian zones to protect or buffer streams from nutrient inputs in the catchment, helping to prevent eutrophic conditions and the associated algal blooms, fish kills and nuisance insect plagues (Withers and Jarvie 2008). Healthy riparian zones also provide opportunities for recreation in built urban landscapes and philosophical value to people because they provide a place of relaxation and a connection to nature. Thus, healthy riparian zones are of unique importance for delivering a wide range of ecological and societal services.

Ecological resistance and resilience

One uniquely important role of riparian zones is buffering the aquatic environment from disturbance in the catchment and promoting system recovery after a disturbance. The buffering function supports a phenomenon that is often termed ‘ecological resistance’, while the recovery function supports a phenomenon that is often termed ‘ecological resilience’. An ecosystem with high ecological resistance and resilience will remain quite stable with healthy function even when disturbed. This is an important characteristic because if ecological systems are too strongly or frequently disturbed, such as in the urban environment, they can change their nature and operate at sub-optimal levels (Holling 1973, Gunderson 2000, Folke et al. 2002, Folke et al. 2004). For example, a wetland continuously exposed to high nutrient levels may transition from a clear-water state dominated by macrophytes and supporting high biodiversity to a turbid-water state dominated by algae with low biodiversity (Scheffer and Carpenter 2003, Davis et al. 2010). A healthy riparian zone can help prevent undesirable state transitions such as this through a variety of mechanisms, highlighting the importance a healthy riparian zone.

Riparian zones support ecological resistance and resilience in streams and rivers in numerous ways. Resistance is provided by vegetation, soils and microbes, which filter and process nutrients as they move from the catchment to the stream, reducing nutrient concentrations instream and associated water quality stress (Dosskey et al. 2010). Resistance is also provided by stream-side trees that shade the stream and reduce thermal stress for aquatic biota, and by log-associated pools that provide refuges for biota during times of drought. Resilience is provided by floodplain habitats (backwaters, wetlands) that act as refuges from the high flow in the channel and support sub-populations of sensitive species that can recolonize the channel once high flows have subsided (Sedell et al. 1990, Negishi et al. 2002). Stream-side trees that shade sections of the channel during no-flow periods also confer resilience by increasing the survival and diversity of drought-tolerant microcrustacean seed banks (Strachan et al. 2016). Riparian corridors also imbue streams and rivers with resilience because they provide corridors for biotic dispersal that facilitate population recovery after local species loss (Blakely et al. 2006, Parkyn and Smith 2011, Canessa and Parris 2013).

The urban environment imposes numerous sources of stress on stream systems. For example, scouring flows associated with stormwater runoff can dislodge invertebrates, alter the habitat they rely on for food or shelter, or cause them to be covered with silt, reducing their fitness and survival (Lenat and Crawford 1994, Negishi et al. 2002). Non-nutrient pollutants such as heavy metals, pesticides, herbicides, hydrocarbons and pathogens place a chronic stress on benthic invertebrates (Pratt et al. 1981, Overmyer et al. 2005, Gresens et al. 2007), reducing their growth, reproductive success and survival (see review by Beasley and Kneale 2002). High water temperatures associated with runoff from impervious surfaces can reduce the growth and development of some stream organisms, particularly fish (see review by Hester and Doyle 2011). Similarly, crashes in dissolved oxygen caused by low flows, warm water temperatures or by the decomposition of algal blooms or other benthic organic matter (e.g., sewage) can cause mortality in invertebrates and fish (Anderson et al. 2002, Mallin et al. 2006). Thus, ecological resistance and resilience is particularly important in an urban setting because of the severity and high frequency of disturbance created by the built environment.

Urban riparian zones: management need and the state of the science

Urban riparian zones can vary considerably (see Fig. 1), but they are typically highly degraded. Direct degradation occurs when roads fragment riparian corridors, when vegetation is cleared to provide amenity or when encroaching residential development narrows the vegetative buffer. Indirect degradation occurs when the key ecological processes that sustain riparian zones are altered. For example, the direct piping of stormwater runoff into stream channels prevents riparian vegetation and soils from filtering nutrients and sediments in surface flows (Paul and Meyer 2001, Groffman et al. 2003, Walsh et al. 2005b). Similarly, channel incision, the construction of levee banks, dams and weirs all alter the lateral flow of water between the main channel and the floodplain, disrupting the transport of water and nutrients to and from riparian areas (Kaushal et al. 2008, Hughes et al. 2014). The loss of ecological function in degraded riparian zones is discussed in detail under the heading ‘Urban threats and stress to riparian processes’ and reduces the ecological resistance and resilience of the waterway.

In Australia and around the world, considerable management attention has been devoted to protecting or repairing riparian land (Bernhardt et al. 2005, Brooks and Lake 2007). Much of this work has taken place in agricultural landscapes; however, attention is now turning to urban riparian land (Groffman et al. 2003, Hession et al. 2003). This shift reflects the movement of people from rural to urban localities worldwide, along with a growing awareness that healthy green spaces improve the liveability of cities and the health of their occupants (Chiesura 2004, Tzoulas et al. 2007).

Although there is a strong management need to protect and repair riparian land, there has been comparatively little scientific study of the importance of riparian zones to the health of urban streams, particularly in Australia. Much of what we know, and present in this document, has been gleaned from agricultural studies or from urban studies conducted overseas. To date, there is evidence that local riparian zones can influence the physical attributes of urban streams (Hession et al. 2003, Roy et al. 2005, Collier and Clements 2011); however, there remains considerable scepticism about their ability to deliver benefits to instream biota (see summary by Bernhardt and Palmer 2011, Violin et al. 2011). For example, studies in the USA have found that small-scale riparian repair did little to improve instream biotic communities (Hession et al. 2003, Roy et al. 2005, Roy et al. 2007). Similarly, studies in south-eastern Australia have found little link between biotic communities and local-scale riparian conditions (Walsh et al. 2007, but see Walsh and Webb 2016). Many urban scientists argue that unless polluted scouring urban flows are controlled at the catchment scale, that local riparian improvements will have little effect on stream health (Walsh et al. 2005a, Walsh et al. 2007, Imberger et al. 2011, Imberger et al. 2014). In contrast, other research suggest that local-scale improvements in riparian condition can deliver benefits to the biota of urban streams (May et al. 1999, Morley and Karr 2002, Urban et al. 2006, Wasson et al. 2010, Gwinn et al. 2017). These studies propose that relatively intact riparian zones attenuate the impacts of urbanisation by absorbing and dampening urban flows (May et al. 1999), by providing more food (coarse organic matter, i.e. leaves) for instream shredding invertebrates (Gwinn et al. 2017), or by improving the dispersal and recolonization opportunities for semi-aquatic invertebrates (Urban et al. 2006, Smith et al. 2009).These conflicting results outlined above are likely driven by differences in the landscape under study, the spatial extent of the research, the study organism/process and by the use of different methodologies; however, they complicate our ability to understand how important urban riparian zones are and the likely benefits that can be gained by repairing them. While we wait for additional research to reveal ‘where, when and for what’ urban riparian zones are important, we can seek guidance from knowledge gathered in other settings. These guidelines amass what is broadly known about riparian zones in both Australia and overseas, and apply it to an urban context. Where possible, we prioritise knowledge gleaned from studies in urban areas and in Australia.

Variation in the condition of urban riparian zones. Panels (a) and (b) show relatively intact riparian buffers, panels (c) and (d) show heavily degraded riparian zones in Perth, Western Australia. Photos: Leah Beesley.

Scope and how to use this document

These guidelines take a process-oriented and site-specific approach to the management of urban riparian zones. This approach stems from recognition that it is the ecological processes supported by the land, not the land itself, which underpins waterway health (Palmer et al. 2014b). The site-specific approach stems from recognition that the majority of restoration projects occur at small spatial scales (Bernhardt and Palmer 2007, 2011), and that stream function varies among rivers and along their length (Vannote et al. 1980, Dodds et al. 2015); thus, there is a strong imperative to produce restoration guidelines that are tailored to the local and regional setting (Richardson et al. 2005, Thomas 2014). **Managers wanting to undertake landscape-scale protection and restoration of urban waterways are encouraged to use other resources.**

This document identifies the ecological processes performed by riparian zones, the urban threats that stress these processes, and how the urban setting can limit their recovery. We present an array of on-ground actions that can be used to repair ecological processes. To assist managers in their decision-making process we present a management framework that provides guidance on which on-ground actions should be prioritised given the natural and urban setting of the restoration site. The framework also stresses the importance of effective monitoring and evaluation; however, we discuss this only briefly as there are numerous documents that comprehensively deal with this component of restoration.

For the purposes of this document we define the riparian zone as:

'*that part of the landscape which exerts a direct influence on stream channels and on the aquatic ecosystems within them and which in turn is affected by the geomorphology of the stream channel and the flow regime. Thus, we include the land that adjoins, directly influences, or is influenced by a body of water, where a body of water could be a creek or stream (even if it flows only occasionally), a river, a lake, or a wetland (Price and Tubman 2007).*'

While this document focusses on aspects of the riparian zone that affect the aquatic environment, we also include functions important for terrestrial plants and animals. Our inclusion of terrestrial functions stems from recognition that riparian corridors play an important role in the conservation of terrestrial flora and fauna, and that the planning and design of riparian zones should include both aquatic and terrestrial considerations.

For those seeking additional reading we recommend the following resources;

Lovett, S., and Price, P. (2007) Principles for riparian lands management, Land and Water Australia, Canberra, ACT

Hansen, B., Reich, P., Lake, P.S., and Cavagnaro, T. (2010) Minimum width requirements for riparian zones to protect flowing waters and to conserve biodiversity: a review and recommendations with application to the state of Victoria. School of Biological Sciences, Monash University, Melbourne.

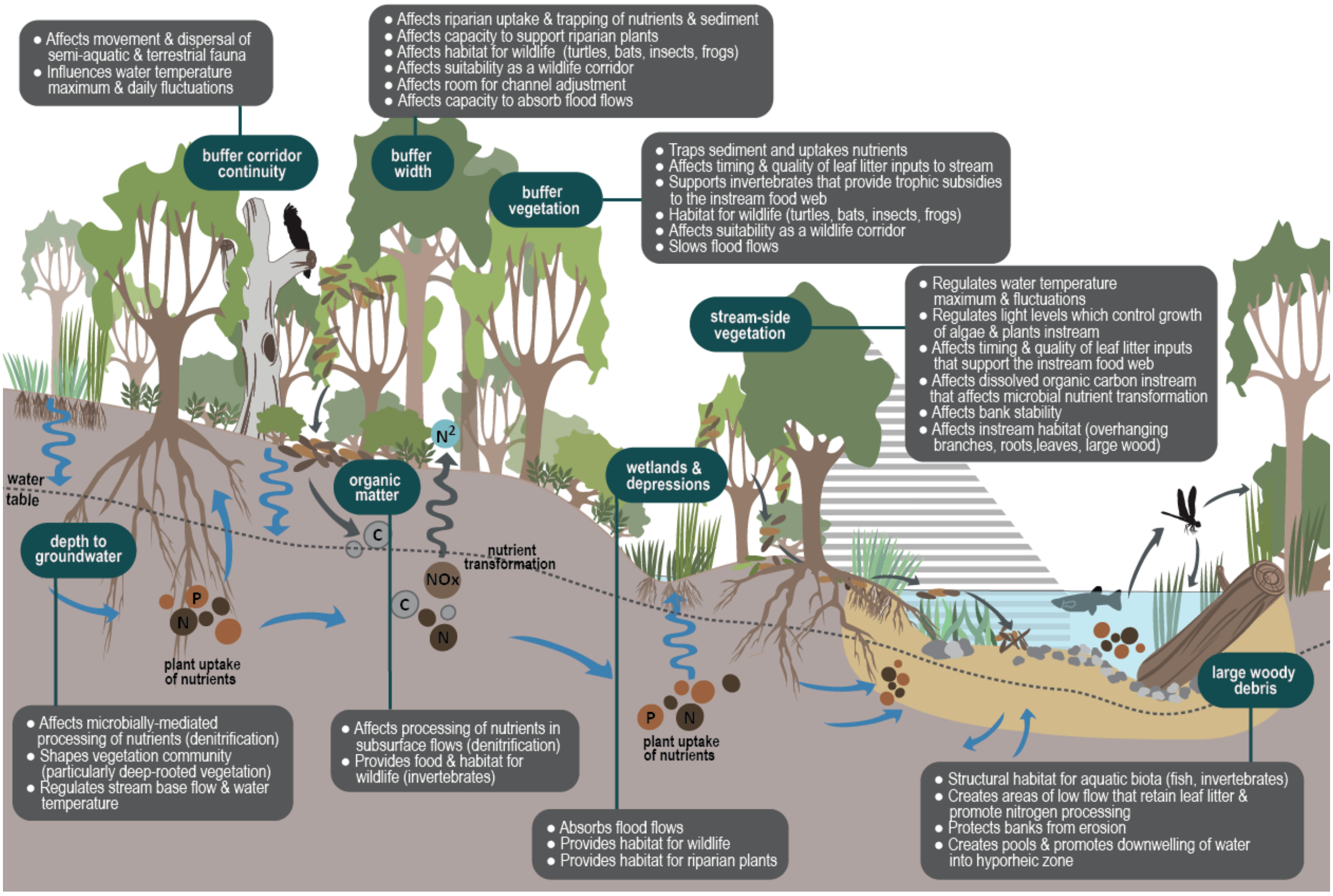
Wenger, S.J., and Fowler, L. (2000) Protecting stream and river corridors: Creating effective local riparian buffer ordinances.

Schueler, T. (2005) An integrated framework to restore small urban watersheds, version 2. Office of Water Management, US Environmental Protection Agency. Washington, DC.

Cramer, M.L. (ed) (2012) Stream habitat restoration guidelines. Co-published by the Washington Departments of Fish and Wildlife, Natural Resources, Transportation and Ecology, Washington State Recreation and Conservation Office, Puget Sound Partnerships and the US Fish and Wildlife Service, Olympia, Washington.

Riparian ecological processes and their importance to healthy waterway functioning given the natural site setting

The riparian zone shapes numerous ecological processes that underpin the health of the aquatic and terrestrial environment (Fig. 2); however, the importance of its influence varies in accordance with landscape and local characteristics. This section introduces 10 ecological processes regulated by the riparian zone and discusses the natural settings where riparian functions are of high, medium and low importance. A summary of the settings where riparian processes are important is provided in Table 1 at the end of this section.



Riparian attributes and the aquatic and terrestrial ecological functions they support. Attributes are shown in the light grey circles and the ecological functions are shown in the dark grey boxes. Note that some functions are influenced by multiple riparian attributes.

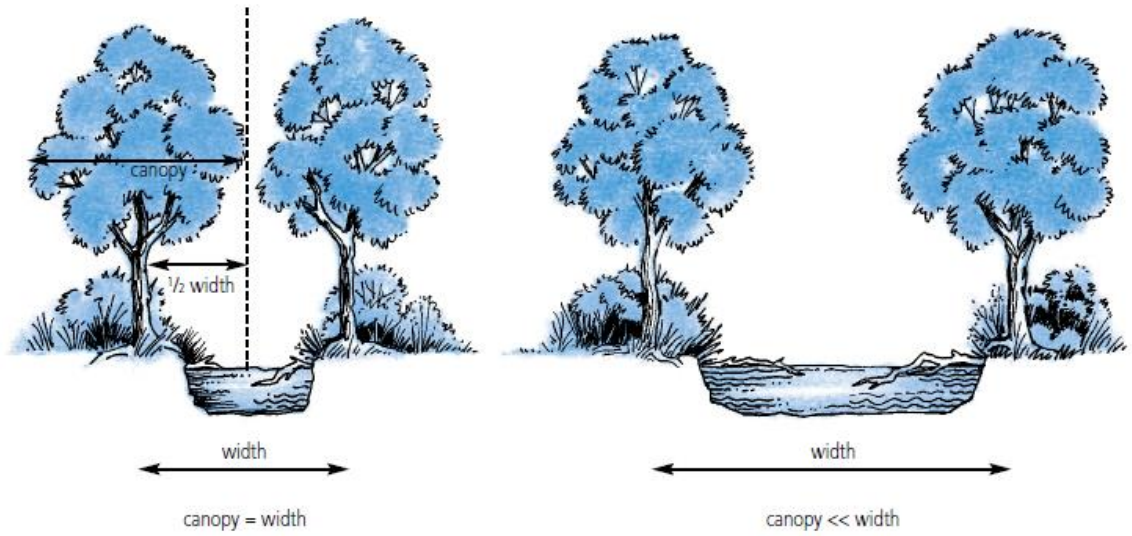
Processes that support the instream aquatic environment

1. Light and temperature regulation

Riparian vegetation plays a key role in regulating the light and thermal regime of streams (Sweeney 1993, Bunn et al. 1999a, Rutherford et al. 2004). This regulation occurs primarily because vegetation in the streamside zone absorbs incoming light (short-wave radiation), preventing it from reaching the stream (Rutherford et al. 2004). However, in Australia, tannins leached from riparian vegetation (e.g. eucalypt leaves) can also regulate light because they reduce light penetration into the water column (Boulton et al. 2014). Typically, streams that are well shaded by riparian vegetation (> 75% canopy cover) exhibit reduced thermal maximums and reduced diurnal variability in temperature (Bunn et al. 1999a). Studies in Australia have revealed that riparian vegetation can reduce maximum instream temperatures by 3–5 °C (Bunn et al. 1999a, Rutherford et al. 2004).

This process of regulating light and temperature is quite important because light and temperature control a variety of stream processes. For example, the amount of light that a stream receives can determine the food base of the stream and determine if it will be a net producer of energy through primary production (i.e. high light exposure) or a net consumer of energy via external inputs (i.e. low light exposure; Bunn et al. 1999a, Davies et al. 2007). Similarly, the temperature of a stream exerts a strong influence over energy movement through the system. The metabolism of most biota is related to temperature, and thus, higher temperatures can increase the productivity of a stream through higher rates of growth and higher rates of food consumption for a variety of organisms (Webster and Benfield 1986, Kaushal et al. 2010, Tank et al. 2010). At extreme conditions, higher temperatures can surpass the tolerance ranges for biota by creating conditions of low dissolved oxygen and temperatures beyond where biota can physiologically function, causing direct mortality (Kaushal et al. 2010, Boulton et al. 2014). Lastly, water temperature can provide cues for important processes in the life history of species, such as cues for insect emergent (Hynes and Hynes 1970) and cues for fish spawning (King et al. 2016). These are only a few examples of the role that light and temperature can play in a stream ecosystem but highlight their importance to the integrity of ecosystem function.

There are numerous factors that determine how influential the riparian zone is at regulating the light and thermal regime of a stream or river site. The capacity of vegetation to shade the stream is dictated by channel width and orientation, stream depth, canopy height, foliage density, valley topography and latitude (Bunn et al. 1999a, Rutherford et al. 2004, DeWalle 2010). In general, riparian vegetation provides the greatest shade when the canopy is high (e.g. trees) (Lyons et al. 2000), when the stream channel is narrow (< 10m) and when the channel has an east-west orientation (Davies et al. 2007). Conversely, riparian vegetation has a reduced capacity to control instream light and temperature when the canopy is low (e.g. grass or herb), when the channel is wide (> 30 m) and where the channel has a north-south orientation (Davies et al. 2007). Riparian vegetation exerts a reduced effect on water temperature where there is considerable upwelling of groundwater (Poole and Berman 2001), when there is large inflows of water from upstream lakes or wetlands (Booth et al. 2014), or where highly incised banks shade the stream, such as a gorge.



The ability of trees to shade the stream channel decreases when canopy width is smaller than channel width. Taken from Bunn et al. (1999a).

2. Nutrient processing and sediment trapping

Riparian land regulates the nutrients and sediment of a stream in several ways. The gentle slope, dense groundcover, leaf litter and complex soil microtopographies of riparian land slow runoff and flood flows so that suspended sediments from the catchment or stream bed can deposit and nutrients can be processed (Naiman and and Decamps 1997, Prosser et al. 1999, Dosskey et al. 2010). Nutrient processing occurs by chemical bonding, plant uptake or microbially-mediated transformation. Chemical bonding occurs when soils rich in iron, aluminium and organic matter attract phosphate ions (PO_3^-) trapping it in the soil matrix (Prosser et al. 1999). Plant uptake occurs when shallow-rooted plants such as sedges, herbs and grasses uptake nutrients from shallow soils and when trees uptake nutrients from deeper subsurface waters, assimilating nutrients into their biological tissue (Hoffmann et al. 2009, Roberts et al. 2012). Chemical transformation occurs when denitrifying bacteria convert Nitrate and Nitrite into N^2 gas under anaerobic conditions (Groffman and Crawford 2003, Kaushal et al. 2008). The majority of microbially-mediated nutrient transformation occurs when the water table saturates soil close to the surface that is rich in carbon from leaves and root material (Hill 1996, Groffman et al. 2003, Dosskey et al. 2010, Gift et al. 2010, Fellows et al. 2011)

Although nutrients and sediments are necessary components of stream systems, excessive quantities of either can have detrimental effects on ecosystem function. Thus, natural regulation of nutrient and sediment inputs into streams is important for stream health in numerous ways. Excessive nutrients promote algal growth altering food webs, and can lead to algal blooms and anoxic conditions in downstream receiving waters (Anderson et al. 2002, Boulton et al. 2014). Excessive sedimentation reduces the complexity of instream habitat on a macroscale by infilling pools, causing the loss of deep cool water habitats that act as refuges for fish and other biota. Sedimentation reduces habitat complexity on a microscale by infilling the space between particles in the stream bed (e.g. gravel) reducing habitat for benthic invertebrates (Doeg and Koehn 1994, Harrison et al. 2007, Kemp et al. 2011). Fine sediment can also alter energetics and the food web by increasing turbidity (suspended sediments) reducing light penetration necessary for algal and plant growth, by smothering hard surfaces that support biofilms, and by smothering leaf litter reducing its availability for detritivorous macroinvertebrates (see review by Wood and Armitage 1997). Lastly, fine sediment can directly impact the fitness of organisms by smothering eggs, clogging gills, depleting oxygen, and increasing exposure to sediment-bonded pollutants (see reviews by Wood and Armitage (1997), and Jones et al. (2012)).

There are numerous factors that determine the ability of riparian land to filter nutrients and sediment. These include soil properties (clay content, particle size, iron and aluminium content, redox), slope, water table depth and vegetation characteristics (Prosser et al. 1999, Mayer et al. 2007, Ranalli and Macalady 2010). In general, the riparian zone is highly efficient at filtering nutrients where (i) the soil has a high clay content (rich in Fe and Al) but still retains decent infiltrative capacity (Vidon and Hill 2004, Ballantine et al. 2009), where (ii) the vegetation is dense and complex (Dosskey et al. 2010), where (iii) the riparian profile is sloped enough to promote lateral flow but gentle enough so that flow is relatively slow (2-15% slope) (O'Toole 2014) and where (iv) the water table is relatively shallow so that it promotes nutrient transformation in carbon-rich parts of the soil (Hill 1996, Groffman et al. 2003, Gift et al. 2010). Riparian land will be less efficient at nutrient filtration where there is little vegetation, where soils are highly sandy and low in iron (McKergow et al. 2003, Ballantine et al. 2009) and where the riparian profile is very flat (<1%), such as parts of Perth. In these settings, water and nutrient inputs into the stream are typically driven by vertical rises and falls in groundwater and riparian land exerts less influence (O'Toole 2014, Weaver and Summers 2014). Riparian land will also be relatively inefficient at nutrient filtration when slopes are very steep (>25%) or when the groundwater is deep > 4m (Hill 1996, Ranalli and Macalady 2010, Newham 2011).

3. Bank stabilization

Riparian land stabilises stream and river banks by protecting them from various forms of erosion (Rutherfurd et al. 1999, Rutherford 2007). Scour associated with high flows can be reduced by tree roots and large woody debris that increases channel roughness and deflects flow away from banks (Keller and Swanson 1979, Thorne 1990, Rutherfurd et al. 1999, Treadwell et al. 2007). Groundcover on the bank (e.g. grass, herbs, sedges) also protects soil from erosion during high flows because when it is submerged it flattens against banks providing a protective armour (Rutherfurd et al. 1999). Deep-rooted vegetation such as trees reduce the probability of bank collapse by anchoring the riverbank, while roots and rhizomes of perennial understorey vegetation (grass, shrubs, sedges) increases the tensile strength of the soil (Thorne 1990, Rutherfurd et al. 1999). Trees and other vegetation also stabilize the soils by intercepting rain, up taking infiltrated water, and improving soil drainage (Thorne 1990, Rutherfurd et al. 1999).

Bank erosion can have a substantial influence on stream function because it controls channel geometry (width, depth), affecting both instream habitat and hydraulics (water velocity, depth). In Australia, small stream channels with dense stream-side vegetation are narrower and deeper than channels with sparse vegetation or grass (Huang and Nanson 1997, Rutherford 2007). Narrow channels are more readily shaded by riparian vegetation than wide channels, thus remaining cooler and are energetically more likely to be fuelled by leaf litter. Deeper channels support deeper pool habitat during low or no-flow periods which can be critical for local species persistence (Bond and Lake 2003). Stable banks also contribute less fine sediment into the stream, which reduces ecological issues associated with sedimentation.

There are numerous factors that affect the ability of riparian vegetation to stabilise the stream bank (Table 1). These factors include the erodibility of the bank material, channel width and depth, stream power, and the root depth of riparian vegetation. For example, riparian vegetation will be more influential when bank material is erodible (e.g. sand) but relatively unimportant when it is non-erodable (e.g. bedrock) (McBride and Booth 2005). Similarly, streamside vegetation will be important for bank stabilisation when a stream is exposed to periods of moderately scouring flows (moderate stream power), but less important where streams receive uniform slow flows or extremely scouring flows. The maximum rooting depth of riparian plants typically does not exceed the depth to local groundwater (during dry seasons), so vegetation in areas with naturally shallow groundwater may not be as effective at stabilising eroding banks as vegetation in areas with deep ground water (Rutherford 2007). Stream-side vegetation that consists of both deep and shallow-rooted vegetation will have a greater potential to stabilise the bank than simply shallow-rooted vegetation (Simon and Collison 2002). Lastly, riparian vegetation will exert relatively little influence when channel width is > 50m and when banks extend beyond the root zone (i.e. bank > 2m depth) (Rutherfurd et al. 1999). The effect of logs to stabilise the bank also decreases as stream size increases (Treadwell et al. 2007).

4. Flood attenuation

Riparian land reduces the magnitude of flooding in several ways. Firstly, riparian vegetation absorbs runoff from the catchment, reducing flows into the stream (Rutherford 2007). Secondly, the floodplain and its associated wetlands and depressions store and infiltrate overbank flood waters (Jacobson et al. 2015). Lastly, vegetation on the floodplain and in the channel (e.g. logs) increases flow resistance, slowing flood flows and reducing the magnitude of flood pluses downstream (Rutherford 2007).

Reducing the size of large floods is important to stream health because it reduces the magnitude of disturbance to instream biota. Trapping and storing water in riparian soils also improves low season flows, because it is slowly released and contributes to stream baseflow.

The ability of riparian land to attenuate floods is linked to attributes of the catchment. Riparian vegetation is most influential where the catchment upstream of the site is long and thin with a high drainage density (e.g. many streams drain the catchment), and where it has short, steep headwaters section and the topography upstream of the site is long and low-gradient (i.e. well-developed floodplain) (Rutherford 2007). Conversely, riparian vegetation is least influential where the catchment upstream of the site is short and wide with a low drainage density (e.g. few streams drain the catchment), and where the topography upstream of the site is steep (i.e. poorly-developed floodplain).

Flood water inundating riparian land. Photo: unknown source

5. Channel adjustment

Riparian land allows the stream channel to adjust naturally to changes in flow. Channels typically increase in width or depth when their flow volume increases, and narrow and infill when flow volume decreases (Wolman 1967). The ability of the riparian zone to enable channel adjustment is linked to geomorphic sensitivity, i.e. the erodibility of bed and bank sediments. Channels with highly erodible soils (sand, gravel) adjust more readily than channels surrounded by bedrock (Brussock et al. 1985, Thorne et al. 2015). Channel adjustment is important to stream function because it allows streams to naturally reach a sedimentation-deposition equilibrium and maintain a variety of instream hydraulic conditions (e.g. velocity, depth) that are important for biota (Gurnell et al. 2007, Kondolf 2013).

6. Trophic subsidies

The riparian zone can be critically important to the energetics of streams and rivers. In narrow well-shaded streams, organic matter (e.g. leaf litter) that falls, or is washed, into the stream typically drives the food web because there is little light to stimulate algae or plant growth (Vannote et al. 1980, Reid et al. 2008). Leaves are not consumed directly by animals, rather they are colonised initially by fungi and bacteria which alter the nutrient ratios of the leaves making them more palatable (Webster and Benfield 1986). These 'conditioned' leaves are then broken down into smaller pieces by shredding invertebrates and consumed by other filterer and collector invertebrates, who are in turn consumed by higher order animals such as fish (Graça 2001, Pettit et al. 2012). In large lowland rivers that receive little shading from riparian vegetation, organic matter from the floodplain may still be important to the food web if the floodplain supports productive habitats that are periodically inundated (Junk et al. 1989, Meyer 1990). The riparian zone can also support aquatic food webs via inputs of terrestrial invertebrates (Nakano and Murakami 2001). Studies have found that terrestrial invertebrates can provide up to half the annual energy budget for fishes, particularly in closed-canopy riparian zones (Nakano and Murakami 2001, Baxter et al. 2005).

Trophic inputs from the riparian zone to the stream are important to stream function in several ways. Primarily they influence the amount and type of energy available to fuel the food web (Vannote et al. 1980, Junk et al. 1989). This dictates the productivity of the system and the diversity of animals present. Studies in the USA have found that depriving streams of leaf litter greatly reduces the abundance and diversity of macroinvertebrates (Wallace et al. 1997, Hall et al. 2000). Organic matter from the riparian zone can also reduce instream primary productivity (algal and plant growth) if leachates from the organic matter stain the water a tea colour (Phlips et al. 2000, Boulton et al. 2014). Dissolved organic carbon from riparian vegetation is also pivotal to microbially-mediated nutrient transformation instream, because carbon often limits the growth of microbial populations (Groffman et al. 2005, Hadwen et al. 2010).

There are several factors that influence the importance of riparian organic matter to the food web. In general, riparian trophic subsidies will be most important when autotrophic production is minimal, i.e. low light or low instream nutrients, and when riparian inputs are substantial. This naturally occurs in small streams with dense forested vegetation (Vannote et al. 1980). In Australia, some contention exists about the importance of leaf litter to stream and river food webs. For example, leaf litter has been found to be important for the macroinvertebrates of small Jarrah streams in south-western Australia (Bunn 1986) and to the macroinvertebrates of larger streams and lowland rivers (3rd and 4th order) of Victoria (Reid et al. 2008). However, algae appear to be the dominant driver of the food web of small, well-shaded streams in Queensland (Bunn et al. 1999b), and for some small and large streams in Victoria and NSW (Hadwen et al. 2010). Riparian trophic subsides are likely to also be important where large scale flooding regularly connects the main-channel to productive floodplain wetlands (Junk et al. 1989, Robertson et al. 1999).

Leaves are an important source of food supporting the food web of small streams. Photo: unknown source

Floodplain wetlands, with their productive warm still waters, can be an important source of food for lowland rivers. Photo: Leah Beesley

7. Aquatic habitat

Riparian land enhances the diversity of instream aquatic and floodplain habitats for a variety of biota. In terms of the main channel, overhanging vegetation, leaves, branches, and logs contribute to instream structural complexity. Logs (large woody debris) within the channel slow flow (Elosegi et al. 2016), promoting sediment deposition (Dosskey et al. 2010) and the maintenance of geomorphic features, such as step-pools, bars and benches (Keller and Swanson 1979, Booth et al. 1997, Treadwell et al. 2007, Krause et al. 2014). LWD can also trap finer organic matter, i.e. leaves and sticks, creating debris dams (Keller and Swanson 1979, Speaker et al. 1984). In terms of the floodplain, riparian wetlands, backwaters, feeder creeks and the floodplain proper create a diversity of aquatic habitats (Ward et al. 2002).

Logs, branches and leaves from the riparian zone are important to stream health in several ways. In the main-channel of the stream, branches and logs provide hard surfaces that biofilms (algae and bacteria) can grow on and provide a stable platform for macroinvertebrates to live in, for fish to live under (Wallace and Benke 1984, Beesley 1996, Treadwell et al. 2007), and sites for semi-aquatic insects to lay their eggs (Reich and Downes 2003). On the floodplain, the diversity of permanent to ephemeral habitats creates conditions that support a variety of fauna (Ward et al. 2002). For example, frogs thrive in ephemeral habitats that do not contain fish, turtles inhabit and breed around floodplain wetlands, and waterbirds nest in floodplain wetlands that support large stands of emergent macrophytes (Ward et al. 2002).

There are several factors that influence the ability of riparian land to enhance aquatic habitat. Vegetation type is pivotal - streams surrounded by grass or shrubs cannot contribute logs to the stream like forested reaches do (Lyons et al. 2000). Channel width and flow is also important, because logs and other riparian inputs make a much larger structural impact on the small streams than large ones (Minshall et al. 1983, Speaker et al. 1984). Large wood and leaves are also more likely to be retained in streams with low flow than very high flow (Cadol and Wohl 2010). The extent and complexity of floodplain habitat is also important; lowland sites with complex and well-developed floodplains support a diverse array of floodplain habitats whereas upland sites typically support few if any floodplain habitats (Ward et al. 2002).

Large woody debris in the middle Canning River, Perth. Photo: Leah Beesley.

Overhanging vegetation providing cover for instream aquatic life, upper Canning River. Photo: Leah Beesley.

Processes that support the terrestrial environment

Riparian processes in the terrestrial environment are not directly important to stream health, but we have included them because they have an indirect link to stream function and because most managers will wish to deliver benefits to the urban terrestrial environment as well as the stream. We believe that overlooking terrestrial needs during restoration would be a lost opportunity.

8. Riparian vegetation

Compared to the surrounding landscape, riparian land supports a dense, diverse and often unique assemblage of plants (Wissmar and Swanson 1990, Naiman and and Decamps 1997). Many of the plants that are abundant in riparian zones are those that require more water than the adjacent terrestrial land can provide. Plants in the riparian zone must be able to cope with frequent disturbance – i.e. periodically being inundated with flood water.

The extent to which riparian land will support a vegetation assemblage that is different/unique from the wider landscape will be linked to the climate and the complexity of the natural vegetative assemblage. Riparian land, with its increased access to water, will be particularly important for the survival of water-loving plants in dryland areas and less important in temperate or tropical climates. Riparian land will be particularly important for the creation of a unique vegetation assemblage where the vegetation type is naturally complex, i.e. includes multiple structural components (overstorey, understorey, groundcover) and less important where it is naturally simple, i.e. contains a single structural layer (e.g. grassland).

Melaleucas and other water loving vegetation, Bannister Creek, Perth. Photo: Belinda Quinton

Sedges and other semi-aquatic vegetation adjacent to an urban waterway, Perth. Photo: Belinda Quinton

9. Terrestrial habitat

Riparian land, and the vegetation it supports, provides important habitat to many terrestrial animals. Indeed, studies around the world have shown that riparian land typically supports a much high number and density of animals compared to the surrounding landscape (Gregory et al. 1991, Bentley and Catterall 1997, Tockner and Stanford 2002). The preference for riparian land exists not only because it provides a good source of water, but also because it provides a good source of food. For example, adult semi-aquatic insects emerging from the stream can support between 25 to 100% of the food requirements of birds, bats, lizards and spiders living in the adjacent riparian land (Fisher and Goldney 1997, Lynch et al. 2002). Food is also supplied by riparian plants, whose greater access to water and nutrients means that they can produce a greater number of leaves, flowers and fruits than adjacent vegetation (Catterall et al. 2007). Riparian land also provides shelter from harsh environmental conditions, particularly in hot environments, and the complex vegetation it supports provides protection from predators and places for nesting and roosting (Catterall et al. 2007).

The importance of riparian land as habitat to terrestrial wildlife will depend upon the availability of food and water across the broader landscape. Riparian land will be most important where the surrounding land provides little food and water (e.g. arid environments) and will be less important where the surrounding land is similarly rich in food and water (e.g. some wet tropical environments).

A common sheathtail bat. Photo: Daniel Kamien

A growling grass frog. Photo: Michael Smith

10. Terrestrial corridor

Riparian land can provide a corridor that allow animals to move through the landscape to disperse and to access resources, e.g. food (Knopf and Samson 1994). The natural importance of riparian land as a corridor will reflect the extent to which riparian vegetation provides a distinct habitat that is preferable to the surrounding landscape. For example, riparian vegetated land in a dryland environment provides a cool microclimate with complex habitat that supports the survival and movement of animals, and will be preferentially used for movement (Catterall et al. 2007). Riparian land will be less important as a corridor in more mesic and tropical environments.

Southern brown bandicoot. Photo: Ken Stepnell

Yellow-faced honeyeater. Photo: Geoffrey Dabb

Table 1. Ten riparian processes and their natural importance to stream function at the site. Note, multiple influencing factors are provided for each cell in the table to guide the recovery scoring. Note the factors are not prescriptive; for example, a low score could be obtained for a given function because all limitations occur at the site, or because one limitation is very severe. Practitioners should consult experts and those with local knowledge to ensure an appropriate score is given.

Importance to Natural Stream Function			
Riparian Process	High (score 2)	Moderate (score 1)	Low (score 0)
1. Light & temperature regulation	Forested vegetation; narrow channel width (< 10 m); E-W orientated. *e.g. northern and eastern Melbourne, Perth*	Shrub or sparse vegetation *e.g. Geraldton* OR narrow channel width (<10 m) with a N-S orientated OR intermediate channel width with a E-W orientation (10-30 m)	Grass/herb vegetation *e.g. western parts of Melbourne* OR wide channel width (>30 m) OR considerable upwelling of groundwater
2. Nutrient filtration & sediment trapping	Moderate clay content, rich in Fe & Al with good soil permeability; dense complex vegetation; gentle slope (2-15°); shallow water table (< 4m below ground during wet season) *e.g. parts of Melbourne*	Soils have high clay content reducing permeability, or are very sandy; vegetation is dense & complex & slope is moderate (15-25°). Water table is deep (> 4m below ground during wet season). *e.g. parts of Melbourne*	Sandy soils low in Fe and Al and very flat (<2°) *e.g. parts of Perth*; OR steeply sloped (>25°). Sparse vegetation; water table is deep (>4 m below ground during wet season) *e.g. parts of south-eastern Queensland*
3. Bank stabilization	Soils are highly erodible (e.g. sand); site is exposed to moderate stream power; channel < 30 m wide & bank < 1 m deep; deep and shallow-rooted vegetation. *e.g. parts of Perth, Adelaide and south-western Melbourne*	Soils are moderately erodible (e.g. gravel, clay); site is exposed to high stream power *e.g. parts of Melbourne, Perth hills* OR channel 30-50 m wide & bank 1-2 m deep; deep-rooted vegetation only	Soils have low erodibility (e.g. boulder, bedrock) OR site is exposed to low stream power OR channel > 50m wide & bank >2 m deep; shallow-rooted vegetation only
4. Flood attenuation	Upstream catchment is long & thin in shape; high drainage density, with a short, steep headwater section & then a long low-gradient section. Floodplain contains numerous wetlands or ponds	Upstream catchment has high drainage density BUT floodplains upstream are steep & narrow OR upstream catchment has low drainage density AND floodplains upstream are flat & wide	Upstream catchment has a low drainage density & high gradient floodplain section – i.e. poorly developed floodplain with no wetlands or ponds
5. Channel adjustment	Highly erosive bank soils (e.g. sand, gravel) *e.g. parts of Perth, Adelaide and south-western Melbourne*	Moderately erosive bank soils (e.g. clay, cobble) *e.g. parts of Melbourne*	Bedrock channels (i.e. little to no erosion)
6. Trophic subsidies	Low light to channel; closed riparian canopy; low nutrients (e.g. narrow forested stream) OR regular inundation of productive floodplain habitat	Moderate light to channel; moderate nutrients OR infrequent inundation of productive floodplain habitat	High light to channel; open riparian canopy; moderate nutrients OR no regular inundation of floodplain habitats (e.g. lowland river)
7. Aquatic habitat	Narrow channel (< 10m); treed vegetation; low flows OR lowland sites with well-developed floodplain	Intermediate channel width (10-30 m); shrub vegetation; moderate flow OR lowland site with moderately developed floodplain	Wide channel (> 30 m); grass vegetation; high flows OR lowland sites with poorly developed floodplain
8. Riparian vegetation	Semi-arid, arid or dryland climate; vegetation includes trees, shrubs & groundcover *e.g. Geraldton*	Mediterranean or mesic climates; vegetation includes trees, shrubs & groundcover *e.g. Perth*	Tropical environment OR grasslands *e.g. parts of north-east Melbourne & Queensland*
9. Terrestrial habitat	Semi-arid, arid or dryland climates	Mediterranean or mesic climates	Tropical environments
10. Terrestrial corridor	Semi-arid, arid or dryland climates	Mediterranean or mesic climates	Tropical environments

Urban threats and stress to riparian processes

The riparian zone and the ecological processes it performs are altered by urbanisation in many ways (See Fig. 3). This section introduces the key threats and discusses how they stress riparian ecological function and cause unwanted environmental problems. At the end of this section we present a qualitative method for broadly quantifying urban stress to riparian ecological processes.

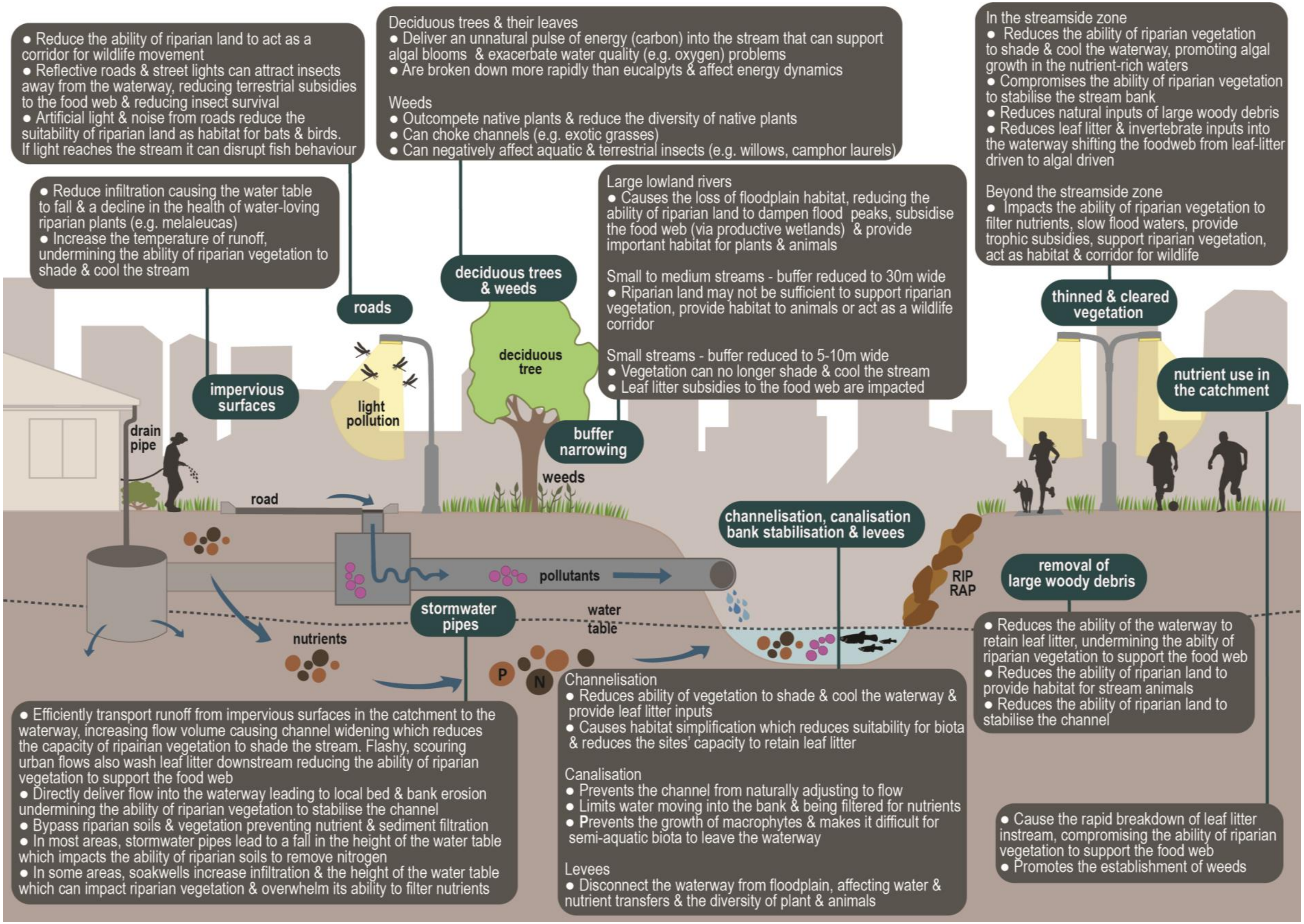
Urban threats

Impervious surfaces and stormwater management (including sub-surface drainage)

Altered catchment hydrology, associated with the direct transfer of runoff from impervious surfaces (i.e. roads, buildings) to streams in urban areas, stresses riparian function in numerous ways. For example, the direct piping of stormwater runoff, and/or subsurface water, into stream channels prevents riparian vegetation and soils from filtering nutrients and sediments in surface flows (Groffman et al. 2003, Walsh et al. 2005b). Falling water tables below the riparian zone caused by reduced catchment-wide infiltration, and eroding stream channels, reduce the ability of the riparian zone to filter nutrients from subsurface flows (Groffman et al. 2003, Groffman and Crawford 2003). In instances where urbanisation results in a rise in the water table, such as in certain parts of Perth (Barron et al. 2013a, Barron et al. 2013c, Bhaskar et al. 2016), the denitrification capacity of riparian soils may be enhanced by urbanisation, but do little to prevent the inflow nutrient-laden, groundwater into the stream because groundwater moves predominantly vertically in this flat landscape (Barron et al. 2013b, O'Toole 2014). Urban changes in water table height are likely to impact the ability of the riparian zone to support native vegetation by altering plant access to water and nutrients (Bornette and Heiler 1994). Stormwater runoff over impervious surfaces increases the temperature of urban streams by several degrees (Krause et al. 2004, Somers et al. 2013), reducing the ability of stream side vegetation to keep water cool. In addition, frequent, scouring urban flows reduce the ability of riparian vegetation to stabilise the stream bank, promoting channel widening and deepening (Wolman 1967, Booth et al. 1997, Vietz et al. 2014). Lastly, scouring urban flows reduce the capacity of streams to retain leaf litter (Paul et al. 2006), reducing the extent to which riparian vegetation can support the stream food web (Yule et al. 2015).

Stormwater runoff along a paved road surface, Perth CBD. Photo: Leah Beesley

The direct piping of stormwater to a stream channel, Armadale, Perth. Photo: Leah Beesley



A conceptual depiction of how key urban threats (shown in teal polygons) degrade the ecological processes that support healthy waterway functioning.

Buffer narrowing

A high demand for land in urban areas leads to encroachment of the built environment into the riparian zone, resulting in buffer narrowing (May et al. 1999), which impacts numerous riparian functions (see Fig. 4). For lowland rivers, buffer narrowing subsumes important floodplain habitat (Hughes et al. 2014), impacting on the ability of riparian land to dampen flood peaks, subsidise the food web, and provide quality aquatic and terrestrial habitat. For smaller streams, the stress created by buffer narrowing depends on the width of the remaining buffer. If the buffer remains greater than 30 m, the impacts are most likely to be on the ability of the riparian zone to support native riparian vegetation, to provide habitat for wildlife, and to act as a corridor for wildlife (Fischer and Fischenich 2000, Bentrup 2008, Senzaki et al. 2016). When buffers are reduced to less than 5-10 m width then functions such as light and temperature regulation, trophic subsidies and nutrient filtration are likely to be impacted (Fischer and Fischenich 2000, Kiffney et al. 2003). Marked buffer narrowing also reduces the capacity for the channel to naturally adjust in relation to urban increases in flow (Thorne et al. 2015, Vietz et al. 2016).

Narrow land surrounds a man-made drain in Cannington, Perth. Photo: Jennifer Middleton

Vegetation clearing/thinning

Vegetation is commonly cleared in urban riparian zones to provide visual and recreational amenity (paths, playgrounds, parks), to improve human safety, and reduce flood risk (Fig. 4); however, the replacement of trees and understorey by grass or bare ground impacts a variety of riparian functions. Vegetation **thinning in the stream-side zone** (0-10 m from the channel), reduces the ability of the riparian zone to moderate water temperature (Kiffney et al. 2003, Nelson et al. 2009, Collier and Clements 2011, Booth et al. 2014). Increased light also encourages algal growth in the nutrient-rich urban waterways (Peterjohn and Correll 1984, Kiffney et al. 2003). Together, algal blooms and elevated water temperatures reduce oxygen levels instream, particularly at night, which can detrimentally affect stream biota (Anderson et al. 2002). The thinning of stream-side vegetation also reduces the ability of the riparian zone to stabilise the stream bank (Rutherfurd et al. 1999). The collapse of stream banks can be beneficial in an urban setting if it contributes coarse material (e.g., gravel) to streams, or if it adds large woody debris to the channel (Vietz et al. 2012). However, in general, channel collapse and stream widening is considered negative in an urban environment because it causes the loss of shade trees and increases in fine sediment, which adversely affect instream processes and aquatic habitat. The loss of stream-side trees can also reduce LWD inputs into the stream and lead to a simplification of instream habitat (May et al. 1999, Roy et al. 2005). Lastly, from a trophic perspective, the loss of stream-side trees reduces leaf litter and invertebrate inputs into the stream (Gregory et al. 1991). This switches the stream from one supported by allochthonous inputs to one reliant on autochthonous (i.e., algal) productivity (Yule et al. 2015), and puts the instream invertebrates that feed on leaves (i.e., shredders) at a disadvantage (Gwinn et al. 2017).

Vegetation **thinning beyond the stream-side zone** can also impact the ability of the riparian zone to filter nutrients, slow flood waters, provide trophic subsidies, support riparian vegetation and provide habitat and a corridor for wildlife. For example, the decline in leaf litter that occurs as trees and shrubs are removed, leads to a decrease soil organic matter, which reduces the ability of saturated soils support the microbial processing of nutrients (Groffman et al. 2003, Mayer et al. 2010). A decline in the quantity of organic debris (e.g., leaf litter) in the buffer also reduces the amount of organic matter that can leach, or be transported, into the stream during floodplain inundation. If vegetative loss reduces the density of terrestrial insects it may also impact subsidies to the stream food web. The loss of complex vegetative structure (i.e. overstorey, understorey, ground cover) not only reduces native plant biodiversity, it reduces the suitability of riparian land as a habitat for insects and spiders (Harrison and Harris 2002, Laeser et al. 2005, Williams 2011), birds (Stagoll et al. 2010) and other fauna. The loss of hollow trees can also be detrimental in urban riparian zones because it reduces nesting or roosting habitat for birds, possums and bats (Rhodes et al. 2006, Treby 2013). The replacement of trees with simple vegetation, such as grass, is known to restrict the movement of birds (Shimazaki et al. 2016), and mammals (FitzGibbon et al. 2007) and may restrict the movement of insects (see Smith et al. 2009). Lastly, the loss of buffer vegetation also increases the infiltration of artificial light (i.e. street lights) and road noise, which can negatively impact on stream fauna - see ‘Roads and habitat fragmentation’ below for greater discussion of this issue.

Vegetation cleared and replaced with grass around an urban drain, Perth. Photo: Leah Beesley

Vegetation thinned around a section of the mid Canning River, Perth. Photo: Leah Beesley

Replacement of native with deciduous vegetation and the introduction of weeds

In Australian urban areas, native evergreen riparian vegetation is commonly replaced with European deciduous trees. While deciduous trees can continue to shade the stream and stabilise the bank, they alter the energy dynamics and trophic subsidies of the system. For example, deciduous trees create an unnaturally large input of carbon (i.e., leaves) into the stream during their autumn fall, whereas native trees contribute leaves on a more continuous basis (Miller and Boulton 2005). Deciduous trees also typically have soft leaves that breakdown much faster than most native Australian riparian trees (*Eucalyptus*, *Melaleuca*) (Imberger et al. 2008). The large, timed injection of carbon into stream systems in combination with eutrophic urban waters, can result in unwanted algal blooms (Pidgeon and Cairns 1981, Pen 1999). The rapid breakdown of deciduous leaf litter in urban streams also reduces the amount of food available for specialist invertebrate taxa that feed predominantly on leaves (i.e., shredders) (Rosemond et al. 2015).

Deciduous street trees, Subiaco Perth. Photo Jen Middleton

Weedy plant species typically dominate urban riparian zones, because of their productive life histories and their wide physicochemical tolerances. By outcompeting native plants for space and light, and they can reduce native plant diversity (Burton et al. 2005, Richardson et al. 2007), and the suitability of riparian vegetation for fauna (Tickner et al. 2001). In Australia, exotic perennial grasses such as Kikuyu (*Pennisetum clandestinum*) and trees such as willow (*Salix* spp.) can choke the stream channel, reducing light and trapping sediment (Bunn et al. 1998, Tickner et al. 2001). Willows can also reduce the abundance and composition of terrestrial arthropods in riparian land (Greenwood et al. 2004).

Invasive grasses blocking a channel, Midland Perth. Photo: Leah Beesley

Increased nutrient load in the catchment

The catchment-wide use of organic and inorganic fertilisers, coupled with seepage from septic tanks and effluent from wastewater treatment plants and industry, causes urban streams and rivers to be highly loaded with nutrients (Grimm et al. 2005, Wollheim et al. 2005, Gücker et al. 2006). These high nutrient levels can compromise riparian ecological function by reducing the capacity of riparian soils to process nutrients and their capacity to provide trophic subsidies to streams. The elevated nutrient levels of urban streams can also impact the ability of the riparian zone to provide trophic subsidies to streams, because high nutrient concentrations accelerate the breakdown of instream leaf litter, reducing the food available for invertebrates (Rosemond et al. 2015). High nutrient levels can also promote the establishment of weed species in Australia because they grow faster in the presence of elevated nutrients than natives (Milberg et al. 1999) and because some high nutrient levels are toxic to some native plants (Granger et al. 1994).

Inorganic fertiliser. Photo: Leah Beesley

Excessive algal growth in a nutrient-rich urban stream, Perth. Photo: Leah Beesley

Channelisation, canalisation, bank stabilisation and levees

Engineered approaches to increase flow conveyance and reduce flooding in urban areas, such as channelization/ canalisation, the lining of stream banks with hard surfaces (concrete, rip rap) and the construction of levees, cause notable impacts to riparian ecological function. For example, channelization (i.e., straightening of stream channels) using earth moving equipment causes the loss of stream-side trees that shade the stream, and provide trophic subsidies (Brooker 1985). The simplification of instream hydraulic diversity caused by channelization (see

Gurnell et al. 2007) also undermines riparian trophic subsidies, because the habitats that naturally retain leaf litter are no longer present in the channel (Speaker et al. 1984, Brooker 1985). Hard surfaces, such as concrete lining or rip rap, replace the function of trees to stabilise the bank, but prevent the channel from adjusting naturally to changes in flow (Gurnell et al. 2007, Vietz et al. 2016). Concrete lining (i.e. canalisation) also prevents the exchange of water between riparian soils and the stream, which removes the ability of riparian zone to filter nutrients and can lead to vegetation changes as plants have reduced access to water (Paul and Meyer 2001, Walsh et al. 2005b). Concrete lining of waterways can impact semi-aquatic fauna such as frogs, turtles and invertebrates by making it difficult for individuals to leave the waterway or by preventing the development of stream-edge macrophytes stands that are important for habitat and oviposition (Brooker 1985, Hamer and Parris 2011, Thornhill et al. 2017). Levees disconnect the river from its floodplain, reducing the frequency of floodplain inundation reducing organic matter subsidies from the floodplain to the main river channel, and the opposing transfer of nutrients and sediments from the main channel to the floodplain (Tockner et al. 1999, Tockner and Stanford 2002). Reduced inundation leads to changes in the assemblage of riparian plant assemblages and reduced faunal diversity (Naiman and and Decamps 1997, Tockner and Stanford 2002, Francis et al. 2008).

Wood revetment and channelisation of Bennet Brook drain, Perth. Photo: Leah Beesley

Concrete-lined trapezoidal drain Adelaide. Photo: unknown source

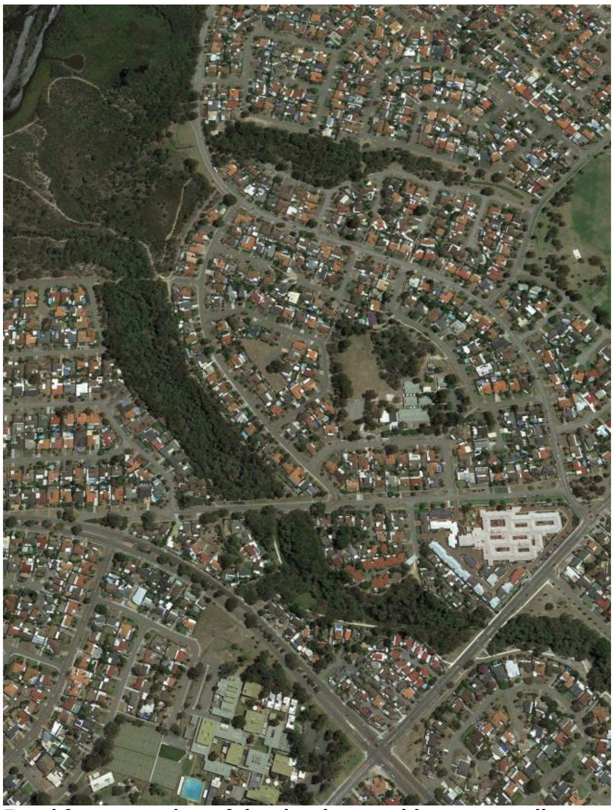
A rock-lined channel, Perth. Photo: Leah Beesley

Removal of large woody debris

Logs are often removed from urban streams and rivers to reduce the risk of local flooding, or to increase the navigability of urban waterways (Booth et al. 1997, Erskine and Webb 2003). Scouring urban flows may also push logs downstream and out of a given stream reach (May et al. 1999). The removal of large woody debris (LWD) impacts several riparian functions. For example, the removal of LWD reduces the ability of the stream to retain leaf litter in debris dams and pools, reducing the ability of the riparian zone to provide trophic subsidies to streams (Elosegi et al. 2016). The loss of LWD also directly reduces the amount of aquatic habitat available by reducing cover for fish (Lyons et al. 2000, Howson et al. 2012), stable habitat for macroinvertebrate colonisation (Beesley 1996, Hrodey et al. 2008), and sites for insect oviposition (Reich and Downes 2003). The removal of LWD will simplify instream habitat as geomorphic complexities produced by large wood, e.g. bars, step-pools, pool and side channels, are lost from the channel (Booth et al. 1997). Lastly, the loss of LWD may accelerate bank erosion, particularly if pieces of wood that protected the bank from scouring flows are removed (Booth et al. 1997).

Roads and habitat fragmentation

Road networks criss-cross urban landscapes, bisecting riparian land (May et al. 1999) reducing their ability to provide a movement corridor for animals (Urban et al. 2006, Parker et al. 2008). Studies of frogs in Melbourne have revealed that species richness decreases as road cover increases (Parris 2006), and roads are implicated as a major barrier to dispersal. Roads are known to increase the mortality of freshwater turtles (Langen et al. 2012) and can isolate turtle populations in urban landscapes making them more vulnerable to local extinction (Gibbs and Shriver 2002); although some species in Australia appear relatively resilient to urbanisation (Roe et al. 2011, Hamer et al. 2016). Road crossings, and their associated culverts, have been found to restrict the distribution of semi-aquatic insects along urban streams by creating a physical barrier to upstream flight (Blakely et al. 2006). Roads and other reflective surfaces can also appear like a water surface to semi-aquatic insects, attracting individuals away from the stream and fooling them to lay their eggs on the asphalt (see review by Smith et al. 2009). Street lights can also attract insects away from streams (Perkin et al. 2011) impacting dispersal and terrestrial subsidies to the stream food web. Artificial light and noise from roads can reduce the suitability of riparian land for fauna by altering the foraging efficiency of bats and birds (Scanlon and Petit 2009, Senzaki et al. 2016). In general, urban habitat fragmentation will pose the greatest stress to wildlife species with ground-based dispersal, with large home ranges and those that are not adapted to edge environments (Bennett 2003).



Road fragmentation of the riparian corridor surrounding Bannister Creek, Perth, WA. Image Google Earth

Altered fire regimes

Urban remnant vegetation typically experiences an increase in the frequency of fire (Price and Bradstock 2014). Fire will detrimentally impact the ability of riparian land to support numerous riparian ecological functions, including light and temperature regulation, nutrient filtration and sediment trapping and trophic subsidies. Indeed, a recent study revealed that fire creates many of the same stresses to streams as urbanisation; hence fire in an urban riparian zone is likely to amplify the stress faced by urban streams and rivers (Beesley et al. 2017). An increased frequency of burning will also cause a shift in the vegetation structure towards fire-adapted species, and promote the invasion of weed species (Milberg and Lamont 1995, Askey-Doran et al. 1999). Fire may exterminate local populations of native wildlife that are trapped inside riparian remnants and cannot escape. Control burns used to reduce fire risk and improve human safety may also impact insect diversity if they occur during the cool months when insect life stages are dormant (New and Sands 2002).

Summarising stress to riparian ecological processes

When managing urban riparian zones, it is useful if we can objectively describe how stressed, or altered, the various ecological processes are. Describing stress requires an understanding of the natural state and departure from that state. This is difficult to achieve for ecological processes because they are difficult to measure and because we rarely have measures of their reference 'historical' condition. An alternative approach is to measure riparian structural attributes and to use changes in these attributes as a proxy for the stress to ecological processes. This indirect method is commonly adopted and is arguably justified because structural attributes (e.g., buffer width, canopy cover, leaf litter) underpin ecological function (Jansen et al. 2004); i.e. an alteration to structure will translate into an alteration in process/function. Thus, a structural approach provides a pragmatic and rapid method to describe urban stress to riparian ecosystem processes.

There are numerous rapid assessments of riparian structural condition already in circulation in Australia, such as the Rapid Riparian Assessment (RRA) tool (Taylor et al. 2005), the Rapid Appraisal of Riparian Condition (RARC) (Jansen et al. 2005), the Tropical Rapid Appraisal of Riparian Condition TRARC (Dixon et al. 2006). Many states also have riparian assessment embedded within their indexes of river condition (e.g. Western Australian index of river condition see http://water.wa.gov.au/water-topics/waterways/assessing-waterway-health/south-west-index-of-river-condition). Any of these rapid assessments could be used to provide a summary of the structural condition. Here we use the RARC version 2 to provide a summary of structural condition and by linking structural attributes to ecosystem processes to provide a qualitative estimate of stress to ecological function. A similar approach could be taken using other riparian assessment methods.

To assess stress for a given restoration site, the site must firstly be assessed using the RARC so that scores are determined for all indicators within the six sub-indices (habitat, cover, natives, debris, features, others). The indicators for each sub-index are shown in Table 2, and Table A1 (Appendix 1) describes the scoring for each indicator. The scores for each indicator should be entered into Table 2. We have aligned the RARC indicators with ecological function in Table 2 using information from Jansen et al. (2005) (see Jansen et al. 2005 Table 1) in conjunction with general knowledge. The qualitative measure of stress to each ecosystem process is obtained by summing the RARC indicator scores for each process, dividing the summed score by the possible maximum score and then taking the inverse of the number (see Table 2). The reciprocal transformation (i.e. inverse) transforms low numbers into higher numbers and higher numbers into lower numbers, which is important because our intention is to rank alteration or stress highly rather than rank good condition highly.

We consider that the RARC indicators capture the vast majority of riparian structural attributes that influence ecological processes in urban riparian zones (see Fig. 2). We have added a few additional indicators, such as channelisation and hard-lining, bank condition and channel incision as these are also good indicators of stressed riparian processes, and they are easy to assess. The current list of features often considered in foreshore condition assessments such as http://www.water.wa.gov.au/__data/assets/pdf_file/0015/3318/11183.pdf (Water and Rivers Commission 1999) does not describe changes in the height of the water table – an attribute that influences microbial processing of nutrients in the sub-surface zone, but this feature is difficult to assess.

Table 2. The 10 riparian processes and their alignment with RARC indices modified from Jansen et al (2005). The range of scores for each indicator is shown for cells where the indicator contributes to the delivery of a certain ecological process. The scoring categories are provided in Appendix 1. Stress to each ecological function is determined by summing scores across all sub-indices, and is described by the ratio of the actual score to the maximum score possible. The summary score standardises scores so that they have a range of 0 to 2; where 2 is poor condition (high stressed) and 0 is good condition (low stress).

RARC Sub Index	RARC Indicator	Riparian Process									
		1. Light & temp regulation (LT)	2. Nutrient filtration & sediment trapping (NS)	3. Bank stabilization (BS)	4. Flood attenuation (FA)	5. Channel adjustment (CA)	6. Trophic subsidies (TS)	7. Aquatic habitat (AH)	8. Riparian vegetation (RV)	9. Terrestrial habitat (TH)	10. Terrestrial corridor (TC)
Habitat	Longitudinal connectivity	0-4									0-4
	Width of riparian vegetation (i.e. buffer width)	0-4	0-4		0-4	0-4	0-4		0-4	0-4	0-4
	Proximity to nearest patch of intact native vegetation										0-3
Cover	Canopy in streamside zone (trees >5m tall within 5m of bank)	0-3		0-3				0-3			
	Canopy (>5m tall)		0-3		0-3					0-3	
	Understorey (1-5m tall)		0-3	0-3	0-3					0-3	
	Ground (<1m tall)		0-3	0-3	0-3					0-3	
	Number of layers									0-3	
Natives	Canopy (> 5m tall)						0-3		0-3	0-3	
	Understorey (1-5m tall)						0-3		0-3	0-3	
	Ground (<1m tall)						0-3		0-3	0-3	
Debris	Leaf litter		0-3					0-3		0-3	
	Native leaf litter						0-3		0-3		
	Standing dead trees (> 20 cm dbh)									0-1	
	Hollow-bearing trees									0-1	
	Fallen logs (>10 cm diameter)				0-2					0-2	
Features	Native canopy species regeneration (< 1m tall)								0-2		
	Native understorey regeneration								0-2	0-2	
	Large native tussock grasses								0-2	0-2	
	Reeds							0-2	0-2	0-2	
	Floodplain wetlands & topography		0-4		0-4		0-4	0-4		0-4	
Others	Channelisation & hardlining			0-3		0-3		0-3			
	Bank condition			0-2	0-2		0-2				
	Channel incision				0-2		0-2				
	Levees present				0-1		0-1				
Maximum possible score		11	20	14	24	7	25	15	24	42	11
Site score (ss)		$\sum LT_{scores}$	$\sum NS_{scores}$	$\sum BS_{scores}$	$\sum FA_{scores}$	$\sum CA_{scores}$	$\sum TS_{scores}$	$\sum AH_{scores}$	$\sum RV_{scores}$	$\sum TH_{scores}$	$\sum TC_{scores}$
Summary stress score		$2-(LT_{ss}/5.5)$	$2-(NS_{ss}/10)$	$2-(BS_{ss}/7)$	$2-(FA_{ss}/12)$	$2-(CA_{ss}/3.5)$	$2-(TS_{ss}/12.5)$	$2-(AH_{ss}/7.5)$	$2-(RV_{ss}/12)$	$2-(TH_{ss}/21)$	$2-(TC_{ss}/5.5)$

Potential for recovery

In an urban setting, numerous factors limit the recovery of riparian functionality. Influential factors include space, amenity and infrastructure constraints, drainage needs, the ability to implement catchment-wide stormwater management and landscape fragmentation. Below we discuss these factors, and others, and provide a summary table that can be used to rapidly assess the recovery potential of the various riparian processes of a given stream site, see Table 3 at the end of this section.

Space and amenity constraints

Urban riparian land is a multifunctional space that houses essential infrastructure, provides amenity to people, and supports healthy stream/river function and associated biodiversity. Urban land is limited and expensive, making it difficult to procure land for restoration goals (Bernhardt and Palmer 2007, Landers 2010). Space limitations restrict the ability of managers to increase buffer width – which impacts the ability to repair many riparian functions, such as light and temperature regulation, nutrient filtration, trophic subsidies and the ability to let the channel self-adjust to changes in flow volume (see Table 3). Recreational amenity such as paths and playing fields, and aesthetic amenity linked to appreciation of 'neat' European-style landscapes can also limit the ability to repair native Australian riparian vegetation and its associated ecological functions (see Table 3).

An urban drain tightly abutted by residential housing. Belmont, Perth. Photo: Leah Beesley

Drainage needs

The primary function of many urban waterways is flood mitigation, i.e. the efficient transport of stormwater off the site. This drainage need is so important that riparian restoration practices will generally only be considered if they do not compromise the drainage capacity of the site. For example, care needs to be taken when adding large wood jams back to urban streams because it may increase the stage of floods (Rutherford 2007) unless the channel has been widened. Note that the flood risk associated with the addition of individual snags is negligible (see Cottingham et al. 2003), and that riparian revegetation typically has a minimal impact on flood levels at a given site (Rutherford 2007). Indeed, riparian revegetation typically increases storage of water in the catchment reducing stage heights at sites lower in the drainage network (Rutherford 2007).

Catchment-wide stormwater management

Many actions to repair riparian function will fail if stormwater has not been firstly managed at the catchment scale. For example, riparian revegetation will do little to trap and filter nutrients if stormwater is still being piped directly to the stream channel. Stream-side vegetation may be insufficient to stabilise the stream bank if scouring urban flows have not first been attenuated (Allen and Leech 1997, Abernethy and Rutherfurd 1999), and leaves dropped into the channel from fringing vegetation may be washed downstream rather than entering the food web (Paul et al. 2006). Lastly, additions of large woody debris may fail to increase instream habitat complexity if they become buried under high instream sediment loads or stranded out of the water as the channel incises (Booth et al. 1997).

Instream flow-regulating structures

A flow-regulating structure upstream of a site can modulate scouring urban flows and increase the success of riparian restorative actions. For example, a dam, weir, or instream wetland upstream of a site can modulate flow downstream such that bankside vegetation will successfully stabilise the stream channel. Structures that reduce instream flow should also improve the ability of the riparian zone to contribute trophic subsidies to the stream because slower flows increase the retention of leaves within the site – hence increase the opportunity for them to enter the food web. Similarly, upstream structures that slow flow will also improve the repair of wood (aquatic habitat) at the site, because slower flows are less likely to transport large wood out of the reach.

Weirs can stabilise flows downstream & in the upstream weir pool. Photo: Stephen Beatty

Integrity of upstream riparian corridor

The integrity of the riparian corridor upstream of the site will influence the capacity for site-scale riparian changes to repair instream water temperature and the food web. In terms of temperature, studies in south-western Australia have found that if the 1.2 km riparian corridor upstream of the restoration site is not 75% shaded then site-specific riparian restoration may do little to reduce instream water temperature (Rutherford et al. 2004). However, if site repair is substantial i.e. > 600m river length is revegetated, then thermal improvements maybe achieved at the downstream end of the repaired urban stream reach (Rutherford et al. 2004). In terms of the food web, there is little knowledge to inform restoration; however, the longitudinal continuity of energy movement (food) in streams (Vannote et al. 1980) suggests that the repair of trophic subsidies would also be adversely affected by disjunct riparian corridors upstream.

Connectivity to patches of remnant vegetation

Riparian land that has an unbroken vegetated corridor connecting it to parcels of remnant bushland will be more likely to support wildlife after restoration than land that does not, because its connectivity to refuge habitat increases the likelihood that species will recolonise it.

Riparian vegetation with a moderate connection to remnant bushland. Image Google Earth

Riparian vegetation with little to no connection to remnant bushland. Image Google Earth

Wastewater treatment plants and septic tanks

The discharge of warm wastewater into an urban drainage line (see Lawrence et al. 2013) is likely to limit the ability of bank-side tree planting to repair water temperature. Wastewater treatment plants that discharge water with elevated nutrient levels may also limit the capacity of the riparian buffer to mitigate nutrient inputs.

Undesirable outcomes

Often there are trade-offs inherent in riparian restoration that should be considered before implementing management actions. For example, if removing a levee and reconnecting the river to a wetland facilitates the spread of an invasive fish species, then this trade-off should be considered before implementing this action (Jackson and Pringle 2010). Similarly, if the addition of LWD poses a threat to downstream infrastructure such as bridges or pipelines, its addition to streams should be managed to mitigate or minimise the risk (Wohl et al. 2016). Navigating such management trade-offs can be a difficult problem for managers where the costs and benefits are not always clear; thus, a thorough consideration of all possible risks is important for delivering desirable outcomes.

A smooth newt, native to Europe and introduced into waterways in Melbourne. Photo: Peter Robertson

A pearl cichlid, native to south-America and introduced to a wetland in Perth. The species has now invaded the wider metropolitan area. Photo: Dave Morgan

Future development and clearing regulations

Future urban development upstream of a site is likely to lead to increased flow volumes instream, which can compromise riparian restoration. For example, if future development increases scouring instream flows this will lead to further channel widening, which will reduce buffer width from the inside, affecting all riparian functions linked by buffer width, particularly the room available for channel adjustment (see Table 3). Legislation preventing the clearing of native vegetation in the riparian buffer (environmentally sensitive areas) will be pivotal to the repair of riparian vegetation.

New urban development in south-eastern Perth. Photo Leah Beesley

Table 3. The 10 riparian processes and their potential for recovery in an urban setting. Note, multiple influencing factors (limitations) are provided for each cell in the table to guide the recovery scoring. Note the factors are not prescriptive; for example, a low score could be obtained for a given process because all limitations occur at the site, or because on limitation is very severe. In addition, a factor should not be considered a limitation if restorative works are anticipated to improve the feature. Practitioners should consult experts and those with local knowledge to ensure an appropriate score is given.

	Potential for Recovery		
Riparian Process	High (score 2)	Moderate (score 1)	Low (score 0)
1. Light & temperature regulation	>10m of land is available bordering the stream (i.e., buffer width); riparian land on upstream 1km reach has good vegetative cover (i.e., shading); no wastewater treatment plant upstream discharging warm water.	Intermediate buffer width available (3-10m) Or intermediate vegetation of upstream reach OR the sunny-side of stream needed for amenity (i.e. not available for revegetation).	Little land available bordering stream (< 3 m); riparian land on upstream 1km reach has little vegetation and limited revegetation potential; wastewater treatment plant upstream of site discharging warm water.
2. Nutrient filtration & sediment trapping	Stormwater is, or will be, delivered overland to riparian zone. Riparian land is moderately sloped (5-30°) and buffer > 30m wide.	Stormwater piped to channel & riparian buffer is wide with a flat or gentle slope (<15°) OR Stormwater is, or will be, delivered overland & riparian land is either very narrow (<10m wide) or wide (> 30m) width.	Stormwater directly piped into stream channel – little overland flow at site. Land is steep (>30°) or narrow (<10m wide).
3. Bank stabilization	Scouring urban flows have been repaired by catchment WSUD or the site is immediately downstream of flow regulating structure (e.g., weir, detention basin).	Widely distributed stormwater infiltration across catchment or not far downstream of flow regulating structure.	Scouring urban flows associated with direct connection of stormwater throughout the catchment.
4. Flood attenuation	Riparian land is relatively flat (<15°) & buffer is wide (> 100m).	Riparian land is moderately sloped (15-30°) OR moderately wide (10-100m).	Riparian land is steep (>30°) OR narrow (<10m wide).
5. Channel adjustment	A buffer of >10 times bankfull distance available on either side of stream	A buffer of 3-10 times bankfull distance available on either side of stream	Little land bordering stream. Buffer is < 3 times bankfull distance.
6. Trophic subsidies	Scouring urban flows have been largely repaired by catchment WSUD or site immediately downstream of flow regulating structure (e.g., weir, detention basin); riparian buffer >20m wide.	Widely distributed stormwater infiltration across catchment has partially repaired urban flow velocity Or site not far downstream of flow regulating structure. Riparian buffer 5-20m width.	Scouring urban flows associated with direct connection of stormwater in catchment; riparian buffer <5m wide.
7. Aquatic habitat	Regulating structure (e.g., weir, detention basin) upstream reducing flow at the site. Channel hard lining can be removed, adequate space for channel reshaping if necessary & there is vehicle access to site for LWD addition.	Widely distributed stormwater infiltration across catchment or not far downstream of flow regulating structure. Intermediate room and accessibility for channel reshaping & LWD addition.	Scouring urban flows still present due to conventional stormwater management. Channel hard lining cannot be removed, no space for channel changes, no access to site for LWD addition.
8. Riparian vegetation	Moderate amount of land available for revegetation (buffer width >30m); legislation in place to prevent clearing of native vegetation in the riparian buffer.	Low amount of riparian land available for revegetation (10-30m); legislation is or isn't in place to prevent clearing.	Little land available bordering stream (< 10 m); no legislation in place to prevent clearing of native vegetation in riparian buffer.
9. Terrestrial habitat	Buffer width > 50m OR site has high functional connectivity to a large remnant patch of vegetation – i.e. an unfragmented & well-vegetated corridor exists to an adjoining large habitat patch or a patch known to contain high biodiversity.	Buffer width 10-50m wide OR site has moderate connectivity to remnant vegetation patch - this could be a connected corridor that has poor vegetation cover, or a fragmented corridor that is close to a remnant patch such that it will allow bird passage but not terrestrial fauna.	Buffer width < 10 m OR site has poor connectivity to remnant vegetation patch – e.g. numerous roads preventing animal movement, large distance to remnant patch, small sized remnant patch.
10. Terrestrial corridor	Riparian revegetation will link the site to a riparian corridor that joins site to relatively naturally vegetated land (typically upstream).	Riparian revegetation will link the site to a riparian corridor upstream or downstream that is >1 km long (corridor considered to be unbroken stretch > 1km length).	Revegetation will not link the site to a corridor (i.e. site is isolated or cut off from corridors by roads) OR revegetation will assist in the spread of an invasive species. (corridor considered to be unbroken stretch > 1km length).

Guidelines to repair riparian processes in an urban setting

There are many different on-ground actions that can be taken to repair the ecological functionality of urban riparian zones. In this section, we discuss actions that can be undertaken to support the repair of different ecological processes. The actions are described in detail below and summarised in Table 4. While the actions can be directly implemented, we recommend practitioners take a strategic approach to repair – see the next section "A management framework to guide the strategic repair of riparian ecological processes to improve waterway health".

The actions detailed below are those that can be achieved by on-ground implementation at the restoration site. However, it is important to recognise that much of the stress to urban streams comes from altered hydrology and water quality that must be addressed at the catchment scale. Thus, we encourage practitioners to implement catchment-scale Water Sensitive Design measures wherever and whenever possible, particularly in peri-urban areas (Walsh et al. 2005a, Fletcher et al. 2014, Walsh et al. 2015, Burns et al. 2016, Walsh et al. 2016). Interested readers can seek detailed guidance from specialist technical manuals.

Some of the reparative actions described below include natural and artificial approaches, as we recognise that novel methods can sometimes be the only successful option in an urban setting. However, we recommend using natural approaches where possible as they are less likely to cause other unwanted ecological problems (Hughes et al. 2014).

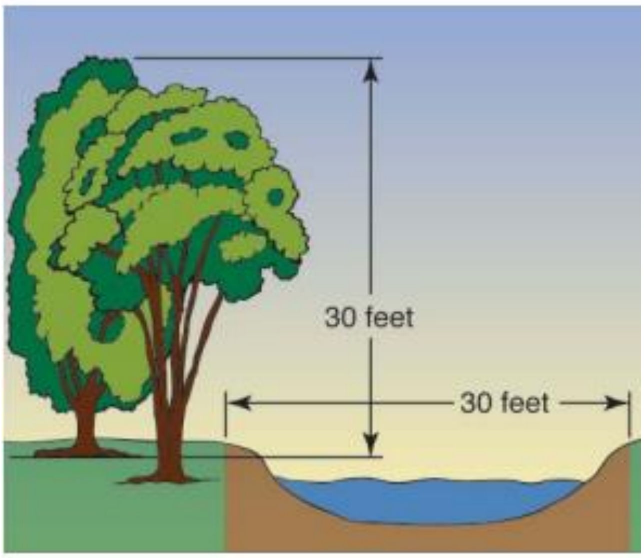
1. Repairing light and temperature regulation

Overarching strategy: shade the waterway channel.

Specific actions/strategies:

1.1) Protect and re-establish shade trees in the stream-side zone

Design Guidelines. For streams with a subcatchment less than 10km^2 or an active channel less than 10m wide, aim for 75% riparian cover across the stream channel (Bunn et al. 1999a). For larger streams, this requires tall trees in high density at the top of the bank to provide maximum shading of the stream. As a minimum rule of thumb for buffer width is to ensure there is 2 to 3 canopy widths back from the stream. This may equate to 10–30 metres in width, depending on the tree species used and the site. The exact buffer width needed to deliver shading depends on site factors such as stream size, latitude and orientation, as well as the type, height and density of vegetation (Bunn et al. 1999a, DeWalle 2010, Sweeney and Newbold 2014). Larger buffers are needed on N-S oriented streams to provide the same amount of shade as on E-W streams (DeWalle 2010). As more shade is provided from the northern bank of east–west running streams (Davies et al. 2007), these banks should be a priority for restoration works.



Tree height should be greater or equal to the width of the stream channel to provide maximal shading. Taken from Bongard and Wyatt (2010)

Similarly, riparian land with a north-westerly aspect should be prioritised for revegetation over land with a south-easterly aspect (Davies et al. 2007). Local native trees should be used and when space is limited taller *trees with denser canopies should be prioritised. In mid-latitude urban areas with limited space, effective shading can still be achieved with 12m buffers if trees are tall (30m high) and densely vegetated (DeWalle 2010).*

Note, non-native deciduous trees can be used to shade the stream; however, their use is discouraged as they have a reduced capacity to deliver to other riparian functions, such as trophic subsidies. However, practitioners may wish to keep existing non-native trees as they serve as better light protection than none at all. Non-native trees can be removed once natives have established if needed – i.e. if they pose a threat to stream health (willows, camphor laurels).

1.2) Increase buffer width

General Advice: Increasing buffer width will be important if it leads to increased stream shading (see action 1.1). Thus, increasing buffer width is likely to provide shade where the existing vegetation buffer is < 10m. However, increasing buffer width will be of little benefit for shading if it is already > 30m wide. Larger buffers are needed on N-S oriented streams to provide the same amount of shade as on E-W streams (DeWalle 2010).

1.3) Use artificial means to shade the channel

Design Guidelines. Streams can also be shaded or partly shaded using artificial means, such as using viewing platforms or shadecloth. We do not recommend the use of shadecloth; however, if it is used as an intermediary measure, i.e. while trees grow, then care should be taken that shadecloth is high enough above the stream that it will not become tangled during flood flows.

Artificial structures, such as viewing platforms, can create some stream shading, albeit very limited. Photo: Belinda Quinton

1.4) Protect from fire

General Advice: To minimise the fire risk to residents, many councils are considering implementing controlled burns of riparian vegetation; however, one side effect of this action is decreased shading of urban streams. Fire, particularly hot burns that destroy the canopy, will reduce tree shading and lead to increases *in instream water temperature. If controlled burns of urban riparian zones will be implemented for other objectives, it would be beneficial to stream shading if these burns are small so that overstorey shading is not impacted.*

2. Repairing nutrient filtration and sediment trapping

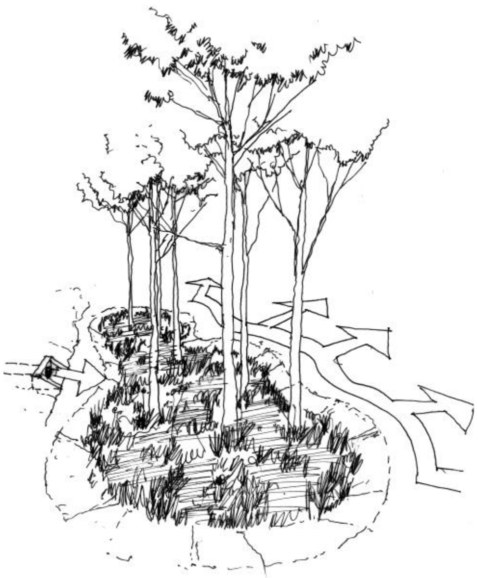
Overarching strategy: redirect catchment runoff so that it filters through riparian land.

Specific actions/strategies:

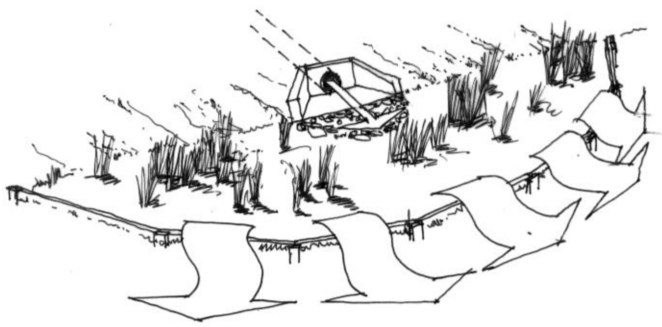
2.1) Relocate / redesign stormwater inputs and subsurface drainage inputs

General Advice: Stormwater runoff should filter through riparian soils rather than being piped directly to the stream channel. Flush road kerbing or kerbless roads can be used on the side of the road that drains into the riparian land (see Torre et al. 2006). Where stormwater pipes/subsurface drainage pipes exist, they should terminate at swales/filter strips/biofilters on the distal (road side) edge of the riparian buffer.

Flush kerbing on the left side of the road leading into a vegetated swale. Photo: Leah Beesley



Stormwater piped from the road into a swale adjoining riparian land © Water By Design (2014).



Stormwater piped into riparian land © **Water By Design (2014).**

2.2) *Increase buffer width*

Design Guidelines: Prescriptive advice on buffer width is difficult to provide because the optimal width required to strip nutrients will depend on soil type, vegetation, slope, sediment load, rainfall intensity and microtopography as well as the nutrient concentration of the incoming water (Dosskey et al. 2010). This complexity is evident by the varying buffer widths (i.e.10 – 60m) recommended for nutrient filtration in Appendix 2 Table A2. In general, buffer widths can be narrower where slope and soil promote infiltration and high residence time of water (i.e. permeable soils with gentle slope), in contrast buffers should be wider *where slope and soil promotes a low residence time of water (i.e. steeper slope, low permeability soils) (Prosser et al. 1999).*

2.3) Create a biofilter (e.g. filter strip, swale) on the distal edge of the riparian buffer

Design Guidelines: For filter strips, grass or sedges should be used with heights that exceed 10 cm (Prosser and Karssies 2001). Grasses that are invasive or weeds should be strictly avoided. Filter strip widths between 2 to 7m are typically adequate to trap sediment losses of < 10 t/ha/yr); 2m is appropriate when the riparian soil slope is low (1-2%) and 7m is appropriate where riparian soil slope is moderate (10%) see Prosser and Karssies (2001) for detailed guidelines. Note, filter strips may be relatively ineffective in flat sandy systems, such as Perth, because there is little lateral surface flow (O'Toole 2014). Placing the grass filter strip as far as possible from the channel is important because it reduces the likelihood that nutrients trapped in the strip will be remobilised during flooding (Bentrup 2008). Sedge species used in filter strip should be chosen according to water requirements, pH and salinity tolerances (see https://watersensitivecities.org.au/wp-content/uploads/2016/07/381_Biofilter_vegetation_guidelines_for_southwestWA.pdf for recommendations for suitable species in your area).

Install a filter strip and swale on the distal edge of the riparian zone. Photo: unknown source

Note, where a swale has been constructed to enhance infiltration, porous media such as sand should be used in the deepest section and nutrient adsorbing media such as clay should be used elsewhere.

2.4) Revegetate the riparian buffer (to increase plant density)

Design Guidelines: There is limited information on the density of vegetation needed to maximise nutrient uptake; however, we assume that nutrient uptake will be maximised if vegetation is as dense as possible given light availability. Increasing vegetation density should also lead to increased organic matter (e.g. leaf litter) which should increase the carbon content of soils, slow the rate of lateral water movement towards the waterway, improve phosphorous binding capacity and promote denitrification (Groffman et al. 2003, Groffman and Crawford 2003, O'Toole 2014). Note, that native nitrogen fixing species, such as Acacia spp. use nitrogen from the atmosphere rather than the soil. These plants should be used sparingly as they will lower the capacity of the vegetation buffer to uptake pollutant N (Barron et al. 2010).

2.5) Reconfigure the slope of riparian land to promote gentle lateral movement of water from the edge of the buffer to the stream

General Advice: There is little information to guide the implementation of this action. However, we recommend that in flat (<2% slope) urban landscapes (e.g. Perth, Adelaide) that the height differential between the incised channel and the land surface, be reconfigured to create a gentle to moderate slope (5-15%) that encourages the gentle lateral flow of surface stormwater from the built environment through the riparian zone to the stream. Such a configuration should promote denitrification in subsurface water (Rassam et al. 2006, O'Toole 2014).

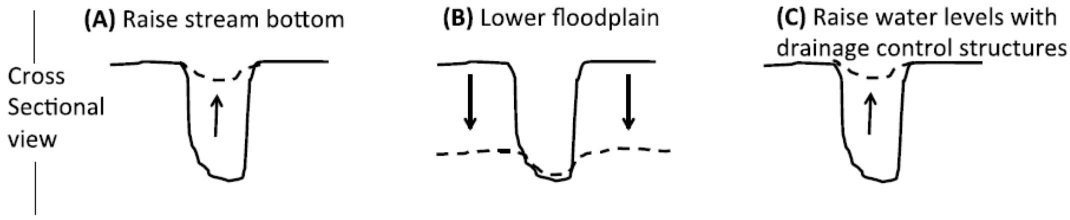
2.6) Raise or lower the local water table to combat urban changes

General Advice: Raising the water table is appropriate in areas where it has been artificially lowered (e.g. Melbourne). The water table can be raised locally by promoting local infiltration of stormwater (see actions 2.1, 2.2) and by promoting overbank flows (see actions 2.8, 2.9). As groundwater rises it will increase nutrient filtration because the interception of groundwater with carbon rich soils will promote denitrification (Groffman et al. 2003, Rassam et al. 2006). Lowering the water table is appropriate in areas where it has been artificially raised (e.g. south-eastern Perth). The water table may be lowered locally by planting deep-rooted vegetation, such as trees (see actions 2.3, 2.5, 4.3). However, the effectiveness of site-scale tree planting may be negligible if larger-scale processes predominantly control water table height (see Bhaskar et al. (2016) for a discussion of catchment-scale options).

Note. Practitioners need to firstly determine if urbanisation, or future development, has caused the water table to rise or fall – see Bhaskar et al. (2016) for a decision support tool.

2.7) Promote hydrologic connectivity by grading the bank, lowering the floodplain, raising the channel or using other methods

General Advice: Grading the bank, lowering the floodplain, infilling the channel or any other methods that increase hydrologic connectivity between the river and the riparian land will promote nutrient and sediment filtration (McBride and Booth 2005, Kaushal et al. 2008, Newcomer Johnson et al. 2016). The floodplain can be lowered across the entire buffer width using earthmoving equipment. This approach is most appropriate for a new greenfield development where there is little existing vegetation to be threatened by extensive channel and floodplain design. Where a partially vegetated buffer already exists, it may be more appropriate to grade the bank from a steep to a gentle slope (Rassam et al. 2006, Kaushal et al. 2008) or to create a terrace stretching away from the active channel. An alternative approach is to raise the channel by infilling it with a coarse sediment (gravel, cobbles). Lowering the floodplain is likely to be a more successful option than raising the channel because coarse gravel added to lift the channel maybe swept away by scouring urban flows. Lowering the floodplain will be most suitable for sites where the water table has fallen (see action 2.7). Raising the channel is more appropriate for sites where the water table has risen (see action 2.7) and may reduce the input of nutrient-rich groundwater into the waterway.



Several ways of promoting hydrologic connectivity. Taken from Newcomer Johnson et al. (2016)

Another engineered and novel approach to promote hydrologic connectivity is to raise the height of water in the channel by using instream engineered structures which partially block flow. For example w-weirs and cross vanes may be more appropriate – see action 3.7 for details. Another approach is to create a 'pond and plug' series in the channel (Boyd 2015). Pond and plug is a technique to improve floodplain connectivity in highly eroded channels and involves borrowing sediment from the eroded channel (or elsewhere) to create 'plugs' that partially block the flow in the channel raising water height to improve connection to the floodplain (See http://www.wetlandrestorationandtraining.com/wp-content/uploads/2014/07/Pond-Plug-Treatment-for-Stream-Meadow-Restoration.pdf for design details). The artificial approaches outlined here may be best suited to new developments where waterways previously did not exist and where a terraced floodplain prevents any flood risk to urban infrastructure and people.

Excavation of a floodplain terrace. Taken from Boyd (2015)

An aerial view of Pond and Plug. Taken from Boyd (2015)

2.8) Reconnect the main channel with adjacent floodplain wetlands

General Advice: Floodplain wetlands are important sites of sediment deposition and nutrient processing; hence, reconnecting the channel to these wetlands is important to reinstate natural function. To this end, levee and regulators blocking feeder creeks from the river to the wetlands should be removed. Main-channel wetland feeder creeks that have become blocked with sediment should be dug out.

Note. Wetlands in urban areas may be sources of nutrients, not just nutrient 'sinks' at some times of the year, and care should be taken when reconnecting them to the river.

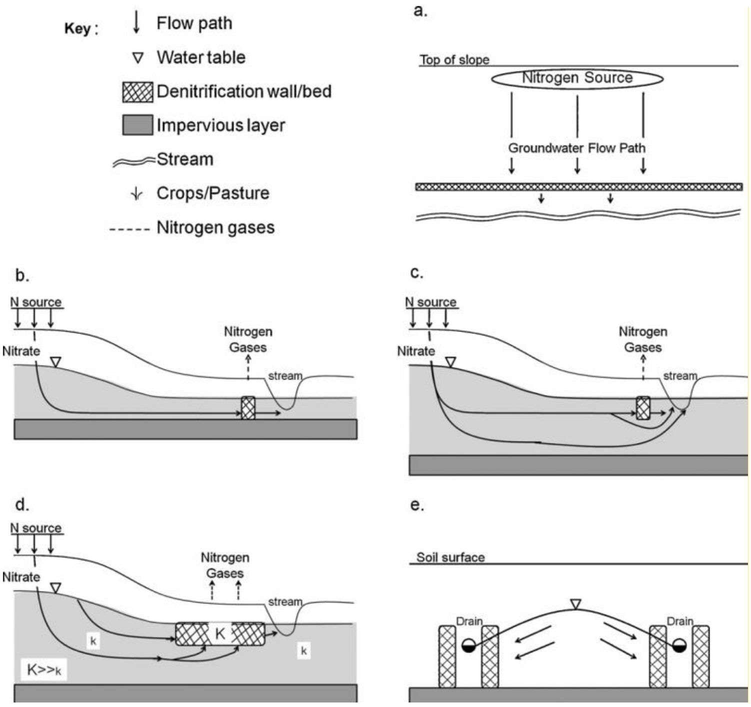
2.9) Line the stream bank and riparian wetlands with wet-dry tolerant plants (i.e. sedges)

Design Guidelines: Channels should be lined, where possible, with wet-dry tolerant sedges (O'Toole 2014). Sedges should be planted on the bank in locations where scouring flows will not dislodge them, e.g. on the inside of meander bends. Sedges should also be planted in parts of the riparian zone that sit topographically low in the landscape and are likely to receive water from the river during high flow. Plant choice should be matched to the expected hydroperiod that it will receive. Effective species for south-western Australia include: Carex appressa, C. tereticaulis, Juncus pallidus – see biofilter vegetation guidelines for southwest Western Australia for additional guidelines https://watersensitivecities.org.au/wp-content/uploads/2016/07/381_Biofilter_vegetation_guidelines_for_southwestWA.pdf

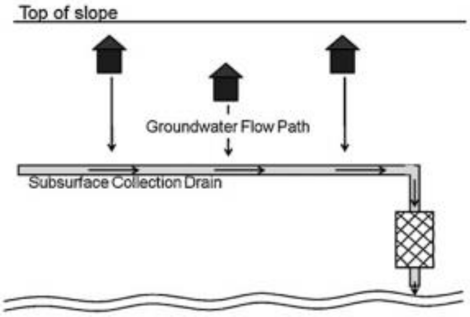
Line stream bank with sedges. Photo: Jen Middleton

2.10) Install permeable reactive barriers (bioreactors)

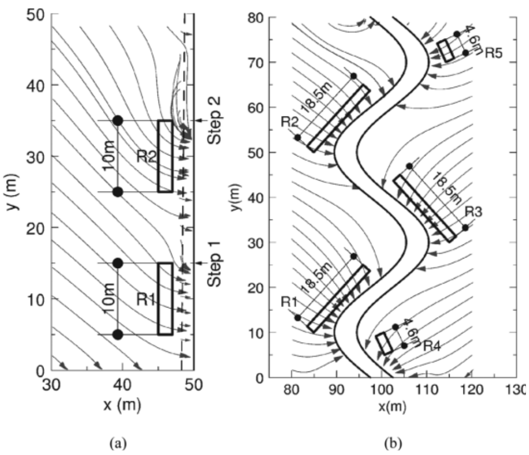
General Advice: Permeable reactive barriers can adsorb nutrients (PO_4, NO_3) or they can promote biologically-mediated nutrient transformation (e.g. denitrification). The media inside the barriers include iron oxide, calcium oxide, limestone, or sawdust (See Barron et al. (2010) for a discussion and review). Permeable reactive barriers should be placed strategically. For example, bioreactors of sawdust (i.e. carbon) that are installed to promote denitrification in the subsurface water of riparian zones where soil carbon is low should be placed at locations of high groundwater and nitrate flux into the stream (see Cui et al. (2016) for details and see Fahrner (2002) for a simple trench example in Perth). Bioreactors can be cost effective and useful to tackle point source nutrient pollution adjacent to streams (i.e. septic tanks, golf course). See Schipper et al. (2010) for a range of schematic designs and design guidelines for bioreactors to increase denitrification.



Various placement of bioreactors to intercept nitrate plumes in groundwater. Taken from Schipper et al. (2010)



Installing a bioreactor to strip nitrogen from subsurface drain water. Taken from Schipper et al. (2010)



Bioreactors placed at locations of highest groundwater and nitrate fluxes in (a) a step-pool domain, and (b) a meandering channel. Taken from Cui et al. (2016)

2.11) Remediate soil

General Advice: Remediating the riparian soil by adding substance that improve nutrient holding capacity, such as clay can be beneficial (O'Toole 2014), particularly in areas receiving high stormwater runoff. We recommend adding clay or clay-like products to riparian filter strips to increase nutrient holding capacity. Where swales are used to capture stormwater runoff, clay or clay-like materials should be added to the edge of the swale but the centre of the swale should be lined with highly permeable materials, such as sand.

2.12) Harvest grass and sedges in filter strips and along the channel's bank

General Advice: Young rapidly growing plants uptake more nutrients than older slowly growing plants, thus harvesting grass and sedges in filter strips or along stream banks (parafluvial zone) can promote vigorous regrowth and nutrient uptake (Bentrup 2008). The removal of plant matter can also prevent nutrients from being released back into the system when plants die. Harvesting plants that are important for bank stabilisation should be undertaken during periods of low flow so that plants can recover prior to scouring urban flows. This strategy is more important for phosphorus than nitrogen management (Bentrup 2008).

2.13) Protect from fire

General Advice: Controlled burns in urban riparian buffers may be undertaken to protect people and urban infrastructure; however, fire is likely to increase sediment and nutrient inputs into the urban waterway (Beesley et al. 2017). Thus, it is important to consider this trade-off and either avoid burning of urban riparian zones or mitigate the increased sediment and nutrient inputs with other management actions discuss above (also see section 1.4).

3. Repairing bank stabilisation

Overarching strategy: reduce the erosional forces acting on the waterway bed and bank by diverting and slowing flows, as well as stabilising sections of bank in erosional zones.

Specific actions/strategies:

3.1) Stabilise the stream bed

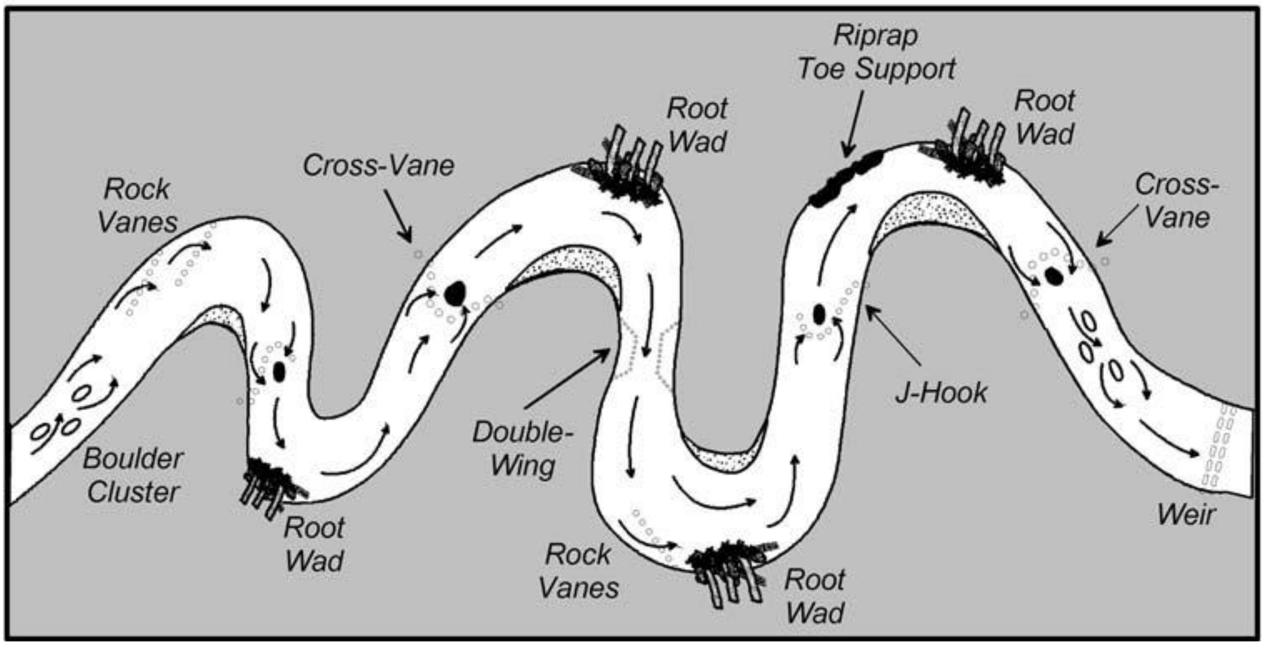
General Advice: There is little point stabilising the stream bank if the stream bed is still adjusting to altered urban flows (Price and Lovett 2002). Thus, either stabilise the bed by repairing catchment hydrology or by letting the channel naturally adjust to urban flows, see Strategy 5 'Repairing the channel's ability to self-

adjust'. If neither of these options are viable, grade control methods can be used such as cross-vanes, j-hooks, w-weirs or root-wad combinations (see action 3.7) (Shields et al. 2000, Miller and Kochel 2010).

3.2) Focus attention on parts of the waterway where erosion is strongest

General Advice: The stream or river bank is exposed to different levels of erosion along its length at a given site. For example, parts of the stream reach where the channel meanders or where there are piped inputs of stormwater will display greater erosion. It is recommended that different bank-stabilisation techniques are strategically implemented in different parts of the reach in accordance with erosional forces. Do this by breaking up the restoration site into subcomponents and address the stabilisation needs of each component individually (Abernethy and Rutherfurd 1999). Revetment (rocks, logs) may be needed in some stream sections, in-stream flow control structures may be need in some areas and replanting may be sufficient elsewhere – see Abernethy and Rutherfurd (1999) and Miller and Kochel (2010) for detailed guidance.

Note. Bank stabilisation should be considered in line with the desire to let the channel naturally self-adjust. In some instances, bank stabilisation may cause urban channels to get deeper and drain water tables further – which may, or may not, be desirable. We recommend letting the channel naturally adjust when the space exists in the riparian buffer (as per Gurnell et al. (2007)).



A hypothetical restoration site divided into subcomponents where different types of bank stabilisation techniques will be implemented. Taken from Miller and Kochel (2010)

3.3) Protect and plant deep-rooted trees and a range of vegetation in the streamside zone

Design Guidelines for the Tree Buffer in the Streamside Zone: Trees should extend away from the bank for at least 5m, PLUS the height of the bank, PLUS an additional width if the bank is actively eroding (Abernethy and Rutherfurd 1999, Rutherford 2007). The erosion allowance is calculated as the rate of bank erosion in metres per year, multiplied by the number of years it will take for replanted vegetation to reach a height of 10 metres (Rutherford 2007). For example, if the dominant overstorey vegetation matures in 20yr and the bank erosion rate is 0.5m/yr, then 10m is the additional width that must be added. Abernethy and Rutherfurd (1999) advise that, "If you do not know the erosion rate for a migrating outside bend, then a rough rule-of-thumb is 1.6% of channel width per year…thus, a 40-m wide meandering channel, where the vegetation takes 50yrs to mature, needs an ADDITIONAL 32m of riparian zone (i.e. total vegetated buffer will be > 37m)".

Design Advice for Vegetation Type and Density: Shrubs and native grasses / herbs should all be planted in conjunction with trees, because bank stabilisation is maximised by the combination of deep-rooted and shallow-rooted vegetation (Simon and Collison 2002). Trees species that provide the greatest increase in shear strength, such as Eucalypts should be prioritised over species that provide less stability such as Sambucus Mexicana (Rutherford 2007). There is relatively little information about the tree density required; however, it is recommended that trees be spaced at about half their mature canopy (Rutherford 2007). Trees should also be planted in higher density around temperate stream banks than arid stream banks (Abernethy and Rutherfurd 1999). It is also recommended that trees be planted in high density and then thinned as trees develop to encourage the establishment of large trees (Abernethy and Rutherfurd 1999). Note, that vegetation should still be planted on undercutting banks as the vegetation that falls into the waterway will help to protect the bank from further erosion (Price and Lovett 2002).

3.4) Line the stream bank with wet-dry tolerant plants (sedges and other plants)

General Advice: Plant shallow-rooted graminoids (e.g. macrophytes) as well as deeper-rooted shrubs to reduce surface erosion of the stream bank (Fischer and Fischenich 2000, Rutherford 2007). Plants should be chosen so that they are tolerant of inundation (Bentrup 2008). Grasses and other shallow-rooted vegetation will also be particularly important for bank stabilisation where the stream bank is low (< 1m high) and the bank slope is low (< 45° angle with stream*) (Lyons et al. 2000). Planting should occur during low flow periods so that plants can establish before high inundating flows occur; in some instances, these plants may require irrigation during their initial establishment (Abernethy and Rutherfurd 1999). Note, geofabric should be used to assist the establishment of macrophytes in areas of the bank prone to erosion.*

Macrophyte replanting by the south-east regional centre for urban landcare. Photo: Julie Bishop

Geofabric planted with macrophytes, Melville Perth. Photo: Jen Middleton

3.5) Add large woody debris (LWD) to the channel

General Advice: To maximise bank stability, LWD should be placed on the outside of, and downstream of, meander bends (Rutherfurd et al 1999) or on the toe of eroding banks (Shields et al. 2000). The greater the density of LWD, and the greater its complexity (rootwads, branches attached), the more effective it will be at protecting the stream bank (Booth et al. 1997, Cottingham et al. 2003). However, if water depth is great enough that the LWD can become buoyant, then simple logs may be a better option for bank stabilisation because they are more likely to become lodged on the stream bank (Booth et al. 1997). Care should be taken with LWD restoration because in urban streams scouring urban flows and sediment are likely to wash or bury LWD; similarly, channel adjustments (deepening and widening) are likely to strand LWD away from water (Booth et al. 1997). When sourcing logs, use native tree species where possible as they last longer instream than non-native softwoods and they do not pose threats to stream health (i.e. avoid camphor laurel, willows, poplar) (Cottingham et al. 2003).

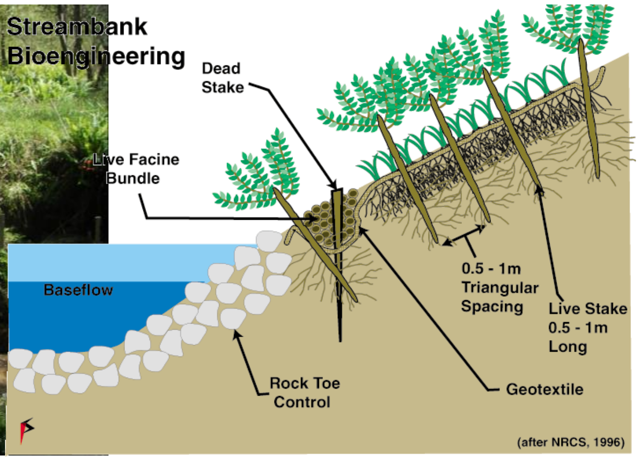
Note. In many cases the patterns of flow deflection around a log at low flow are the opposite of what occurs during high flows (Treadwell et al. 2007). It is often thought that a log oriented with its tip pointing upstream will increase scour on the bank, but often at high flows it will deflect flow away from the bank (Treadwell et al. 2007). Logs have a greater potential to influence flow and reduce bank erosion as stream size decreases (Treadwell et al. 2007).

3.6) Use bank-hardening or armouring techniques (revetment)

General Advice: Bank hardening techniques, such as RIP RAP, tree revetment, geotextiles, gabions or retaining walls can be used to stabilise stream banks, particularly parts of banks that are subject to scouring urban flows (Allen and Leech 1997). In some instances, geofabric textiles should be used to hold the stream bank in place while macrophytes and other shallow-rooted plants become established on the stream bank (Abernethy and Rutherfurd 1999). For further discussion of soft or hard engineering approaches to stabilise stream banks see http://nemo.srnr.arizona.edu/nemo/BMPdocs/StreambankStabilizationManagementMeasures.pdf.

CAUTION - bank hardening techniques, particularly hard engineering approaches, can cause an increase in near-bank velocity, stream power or shear stress which can accelerate bed and bank erosion downstream or upstream of the structures themselves (Rosgen 2001, Reid and Church 2015). Care should be taken when using these techniques and we recommend as per Reid and Church (2015) that they be used only along highly degraded channels in locations where stabilisation is essential to protect urban infrastructure. Where RIP RAP is being employed the largest material possible should be used and rough stones should be preferentially used over smooth stones (Reid and Church 2015).

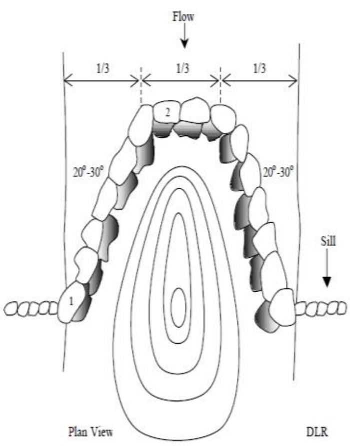
Geotextile revetment of Yosemite Creek, Blue Mountains. Photo: Geoffrey Smith



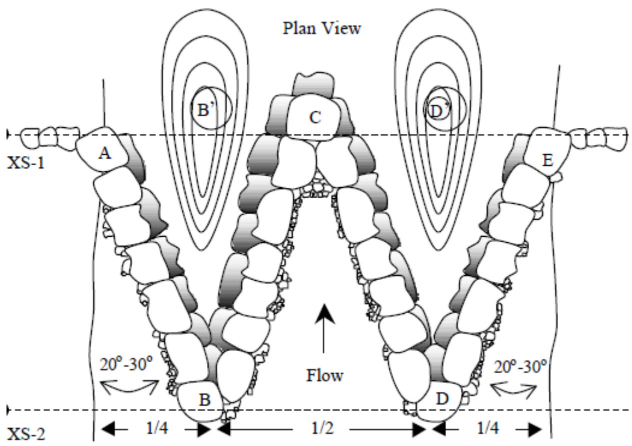
Geotextile fabrics planted out with vegetation to stabilise a str bank. Taken from Iowa State University Forestry Department. http://www.buffer.forestry.iastate.edu/Assets/streambioeng.gi

3.7) Use cross-vane, w-weir or j-hook vane structures

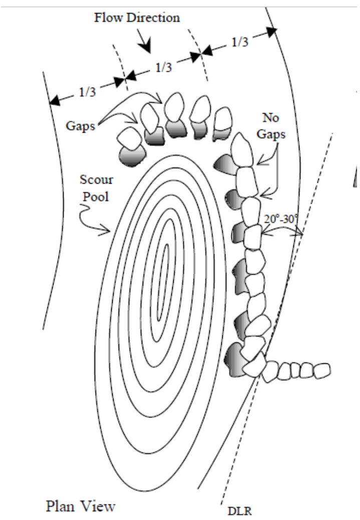
General Advice: Structures like cross-vanes, w-weirs and j-hook structures can stabilise stream banks by reducing near-bank shear stress, stream power and water velocity (Rosgen 2001). See Rosgen (2001) and Miller and Kochel (2010) for detailed design guidelines. We recommend implementation of the root wad/log vane/ j-hook combo as a semi-natural approach to enhance bank stabilisation.



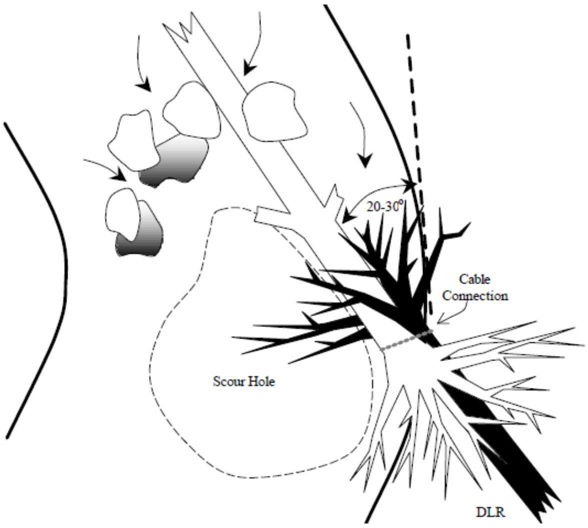
Plan view of a cross-vane. Taken from Rosgen (2001)



Plan view of a w-weir. Taken from Rosgen (2001)



Plan view of the j-hook vane. Taken from Rosgen (2001)



Plan view of root wad/log vane/j-hook combo. Taken from Rosgen (2001)

4. Repairing flood attenuation

Overarching strategy: spread out flood flows into floodplain land and allow its wetlands, depressions and vegetation absorb and slow flow.

Specific actions/strategies:

4.1) Lower the floodplain or raise the channel

General Advice: See action 2.7

4.2) Create floodplain wetlands and topographical depressions 'riparian sponges'

General Advice: The storage capacity of the floodplain can be increased by creating artificial wetlands or ponds inside the buffer zone. These wetlands are often termed 'riparian sponges' because of their ability to trap and infiltrate flood flows. The 'wetlands' are constructed depressions that may remain dry for much of the year but will absorb overbank flows during flood periods. The wetlands should be lined with porous substrate (e.g. gravel, sand) where possible to promote infiltration of floodwaters. We recommend creating wetlands with a variety of sizes and depths if space permits and planting them with sedges to improve riparian habitat for frogs and invertebrates.

A wetland biofiltration basin adjacent to a natural creek line in Perth that treats stormwater before it enters the river and also receives high flows, moderate downstream flows during floods. Photo: Belinda Quinton

4.3) Reconnect the main-channel to adjacent wetlands by removing regulators and digging out blocked creeks

General Advice: For sites that have floodplain wetlands that are disconnected from the main-channel, removing regulators or digging out blocked creek lines will promote the passage of water onto the floodplain and improve the ability of riparian land to absorb floods.

4.4) Revegetate the riparian buffer

General Advice: Revegetating the riparian buffer increases the physical roughness of the floodplain and slows the velocity of flood waters (McBride and Booth 2005). While there is little detailed information to inform the density and types of vegetation that should be planted, practitioners should note that understorey (grasses, herbs) will be most effective at slowing small floods, whereas trees will be more effective at slowing very large floods (Rutherford 2007).

4.5) Increase the width of the buffer

General Advice: There is little guidance about how wide the riparian buffer should be for flood attenuation; however, in general, the wider the buffer the more room is available for floodplain wetlands and other depressions (action 4.2) to absorb water, and the greater the land area available to capture and slow flood waters (McBride and Booth 2005).Typically, increasing buffer width will only assist with flood attenuation if the land around the channel is relatively flat so that flood waters can spread laterally to inundate the buffer area.

4.6) Remove levees and other floodplain barriers to flow

General Advice: The purpose of levees is often to prevent flooding of urban infrastructure; however, they also reduce important functions that occur when floodwaters inundate riparian land, including flood mitigation. The removal of levees will increase the site's ability to absorb flood flows, reducing the hydrological stress on the downstream urban waterway, but it should only be undertaken with proper consideration of risks to people and urban infrastructure.

5. Repairing the stream channel's ability to adjust

Overarching strategy: allow the channel to naturally change its size and position on the floodplain in response to elevated urban flows.

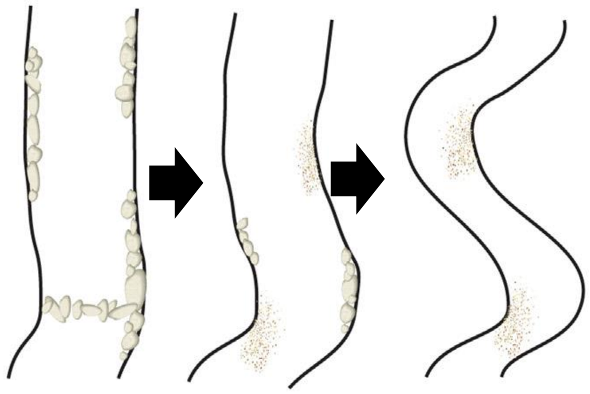
Specific actions/strategies:

5.1) Remove channel hard-lining

General Advice: Removing the hard surface of urban channels, such as concrete lining and various forms of revetment (rock, gambions, wood batons, geofabric etc.), is a prerequisite to allowing the channel to self-adjust (Vietz et al. 2016). Many geomorphologists consider that simply removing hard linings is a more efficient and cost-effective approach to channel self-adjustment than channel reconfiguration (Miller and Kochel 2010, Vietz et al. 2016).

5.2) Recreate channel sinuosity

General Advice: If the urban channel is very straight and has uniform bank sediment it may be necessary to give channel self-adjustment a head-start by using earth-moving equipment to add sinuosity. This man-made sinuosity will assist the channel to create patches of erosion and deposition and start to adjust in a more natural fashion. However, it is important to recognise that not all channels are sinuous and that sinuosity must be appropriate for the slope and substrate of the stream. Meandering channels are generally not appropriate where slope is > 2% (Sardi-Caromile et al. 2004).



Reconfigure the channel to introduce sinuosity. Modified from Vietz et al. (2016)

Note. Channel reconstruction requires considerable earth-moving equipment that may damage riparian vegetation. Managers must trade off the benefits-risks with using this technique.

5.3) Increase buffer width

General Advice: The riparian buffer must be sufficiently wide to allow for natural adjustment (Kondolf 2013). It is hard to be prescriptive about the exact buffer distance needed, because it will depend on the landscape context of the site, including its topography and geology as well as the level of urban development (Vietz et al. 2016). That said, researchers studying small to medium streams in the USA suggest that a buffer of 3 to 10 times bankfull-distance will be sufficient to allow natural channel self-adjustment in a low-level urban setting (Ward et al. 2008). For larger streams, the natural process of channel migration is usually around 1% of the channel width per year - so approximately half the channel's width should be sufficient as a riparian buffer (Rutherfurd et al. 1999). Larger buffers (i.e. widths of 100m) have been recommended for small, peri-urban streams of Melbourne (Sammonds and Vietz 2015) and are encouraged in green-field urban developments, where lower land costs make this approach more affordable (Vietz et al. 2016).

5.4) Identify and protect erosional hotspots

General Advice: Researchers promoting the natural adjustment of urban streams recommend that erosional 'hotspots' be protected with rocks (Brookes 1987, Beagle et al. 2016). A strategic assessment of sinuosity, vegetation, bank slope and height and signs of active erosion should be used to identify erosional hotspots - see Beagle et al. (2016) for additional guidance.

6. Repairing trophic subsidies

Overarching strategy: increase the input and retention of natural organic matter in the waterway.

Specific actions/strategies:

6.1) Protect and plant native vegetation in the stream-side zone

Design Guidelines: Native vegetation should be prioritised over non-native vegetation because its inputs (e.g. leaves, fruits and insects) will be timed suitably and will be of the appropriate quality and quantity to support natural stream function (Price and Lovett 2004). In terms of the width of vegetation needed to support instream food webs, two to three tree widths (10–20 m) is considered ideal, with a number of different vertical structures including ground layer plants such as grasses or sedges, small and tall shrub layers and a sub-canopy and canopy layer (Price and Lovett 2004). However, a minimum of one tree or tall shrub width (5–10 m) will still provide inputs if the vegetation has a healthy crown overhanging the stream.

Over hanging riparian vegetation inputting leaves into the urban stream, Cannington Perth. Photo: Leah Beesley

6.2) Increase channel sinuosity

General Advice: Increasing channel sinuosity increases the area of exchange between the stream and riparian vegetation – increasing leaf litter inputs (also see section 5.2 for more discussion).

6.3) Increase buffer width

General Advice: As the vegetated buffer gets wider the amount of leaf litter available to wash into the stream during overbank flows increases. Maintaining a wider vegetated buffer will be particularly important for lowland river sites where there is significant river-floodplain connection. For small streams (i.e. channel < 10m wide), a vegetated buffer of least 10m either side of the stream should be adequate (Price and Lovett 2004).

6.4) Revegetate the riparian buffer (increase plant density by protecting existing vegetation and replanting)

General Advice: Increasing plant density increases the volume of litter fall into streams and the amount swept into streams during overbank flows. There is little information about the density of plants required; however, we suggest as high a density as light levels will permit. Plants should be natives as per action 6.1.

6.5) Add LWD to the channel

General Advice: LWD in the channel, slows the flow of water helping the site to retain leaf litter. LWD also physically traps leaf litter (i.e. debris dams) in the site making it more likely to enter the food web. See action 7.1 for details about how to add LWD to the channel.

A debris dam trapping leaf litter in an urban channel. Photo: Jen Middleton

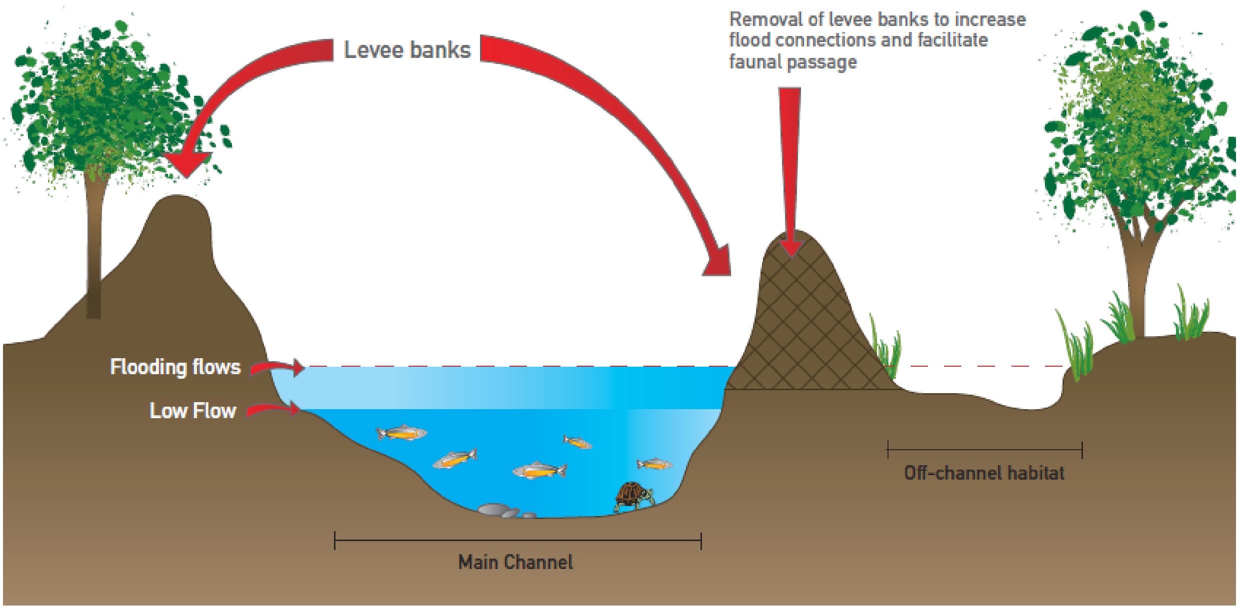
6.6) Promote hydrologic connectivity by grading the bank, lowering the floodplain, raising the channel or using other methods

General Advice: For lowland river sites, the floodplain can be a productive source of energy. Increasing the flow of water between the channel and the floodplain proper and floodplain wetlands promotes energy production. See action 2.8 for details about the physical actions promoting this.

6.7) Remove levees and other floodplain barriers to flow

General Advice: Regulators or levees blocking flow between the main river channel and floodplain wetlands should be removed or new flow paths (i.e. channels) cut. Where channels have become infilled with sediment they should be dug out. New channels can be cut to improve the movement of nutrients, organic matter and animals between the river and floodplain wetlands if needed.

Note. Wetlands should not be reconnected to the waterway if they contain invasive species, or if they are sources of nutrient pollution.



Levee removal to reconnect stream to adjacent floodplain wetland. Taken from King and Torre (2007)

6.8) Manage or redesign gross pollutant traps (GPTs) so that leaves pass to stream

General Advice: GPT's designed to remove plastic from stormwater pipes before they reach the stream often trap large amounts of leaves, preventing their passage into the stream. Where the majority of leaf litter trapped in GPT's is native then GPT's should be managed so that leaves can still enter the waterway.

Leaves trapped in a GPT Blue Mountains. Photo: Geoffrey Smith

Leaves trapped in a GPT Hornsby Shire, NSW. Photo: unknown

6.9) Protect from fire

General Advice: Controlled burns in the riparian zone will destroy leaf litter and other vegetation inputs into streams altering the nutrient and trophic dynamics, thus, they should be avoided to maintain healthy stream function. If controlled burns are required to protect people and urban infrastructure, burning at low intensity, in small spatial patches, and at frequent time intervals may reduce the impact on the nutrient dynamics of the urban stream. Furthermore, and perhaps most importantly, controlled burns should never take place in a riparian zone before heavy rains. When burns occur in riparian zones before heavy rains, streams can be impacted in similar ways to the urban stream syndrome, further degrading urban water ways.

7. Repairing aquatic habitat

Overarching strategy: create a diversity of physical habitat types in the main channel and create wetlands with a diversity of wetting and drying regimes on the floodplain.

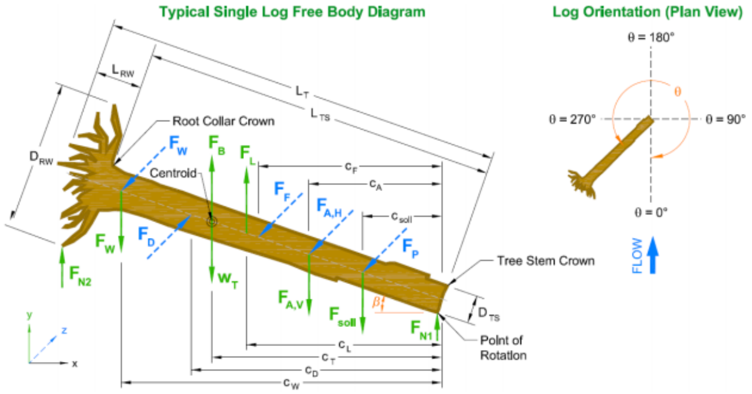
Specific actions/strategies:

7.1) Add LWD to the channel

Design Guidelines: The aim should be to restore a natural load of wood to the stream, logs should only be reinstated if they were naturally present in the stream. Estimates of historical wood loads are available for a variety of bioregions in south-eastern Victoria, see Kitchingman et al. (2016). If no information is available about the historical LWD loading of the stream then approximately 0.01m^3 for every m^2 of channel bed should be used as a guide (Treadwell et al. 1999, Treadwell et al. 2007). When restoring LWD to an urban waterway a variety of sizes should be used, and it should be placed in stable configurations otherwise it may be washed downstream (Booth et al. 1997) and may cause damage to urban infrastructure (Wohl et al. 2016). Wood will have a greater potential to influence instream geomorphic complexity where the stream is narrow – i.e. wood will have little influence on flow and the creation of geomorphic structures where the channel is > 30 times the depth of the water (Price and Lovett 2002). Preferentially use native hard-wood trees over introduced species such as willows (Salix spp.) or poplars (Populus spp.), and install a variety of sizes of wood. When adding LWD to improve habitat - keep in mind its ability to affect bank erosion (see action 3.5) and remember that logs that deflect flow in one direction during low flows will likely send water in *the opposite direction during high flows (Treadwell et al. 2007). Place logs in different orientations to channel flow to create a variety of hydraulic conditions. Logs placed perpendicular to the flow are best at creating scour pools (Treadwell et al. 1999, Erskine and Webb 2003, Erskine et al. 2007). Logs placed parallel to the flow will create scour pools upstream and bars or islands downstream; and logs placed at an angle will create a combination pool and bar (Treadwell et al. 2007). Ideally, LWD should be placed in the centre of the channel and against the bank and should be placed so that some logs have branches extent above the water to create sites for insect oviposition (egg laying) while others have branches below the water to create habitat for instream fauna (Treadwell et al. 1999). For detailed guidance about the reintroduction of wood into Australian streams see Brooks et al. (2006).*

Note. There are often concerns that LWD addition will increase the risk of flooding; however, this is unlikely to occur unless the wood occupies > 10% of the cross section of the channel (Price and Lovett 2002). Do not reorient existing logs in the channel as it is likely to compromise their ecological function (Treadwell et al. 1999) and increase the likelihood that they are washed away by urban flows. Do not source new LWD from the local urban riparian zone.

If concerns exist about the risk to urban infrastructure, we recommend using the Large Wood Structure Stability Analysis Tool produced by http://www.fs.fed.us/biology/nsaec/products-tools.html (Rafferty 2017). The associated resource (Wohl et al. 2016) describes the process and may be a useful accompaniment.



Large wood structure stability analysis tool. Taken from Rafferty (2017)

7.2) Protect, plant and maintain native vegetation in the stream-side zone

General Advice: Adding LWD directly into a stream/river is expensive and a short-term approach to repairing wood habitat in the urban waterway. A longer-term solution is to create a well-treed riparian buffer that will generate its own wood supply. There is little prescriptive advice about the design of the buffer, we recommend that the design guidelines for action 3.3 are followed.

7.3) Remove channel hard-lining

General Advice: Removing hard lining (see action 5.1) will assist the channel to naturally adjust to altered urban flows, which will promote the formation of instream habitat features such as bars, benches, riffles and pools and improve the quality of instream habitat (Gurnell et al. 2007, Vietz et al. 2016). Removing hard-lining is also important for aquatic or semi-aquatic fauna that use riverbanks for habitat, such as platypus and certain species of fish (e.g. freshwater cobbler).

7.4) Recreate channel sinuosity

General Advice: Increasing channel sinuosity using earthmoving equipment (see action 5.2) also assists the channel to naturally adjust to urban flows and promotes the formation of instream geomorphic units such as bars, benches, pools and riffles that increase habitat diversity.

Channel reconstruction, Brentwood Living Stream, Western Australia. Photo: Glen Byleveld. Courtesy of SERCUL and WA Department of Biodiversity and Conservation

7.5) Line the stream bank with wet-dry tolerant plants (i.e. sedges)

General Advice: Lining the streambank with sedges creates complex habitat that protects zooplankton, aquatic invertebrates and frogs from predators. In an urban setting, this action is most likely to be successful where macrophytes are placed in areas protected from scouring urban flows – i.e. depositional areas (e.g. on the inside and downstream of meander bends).

7.6) Add wall boxes or ledges

General Advice: In highly engineered and revetted waterways (i.e. concreted river channels running through the centre of old cities) wall boxes or ledges can be anchored on the edge of the channel and planted with macrophytes and sedges to deliver similar benefits as action 7.5 (Francis et al. 2008). See photos for action 8.7 as a guide.

7.7) Create floating anchored gardens

General Advice: Floating gardens placed along the edge of highly revetted lowland waterways can create patches of low flow along the edge of the channel. If gardens are planted with dense overhanging vegetation they can also provide cover for fish.

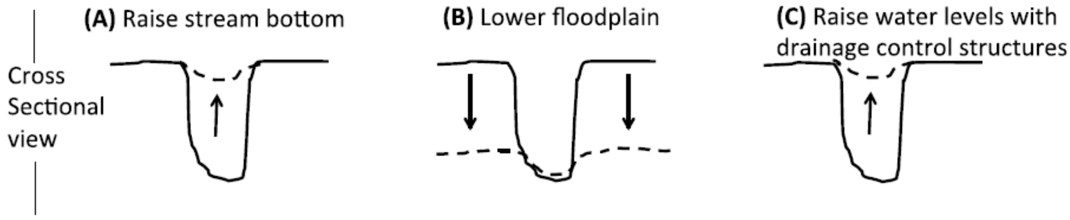
A floating garden in the Seine River, France, supporting trailing vegetation that acts as habitat for fish. Photo: Leah Beesley

7.8) Create floodplain wetlands and depressions

General Advice: Creating or protecting riparian wetlands and other depressions creates still-water habitats that may act as refuges for instream fauna during spates of high flow. These wetland habitats will also provide important habitat for species that would otherwise fare poorly in the main channel either because of the presence of fish or the presence of scouring flows and sediment, e.g. frogs, invertebrates. See action 4.2 for other details.

7.9) Promote hydrologic connectivity between the main-channel and the floodplain

General Advice: Grading the bank, lowering the floodplain, raising the channel, or raising water depth using weirs or other engineering structures increases the extent to which stream/river water flows out onto the floodplain and replenishes a variety of still-water aquatic habitats. See action 2.7 and 3.7 for additional details about the implementation of this strategy.



Several ways of promoting hydrologic connectivity. Taken from Newcomer Johnson et al. (2016)

7.10) Protect from fire

General Advice: Fire is likely to lead to a slug of sediment entering the waterway which may bury instream habitat and cause oxygen levels to crash (Lyon and O'Connor 2008). Fire can also cause an increase in LWD additions to the channel as burnt trees are more likely to fall in (Minshall et al. 1997); however, in general fire should be avoided where possible in urban riparian zones as its negative consequences far outweigh its benefits (Beesley et al. 2017).

8. Repairing riparian vegetation

Overarching strategy: protect and promote natural native vegetation.

Specific actions/strategies:

8.1) Remove weeds

General Advice: Removing weeds, particularly invasive species, will reduce competition between native and non-native species for light and space and will help in the establishment of a native riparian vegetation assemblage. Weed removal should occur before weeds set seed and should target areas where weeds are encroaching into relatively healthy native vegetation patches. Weeds can be removed by hand or by spot-spraying. If spraying take care to use chemicals that rapidly degrade into harmless compounds (e.g. glyphosate), avoid spraying pesticides near the stream channel.

Weed spraying. Photo: unknown source

8.2) Protect native vegetation and revegetate the buffer with natives

General Advice: Native replanting should focus on plants that are well-suited to local microclimates. Plants will be most suitable if they are sourced locally (Askey-Doran 1999). If the area to be revegetated is small then direct planting may be achievable, if the area is large then direct seeding or a combination of planting and seeding maybe necessary. Where direct planting occurs, plants should be placed where the soil type, soil moisture, and light are suitable (Askey-Doran 1999). Planting in patches rather than plant the entire riparian zone maybe beneficial as it may provide an insight into the species that are most likely to survive (Auckland Council 2015). Future planting activities can be undertaken when returning to the site for weed and plant maintenance.

Plant in two stages. The initial planting (stage 1) should include 'coloniser species' that are able to survive in hotter and drier conditions (Auckland Council 2015). This should include trees and shrubs that will modify the microclimate. The secondary planting (stage 2) can include species that require cooler and moister conditions. These more sensitive species should be interspersed between the coloniser species once they are established. If an overstorey of trees already exists then it may be fine to plant both stage 1 and 2 plants together.

Plants should be planted preferentially during cool months when soil moisture is high (Askey-Doran 1999). However, plantings in floodplain areas and along the stream bank may need to occur during low flows otherwise scouring urban flows may dislodge them. Plant at a higher density to account for high mortality; plants can always be thinned later if required. Protect and support plants, particularly tree seedlings by staking them and using a fence or bag to protect them (Auckland Council 2015). Planting should be supported by irrigation where needed, weeding should be ongoing until native plants are well established. See http://www.aucklandcouncil.govt.nz/EN/environmentwaste/coastalmarine/Documents/streamsideplantingguide.pdf for further guidance.

Eucalypt seedling. Photo: Jen Middleton

Planting order and tips

- *Only replant once all earth-moving works are complete*
- *Remove weeds (see action 8.1)*
- *Prepare the soil (tilling, soil amendments)*
- *Use native species where possible, particularly plants sourced locally*
- *Plant from the stream out and plant in patches*
- *Plant in successional stages*
  - *stage 1: plant early successional species OR establish an overstorey to protect understorey vegetation*
  - *stage 2: plant late successional species*
- *Ensure plants are placed in micro-locations suitable to their soil, water and light requirements*
- *Undertake plantings during cool weather when soils moisture is high*
- *Plant a higher density than wanted in anticipation of plant mortality*
- *Stake plants and protect them using a fence or individual bags if humans or herbivores are present*
- *Support plants with irrigation if necessary*
- *Monitor the success of plantings and continue weeding until native plants are established*

8.3) Fence off riparian vegetation

General Advice: Fencing is a good way to prevent humans from trampling and damaging riparian vegetation and spreading weeds. The suitability of this option will depend on (i) the amenity that stakeholders wish to achieve with the site and (ii) the risk to the fence from flood-associated debris. Ensuring there is adequate legislation to prevent the clearing of riparian land is critical to its recovery and long-term persistence in an urban setting.

Fenced riparian land along the Canning River, Perth, Western Australia. Photo: Leah Beesley

8.4) Increase buffer width

General Advice: As the riparian buffer widens there is more room to sustain a greater number and diversity of plant species. A study in Sydney has found that as riparian buffers widen there are fewer edge effects and a higher proportion of native plant species (Ives et al. 2011).

8.5) Lower the floodplain or raise the channel to semi-natural river-floodplain hydrologic connectivity OR alter plant species choice

General Advice: Lowering the floodplain or raising the channel (see action 2.7) can reinstate a more natural river-floodplain hydrologic connectivity that will increase the survival of riparian vegetation. In many urban settings, this will not be achievable. In such instances, we recommend using floodplain depressions (see action 4.2) to create habitat patches that will trap and hold water, or alternatively avoiding species that require high soil moisture or periodic inundation.

8.6) Repair the height of the water table OR alter plant species choice

General Advice: Some riparian species, particularly trees may depend on access to groundwater to sustain them over dry periods. For these groundwater-dependent riparian species it is important to lower or raise the water table to combat urban changes. Strategies to achieve this are briefly presented in action 2.6. In instances where water table manipulation is not possible or practicable we recommend planting species that will survive given the altered access to groundwater. For example, if urbanisation has caused the water table to fall markedly at a site consider planting a eucalypt tree species that is more drought resilient than those that would naturally have occurred.

Note. Lowering the floodplain (action 8.5) effectively reduces the distance between riparian plants and the water table and this maybe a more achievable solution than repairing the water table. This solution will only be appropriate for sites where urbanisation has caused the water table to fall.

8.7) Add wall boxes or ledges

General Advice: In highly engineered and revetted waterways (i.e. concreted river channels running through the centre of old cities) there is limited opportunity to implement many of the actions recommended here. In such instances, anchoring wall boxes or ledges with distinct soil types along different heights of the channel embankment will provide a diversity of habitat types that will support a range of riparian plant species (Francis et al. 2008). Boxes or ledges could be planted out or could be left to be colonised naturally. Boxes are most *likely to be successful if they are placed in recesses – i.e. near steps and jetties, where flows are gentler (Francis et al. 2008).*

Wall ledges on Deptford Creek, Inner London. Photo: Robert Francis

Wall box attached to concrete lined channel, Thames River, London. Photo: Robert Francis

8.8) Create floating gardens

General Advice: Another approach in highly engineered urban rivers is to create an anchored floating garden that can be planted with native riparian vegetation. This approach is particularly useful when the true riparian zone of the river cannot be reclaimed.

A floating garden on the Seine River, France. Photo: Leah Beesley

8.9) Protect from fire or burn appropriately

General Advice: Urban riparian vegetation should be protected from fire because it will exacerbate many of the stresses urban streams face (Beesley et al. 2017). In special circumstances where fire is considered critical care should be taken to only burn part of the riparian corridor so that native wildlife can seek refuge, create a cool burn, avoid burning when heavy rain is likely to flush ash into the stream system.

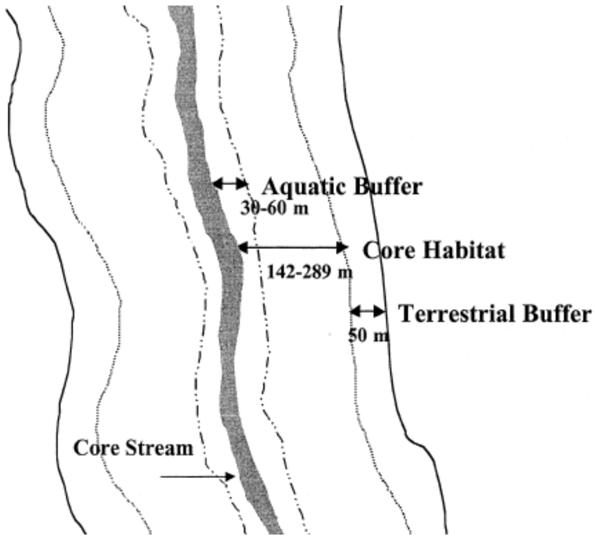
9. Repairing terrestrial habitat

Overarching strategy: create and protect a diversity of physical habitat types in the riparian buffer so that a diversity of animal species (frogs, birds, reptiles, invertebrates) can create a home.

Specific actions/strategies:

9.1) Increase buffer width

General Advice: It is difficult to be prescriptive about the buffer width needed because different animals will require different amounts of space to forage and complete their life cycle. Researchers suggest that a width of 10 to 30m will be sufficient to support small animals such as invertebrates, lizards and some birds (Lynch and Catterall 1999, Catterall et al. 2007). But recent studies indicate that larger widths in excess of 50 to 100m may be needed for many animals, particularly larger species (Semlitsch and Bodie 2003). Researchers also recommend incorporating a 50m outside buffer to protect core habitat from edge effects (Murcia 1995). Recently, a 200-m wide riparian buffer has been recommended to protect the endangered Growling grass frog from urban development (Gilmore and Shepherd 2012). Agricultural guidelines in Victoria recommend maintaining a 200-m wide buffer for native fauna (Hansen et al. 2010).



Proposed buffer widths to protect fauna. Taken from Semlitsch and Bodie (2003)

9.2) Protect native vegetation and revegetate the buffer with natives

General Advice: To provide structural habitat for an array of native fauna, planting should occur to enhance structural diversity. That is, planting should occur so that groundcover (herbs, grasses), understorey (shrubs), and overstorey (trees) are all present, unless naturally absent at the restoration site (e.g. stream running through urban grassland). Uneven planting is encouraged as it will better simulate natural patchiness and provide areas of high- and low-density vegetation that provide nesting and foraging habitat for a variety of species (Catterall et al. 2007). To provide food for an array of fauna it is important to ensure that an array of native plant species are used. Native species should flower, fruit and set seed of appropriate quality and quantity. Care should be taken to ensure that plants do not overly advantage invasive species. Where plant species need to be prioritised, we recommend that managers obtain knowledge about the preferred diets of ecologically important or valued animal species (e.g. bats, birds, bandicoots) and that these plants be used preferentially.

9.3) Lower the floodplain or raise the channel to promote hydrologic connectivity

General Advice: Lowering the floodplain or raising the channel (see action 2.7 for design advice) can reinstate a more natural river-floodplain hydrologic connectivity that will replenish intermittent floodplain *habitats (i.e. wetlands, ponds) that support aquatic and semi-aquatic fauna (e.g. frogs, turtles, invertebrates). This action can be supported by action 9.4.*

9.4) Create floodplain wetlands & topographical depressions 'riparian sponges'

General Advice: Creating or protecting riparian wetlands and other depressions in the riparian buffer that vary in their hydroperiod (i.e. how long the hold water for) is encouraged because it increases the diversity of habitat types, increasing the suitability of the riparian land for an array of fauna (Tockner et al. 2000, Ward et al. 2002). See action 4.2 for other details.

9.5) Protect dead trees and terrestrial woody debris

General Advice: Dead standing trees should be protected as they provide important nesting and roosting habitat for birds and mammals (Lynch and Catterall 1999). Fallen timber should also be kept as it provides important habitat for invertebrates and other ground-dwelling animals (Catterall et al. 2007). Fallen timber can also support fungus, which may be an important food for some species.

A dead tree that has been burnt and contains hollows for wildlife, Rossmoyne Perth. Photo: Jen Middleton

Fallen timber in urban riparian land, Rossmoyne Perth. Photo: Jen Middleton

9.6) Install nest boxes

General Advice: Artificial nest boxes can be used to rapidly create nesting and roosting habitat. The height and density of boxes will depend on the management species of interest. The installation of nest boxes should be accompanied by action 9.2 and 9.5 as nest boxes have a limited lifespan (Lynch and Catterall 1999).

Using a chainsaw to create a bat roosting chamber. Photo: Sydney Arbour Courtesy of Carl Tippler

A bat box installed at Sydney Park, Alexandria. Photo: Carl Tippler

9.7) Fence off the riparian zone

General Advice: Fencing off riparian land may compromise amenity and possibly aesthetics, but it can protect native fauna from dogs, cats and foxes (Lynch and Catterall 1999). This action is encouraged when the riparian land supports valued fauna (e.g. bandicoots, turtles, frogs) that are vulnerable to disturbance or predation.

9.8) Inoculate the soil

General Advice: Where riparian vegetation has been dramatically cleared (e.g. agricultural greenfield sites, brownfield development) soil microbes and invertebrates may be missing. These microbes/invertebrates play important roles breaking down leaf litter - creating habitat and food for other species (Lynch and Catterall 1999). Where the urban riparian site is highly degraded, or where it has been severely disturbed by earthmoving activities, it is recommended that leaf litter, dead wood and soil be transported from a nearby riparian refuge (Lynch and Catterall 1999). Ideally, this would be from a relatively intact location at the site, but it could be from a nearby riparian refuge.

9.9) Place street lights on the far side of adjoining roads

General Advice: Street lights can draw semi-aquatic insects away from the waterway and interfere with the foraging behaviour of other biota (Scanlon and Petit 2009, Perkin et al. 2011, Senzaki et al. 2016). To prevent artificial light from impacting biota lights should be placed on the far side of the road and angled to reduce the light they throw onto riparian land. Where possible dense vegetation should be planted on the edge of the buffer to reduce light penetration into the riparian land. Human safety considerations need to be considered.

9.10) Protect from fire or burn appropriately

General Advice: Fire can destroy important terrestrial habitat such as hollow trees and woody debris. Fire can also cause direct mortality to wildlife that aren't able to escape from the heat and flames. Thus, controlled burns should be avoided to undertaken in such a way as to have as little impact as possible.

10. Repairing the terrestrial corridor

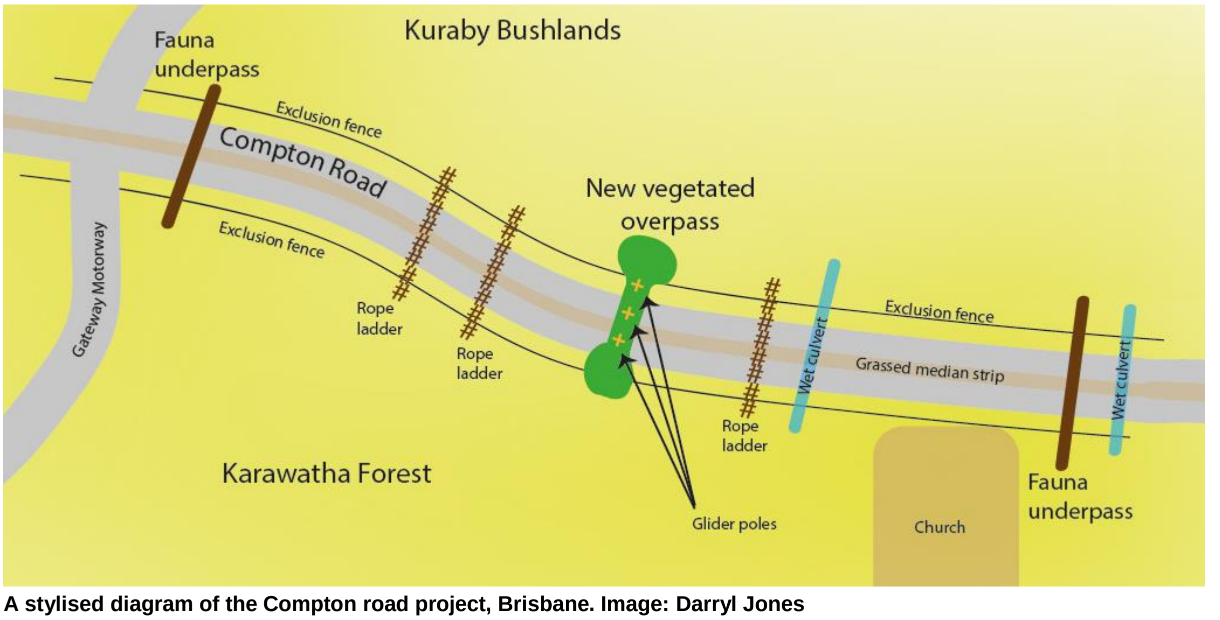
Overarching strategy: connect the site's riparian buffer to well-vegetated stretches of riparian land and to relatively intact parcels of remnant bushland.

Specific actions/strategies:

10.1) Reconnect to adjacent riparian corridor or patch of remnant vegetation

General Advice: A tract of riparian land will only contribute to the creation or extension of a wildlife corridor if it can be connected to an existing riparian corridor or a piece of remnant bushland. Creating a corridor is relatively straightforward if lack of vegetation is the major impediment, all that needs to be done is to revegetate the discontinuous stretch of land, such that it creates appropriate cover for animals. Creating a corridor is considerably more difficult if roads or other barriers exist between the restoration site and the remnant corridor or parcel of bushland; however, some level of connectivity can still be achieved. Novel strategies include vegetated wildlife overpasses, rope ladders, and customised below-road culverts that act as tunnels for animals.

Caution. When connecting newly revegetated land to an existing wildlife corridor care should be taken not to create an ecological trap. An ecological trap occurs if the repaired corridor leads animals away from good quality habitat into poorer quality habitat where their survival is reduced (Jackson and Pringle 2010, Hale et al. 2015). For example, a corridor should not be created that encourages wildlife away from a wetland and into the path of a road, or away from a natural wetland into a polluted stormwater biofiltration basin.



A stylised diagram of the Compton road project, Brisbane. Image: Darryl Jones

A vegetated overpass providing safe passage for wildlife over Compton Rd, Brisbane. A rope ladder providing passage for possums is shown in the foreground. Photo: Darryl Jones

10.2) Increase buffer width

General Advice: It is hard to be prescriptive about the buffer width required to create an effective corridor because habitat requirements vary markedly among species (Loney and Hobbs 1991). However, in an urban setting, where space is limited, most experts recommend creating as wide a buffer as possible (Parker et al. 2008). Wide buffers are promoted because they are likely to contain a more diverse array of habitat types, thus meet the movement needs of more species (Lindenmayer 1994), and because they minimise the ratio of edge to interior habitat. Edge habitat is typically of poorer quality than interior habitat because vegetation is typically thinner and the land has a greater exposure to people and their pets, to road noise and to artificial light (i.e. street lights). In Melbourne, recent studies have recommended that 100m riparian buffers be created around creeks in peri-urban areas to facilitate the movement of the growling grass frog, a threatened species (Gilmore and Shepherd 2012). In general, rules to keep in mind are: (i) the larger the animal(s) of interest the wider the corridor should be, (ii) the longer the riparian corridor the wider it needs to be, and (iii) corridors should be wider where the urban build environment is greater (Bentrup 2008).

10.3) Protect native vegetation and revegetate the buffer with natives

General Advice: Riparian land will only act as a corridor if it provides sufficient cover for wildlife. Revegetating the buffer with dense, structurally complex native vegetation (e.g. overstorey, understorey, groundcover) is recommended. Where movement of a particular species(s) is a management priority, practitioners should investigate their habitat preferences and ensure that they are likely to be met by restoration works.

10.4) Minimise road crossings

General Advice: Road crossings bisecting riparian land should be minimised wherever possible (Wenger and Fowler 2000). Where road crossings cannot be avoided riparian connectivity can still be provided by using flyovers – although care should be taken to ensure the flyover is large enough that a vegetated buffer can still be created under the road. Novel methods such as vegetated flyovers could also be used, see action 10.1.

A road flyover crossing the mid-Canning River, Perth. Photo: Leah Beesley

Table 4. Actions/strategies and the riparian processes they support. Numbers after each action in parentheses refer to the section above where they are discussed in more detail, note the language used to describe an action in this table may differ slightly from the language used to describe the action in the text for any given ecosystem process. Actions are presented in decreasing order of the number of ecosystem processes they support.

	Riparian Process										
Action/strategy	1. Light & temperature regulation	2. Nutrient filtration & sediment trapping	3. Bank stabilization	4. Flood attenuation	5. Channel adjustment	6. Trophic subsidies	7. Aquatic habitat	8. Riparian vegetation	9. Terrestrial habitat	10. Terrestrial corridor	# of functions
Increase buffer width (1.2, 2.2, 4.5, 5.3, 6.3, 8.4, 9.1, 10.2)	✓	✓		✓	✓	✓		✓	✓	✓	9
Protect native vegetation and revegetate the buffer with natives (2.4, 4.4, 6.4, 8.2, 9.2, 10.3)		✓		✓		✓		✓	✓	✓	6
Protect from fire (1.4, 2.13, 6.9, 7.10, 8.9, 9.10)	✓	✓				✓	✓	✓	✓		6
Promote hydrologic connectivity between the waterway & riparian land by grading the bank, lowering the floodplain, raising the channel or other means (2.7, 4.1, 6.6, 7.9. 8.5, 9.3)		✓		✓		✓	✓	✓	✓		6
Re-establish native trees & other native vegetation in the stream-side zone (1.1, 3.3, 6.1, 7.2)	✓		✓			✓	✓				4
Add large woody debris to the channel (3.5, 6.5, 7.1)			✓			✓	✓				3
Reconnect the main channel with adjacent floodplain wetlands by removing levees, regulators and unblocking creek channels (2.8, 4.3, 6.7)		✓		✓		✓					3
Create floodplain wetlands & topographical depressions 'riparian sponge' (4.2, 7.8, 9.4)				✓			✓		✓		3
Line the stream bank with wet-dry tolerant plants (2.9, 3.4, 7.5)		✓	✓				✓				3
Recreate channel sinuosity (5.2, 6.2, 7.4)					✓	✓	✓				3
Fence off riparian vegetation (8.3, 9.7)								✓	✓		2
Remove channel hard-lining (5.1, 7.3)					✓		✓				2
Remove levees & other floodplain barriers to flow (2.8, 4.6, 6.7)				✓		✓					2
Raise or lower the water table below the riparian zone (2.6, 8.6)		✓						✓			2
Add wall boxes or ledges (7.6, 8.7)							✓	✓			2
Create floating anchored gardens (7.7, 8.8)							✓	✓			2
Use artificial means to shade the channel (1.3)	✓										1
Relocate / redesign stormwater & sub-surface drainage inputs (2.1)		✓									1
Create a biofilter (e.g. filter strip, swale) on the distal edge of the riparian buffer (2.3)		✓									1
Reconfigure the slope of riparian land (2.5)		✓									1
Install permeable reactive barriers (2.10)		✓									1

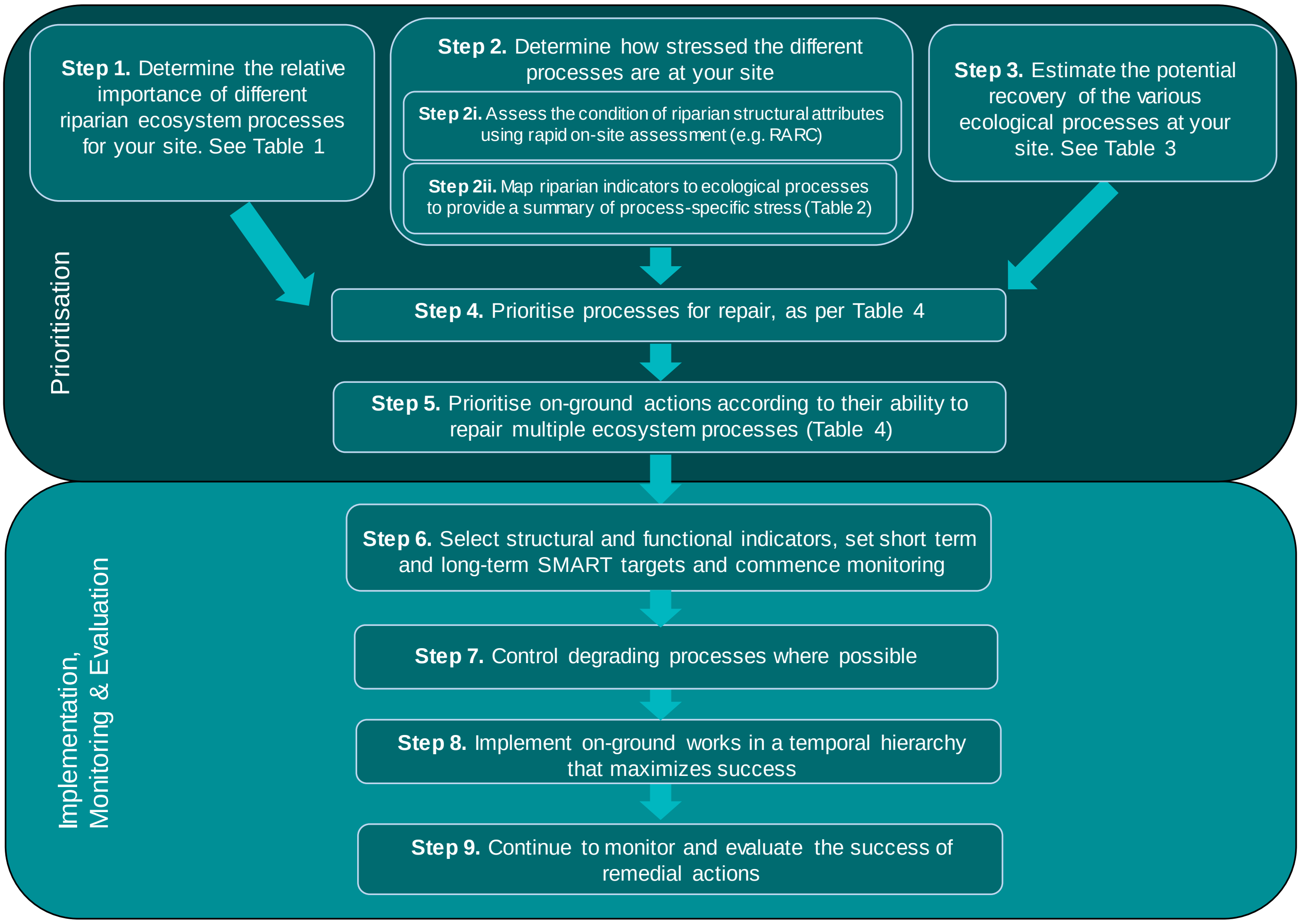
	Riparian Process										
Action/strategy	**1. Light & temperature regulation**	**2. Nutrient filtration & sediment trapping**	**3. Bank stabilization**	**4. Flood attenuation**	**5. Channel adjustment**	**6. Trophic subsidies**	**7. Aquatic habitat**	**8. Riparian vegetation**	**9. Terrestrial habitat**	**10. Terrestrial corridor**	**# of functions**
Remediate soil (2.11)		✓									1
Harvest grass and sedges in filter strips and along the channel's bank (2.12)		✓									1
Stabilise the stream bed (3.1)			✓								1
Identify and protect parts of the bank that are erosional hotspots (3.2, 5.4)			✓								1
Use bank-hardening of armouring techniques (3.6)			✓								1
Use cross-vane, w-weir or j-hook vane structures (3.7)			✓								1
Manage or redesign GPT's so that leaves pass to stream						✓					1
Remove weeds (8.1)								✓			1
Protect dead trees & terrestrial woody debris (9.5)									✓		1
Install nest boxes (9.6)									✓		1
Inoculate soil (9.8)									✓		1
Place street lights on the far-side of adjoing roads (9.9)									✓		1
Reconnect to adjacent riparian corridor or patch of remnant vegetation (10.1)										✓	1
Minimise road crossings (10.4)										✓	1

A management framework to guide the strategic repair of riparian processes to improve the ecological health of urban waterways

Managers can repair (rehabilitate) urban riparian zones using many different techniques; however, their ability to deliver an improvement in stream health can be enhanced if a strategic approach is used. Below we present a management framework to guide managers along a decision pathway.

The framework provided below assumes that managers have already liaised with the community, government agencies and other stakeholders about the goals for their urban stream site, and that protection or improvement in stream ecological function (i.e. health) is an objective. The framework consists of nine steps that contribute broadly to the prioritisation of on-ground actions and implementation, monitoring and evaluation (see Fig. 3).

In the remainder of this section we provide a description of steps to assist managers to prioritise riparian processes for repair (steps 1-5). We then briefly discuss implementation, monitoring and evaluation (steps 6-9) and direct readers to existing resources where these concepts are covered more fully.



A flow diagram depicting management framework.

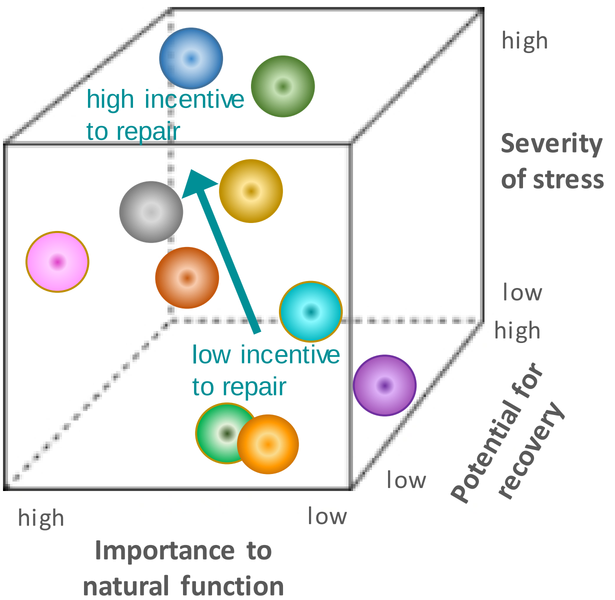
Prioritisation (steps 1 to 5)

There are many on-ground actions that can be implemented to repair urban riparian zones and thus improve the health of their waterways. However, given the unique conditions of your rehabilitation site, certain actions will be more useful than others. Our methodology is based on the premise that greater benefits will be obtained when management targets:

1) riparian processes that are naturally important to waterway health,
2) are highly degraded by urbanisation (or other land use change), and
3) have a good capacity to recover following intervention.

The figure below provides a conceptual depiction of the prioritisation process.

If a site is in excellent condition then its protection and conservation should be prioritised as per https://www.melbournewater.com.au/planning-and-building/waterway-management/pages/vegetation-management.aspx. This approach sees higher priority given to the protection and conservation of native vegetation over restoration and enhancement of native vegetation.



A conceptual representation of the incentive to repair the nine riparian ecological processes. Processes are prioritised for rehabilitation if they (i) exert significant influence on ecosystem function (i.e. naturally important), (ii) if they are highly altered or stressed urbanisation or other land-use change, and (iii) if they have a good capacity for recovery.

Step 1. Determine which riparian processes are important given the local and regional setting

The first step is to determine which of the 10 riparian processes are naturally most important to stream health given the local and regional environmental setting. This is where we use information about the site's channel width, soil conditions, climatic and geologic setting to provide an insight into which riparian processes are most important to the sites' health. A ranking of low (0), medium (1) or high (2) should be given to each process using Table 1. Remember that the table has been provided as a guide only, we recommend that local scientific experts be consulted and their advice heeded.

We remind practitioners that the intention of this framework is to return urban waterways towards some semblance of natural condition. To this end, we recommend that Table 1 is scored with reference to the natural or historical setting of the site, not its current condition. However, we recognise that while rehabilitation is a suitable goal for waterways in peri-urban and moderately urban catchments, it is inappropriate for most inner-city waterways (Hobbs et al. 2006, Francis 2009, Palmer et al. 2014a, Smith et al. 2016). For these 'novel' waterways we encourage managers to prioritise riparian processes according to those that are likely to maximise the delivery of ecosystem services to people.

Step 2. Estimate how stressed riparian processes are

Estimating how stressed the various riparian processes are at your rehabilitation site is difficult because ecological processes are difficult to measure. Here we use the approach described in the section 'Summarising stress to riparian ecological processes' where we use the physical condition of the riparian zone as a surrogate for functional stress.

Step 2i. Survey the riparian zone of the study site using the modified Rapid Appraisal of Riparian Condition (RARC) method, so that rank scores are obtained for all structural indicators. See Appendix 1 for details.

Step 2ii. Determine a qualitative measure of stress to each riparian process by entering RARC indicator rank scores into Table 2 and determining a summary score for each ecological process.

Step 3. Assess the potential recovery of the various ecological processes

Our ability to repair an ecological process at a given site is related to the extent to which underlying degrading factors have been controlled, the extent to which the urban setting allows the implementation of the remedial action, and the extent to which the process is controlled by local or landscape factors. A ranking of low (0), medium (1) or high (2) should be given to each ecological process using Table 3. Again, remember that the table is a guide only - if local knowledge suggests that the site should be ranked differently, then the table does not have to be followed.

Step 4. Prioritise riparian processes for repair

As mentioned earlier, the prioritisation process considers riparian processes to be a priority if they are: naturally important (i.e. Step 1), highly altered/stressed (i.e. poor condition, Step 2), and have a good potential for recovery (Step 3). Priority scores can be obtained by populating Table 5 (below) with values from Tables 1, 2 and 3. The formula for prioritisation for any given riparian process is:

*Function Priority Score = Natural Importance of Function * Alteration or Stress to Function * Potential Recovery*

Table 5. Determining prioritisation scores for the 10 riparian processes.

Riparian process	Natural importance to stream function (A) (output from Table 1)	Alteration or stress (B) (output from Table 2)	Potential for recovery (C) (output from Table 3)	Prioritisation score (A*B*C)
1. Light & temp regulation	x	y	z	P1
2. Nutrient filtration & sediment trapping	…	…	…	P2
3. Bank stabilisation	…	…	…	P3
4. Flood attenuation	…	…	…	P4
5. Channel adjustment	…	…	…	P5
6. Trophic subsidies	…	…	…	P6
7. Aquatic habitat	…	…	…	P7
8. Riparian vegetation	…	…	…	P8
9. Terrestrial habitat	…	…	…	P9
10. Terrestrial corridor	…	…	…	P10

Step 5. Prioritise on-ground actions according to their ability to repair multiple ecosystem functions

When repairing the riparian zone many on-ground actions create improvements to multiple riparian processes. In general, we consider that these actions should be prioritised over actions that deliver benefits to a single process. Table 5 provides a way to assess the net benefit of a range of on-ground actions. To use the table, simply replace the P's with the priority scores obtained using Table 5. The score for each action is obtained by summing the scores across all processes, and the higher the score the more we recommend the action be implemented. We encourage managers to expand the table to capture additional actions that are currently missing, but are considered useful.

Actions that deliver to more processes will be weighted higher than actions that maybe very important to one ecological process only. Where managers have a preference to repair a particular process (for example, nutrients or light and temperature regulation), then they can bypass Steps 1-5 and we encourage them to go to directly to Step 6.

Table 6. Prioritising the on-ground riparian actions/strategies to be implemented at the restoration site via their ability to improve ecosystem functions. The table works by aligning actions with their priority score for each riparian process obtained from Table 5. To use the table, place the priority scores from Table 5 into the boxes labelled accordingly. The total score for each action is determined by summing scores across all functions. Actions with the highest total score should be priorities for implementation. Management guidelines for each action are provided section 'Guidelines to repair riparian processes in an urban setting'' of this document.

	Riparian process										
Action/strategy	**1. Light & temp. control**	**2. Nutrient filtration & sediment trapping**	**3. Bank stabilization**	**4. Flood attenuation**	**5. Channel adjustment**	**6. Trophic subsidies**	**7. Aquatic habitat**	**8. Riparian vegetation**	**9. Terrestrial habitat**	**10. Terrestrial corridor**	**SCORE**
Increase buffer width (1.2, 2.2, 4.5, 5.3, 6.3, 8.4, 9.1, 10.2)	P1	P2		P4	P5	P6		P8	P9	P10	=sum
Protect native vegetation and revegetate the buffer with natives (2.4, 4.4, 6.4, 8.2, 9.2, 10.3)		P2		P4		P6		P8	P9	P10	=sum
Protect from fire (1.4, 2.13, 6.9, 7.10, 8.9, 9.10)	P1	P2				P6	P7	P8	P9		=sum
Promote hydrologic connectivity between the waterway & riparian land by grading the bank, lowering the floodplain, raising the channel or other means (2.7, 4.1, 6.6, 7.9. 8.5, 9.3)		P2		P4		P6	P7	P8	P9		=sum
Re-establish native trees & other native vegetation in the stream-side zone (1.1, 3.3, 6.1, 7.2)	P1		P3			P6	P7				=sum
Add large woody debris to the channel (3.5, 6.5, 7.1)			P3			P6	P7				=sum
Reconnect the main channel with adjacent floodplain wetlands by removing levees, regulators and unblocking creek channels (2.8, 4.3, 6.7)		P2		P4		P6					=sum
Create floodplain wetlands & topographical depressions 'riparian sponge' (4.2, 7.8, 9.4)				P4			P7		P9		=sum
Line the stream bank with wet-dry tolerant plants (2.9, 3.4, 7.5)		P2	P3				P7				=sum
Recreate channel sinuosity (5.2, 6.2, 7.4)					P5	P6	P7				=sum
Fence off riparian vegetation (8.3, 9.7)								P8	P9		=sum
Remove channel hard-lining (5.1, 7.3)					P5		P7				=sum
Remove levees & other floodplain barriers to flow (2.8, 4.6, 6.7)				P4		P6					=sum
Raise or lower the water table below the riparian zone (2.6, 8.6)		P2						P8			=sum
Add wall boxes or ledges (7.6, 8.7)							P7	P8			=sum
Create floating anchored gardens (7.7, 8.8)							P7	P8			=sum
Use artificial means to shade the channel (1.3)	P1										=sum
Relocate / redesign stormwater & sub-surface drainage inputs (2.1)		P2									=sum

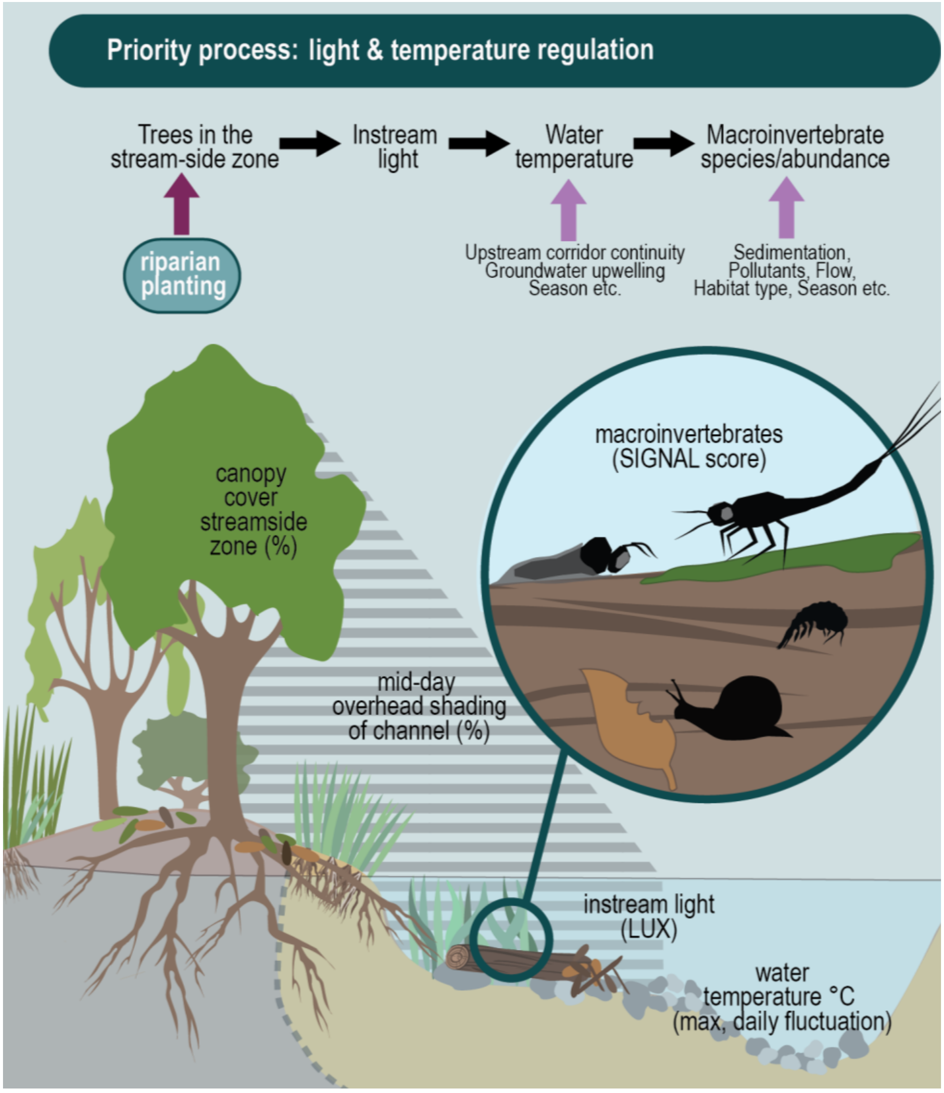
Action/strategy	Riparian process										
	1. Light & temp. control	2. Nutrient filtration & sediment trapping	3. Bank stabilization	4. Flood attenuation	5. Channel adjustment	6. Trophic subsidies	7. Aquatic habitat	8. Riparian vegetation	9. Terrestrial habitat	10. Terrestrial corridor	SCORE
Create a biofilter (e.g. filter strip, swale) on the distal edge of the riparian buffer (2.3)		P2									=sum
Reconfigure the slope of riparian land (2.5)		P2									=sum
Install permeable reactive barriers (2.10)		P2									=sum
Remediate soil (2.11)		P2									=sum
Harvest grass and sedges in filter strips and along the channel's bank (2.12)		P2									=sum
Stabilise the stream bed (3.1)			P3								=sum
Identify and protect parts of the bank that are erosional hotspots (3.2, 5.4)			P3								=sum
Use bank-hardening of armouring techniques (3.6)			P3								=sum
Use cross-vane, w-weir or j-hook vane structures (3.7)			P3								=sum
Manage or redesign GPT's so that leaves pass to stream						P6					=sum
Remove weeds (8.1)								P8			=sum
Protect dead trees & terrestrial woody debris (9.5)									P9		=sum
Install nest boxes (9.6)									P9		=sum
Inoculate soil (9.8)									P9		=sum
Place street lights on the far-side of adjoin roads (9.9)									P9		=sum
Reconnect to adjacent riparian corridor or patch of remnant vegetation (10.1)										P10	=sum
Minimise road crossings (10.4)										P10	=sum

Implementation, monitoring and evaluation (steps 6 to 9)

Step 6. Select structural and/or functional indicators, set short-term and long-term SMART targets, and commence monitoring

Indicators

Before we conduct on-ground restoration activities it is important to collect some pre-intervention data. Without this information it will be impossible to determine if the on-ground works have delivered any improvement to our priority ecological processes and ultimately to waterway health. But what should we measure – what indicators should we choose? We have several choices, we can choose to measure the process we are trying to affect – for example if we are trying to repair light and temperature regulation we could measure UV light absorbance in the waterway (LUX), alternatively we can measure a structural component of the waterway we are trying to change (e.g. water temperature). We could also measure a structural attribute of the riparian zone that affects our ecological process of interest (e.g. canopy cover in the stream-side zone). We may also decide to measure attributes directly linked to our intervention activity (e.g. water temperature), or we can choose to measure attributes that are indirectly affected (e.g. macroinvertebrate SIGNAL score). While relationships are likely to be harder to find between our on-ground works and these higher-level factors they are important if they are the ultimate goal of our restoration activities. When choosing ecological indicators for urban waterways we encourage practitioners to refer to Vietz et al. (2010) as this document provides indicators for hydrology, water quality, geomorphology and ecology.



A conceptual depiction of indicator choice for light and temperature regulation.

Targets

It is also a good idea to set restoration targets. These helps us to assess our progress towards our goals and allow us to quantitatively evaluate the success of our restoration activities. Typically, restoration projects use the conditions of historical or reference sites as targets. These targets may be suitable for peri-urban streams but they are likely to be inappropriate for more urbanised catchments (Hobbs et al. 2006, Francis 2009, Palmer et al. 2014a, Smith et al. 2016). Obviously, the target will depend on the extent catchment urbanisation (peri-urban or urban) and the scale of management intervention. We may set ambitious targets in cases where our site-specific on-ground works are complemented by catchment-scale water sensitive urban design and where < 5% of the catchment is impervious. We should set more realistic targets where highly urban waterways and where there is no capacity to repair flow and water quality at the catchment.

Ideally, managers should use predictive mathematical models based on empirical data for their urban region to determine targets. However, for most regions in Australia these will not be available. We recommend that practitioners consult Davies et al. (2007) for temperature targets for riparian restoration – noting that these are targets for agricultural land and may need to be wound back for an urban setting.

Targets should also be SMART: specific, measurable, ambitious, realistic and time-bound and there should be recognition that to be successful they may also need to be agreed on by stakeholders and supported by government policy (Maxwell et al. 2015). We direct readers towards recommendation three in King et al. (2015) for further discussion about SMART targets and ecological restoration.

Monitoring

Once we have decided on our indicator metrics and their targets, we need to decide where and when we will monitor before we commence our on-ground actions. Many restoration projects adopt a before-after-control-impact (BACI) design as it enables changes in metrics at the restoration site to be separated from natural changes through time. We recommend this type of approach and suggest that sites located a short distance upstream of the restoration site are used as controls. Another approach that may be useful is a gradient type of study - this design uses a collection of many sites where different types of restoration are implemented, including control sites, to learn about the success of management (see King et al. (2015) for a detailed discussion).

Practitioners must also decide where to sample within their restoration and control sites, and decide when and how often to sample. These are typically difficult decisions and depend on the metrics (e.g. indicators) of interest, as well as time and budgetary constraints. In general, monitoring should be sufficient to describe the general condition of the metric at the site – thus more samples should be taken for metrics that exhibit substantial variation through space and time (e.g. nutrient concentrations in riparian soils and the water column), and fewer samples should be collected for metrics that are relatively constant through space and time (e.g. canopy cover). It is also important to be cognisant of the fact that some riparian features may undergo marked seasonal shifts which may complicate monitoring, for example vegetative filter strips and floodplain wetlands may be nutrient sinks at one time of the year and nutrient sources at others (Osborne and Kovacic 1993). These complicating factors highlight the importance of knowing your question and understanding the spatial and temporal scales that are relevant to your question. We strongly advise that scientists and biometricians be consulted to ensure that an appropriate monitoring design is implemented.

Step 7. Control degrading processes where possible

Many on-site restoration measures will be rapidly undone if the processes that have caused their degradation are not fixed. For example, riparian revegetation that increases the inputs of leaves into an urban stream is unlikely to deliver any benefits to the food web if leaves are rapidly washed downstream by scouring urban flows. For the majority of urban streams, the dominant degrading process is the direct connection of stormwater runoff from the catchment to the waterway. Thus strongly recommend that whenever possible that Water Sensitive Urban Design measures are implemented in the catchment prior to the commencement of on-ground actions at the restoration site.

Step 8. Implement on-ground actions in a temporal hierarchy that maximises success

The success of on-ground actions can be increased if the timing of actions are considered. The importance of a strategic temporal approach is clear when earthworks are involved – these destructive actions must be undertaken first otherwise more sensitive interventions, such as riparian planting will be damaged. However, there are some instances when the importance of timing is more nuanced. For example, seedling survival can be increased if larger shade trees are firstly established and if the soil has been amended and weeds removed. The importance of a temporal approach to planting is discussed more fully in action 8.2 p 51 of this document.

It is also important to recognise that some actions may be in conflict with one another. For example, removing concrete lining of a trapezoidal drain to promote naturally channel readjust is in direct conflict with extensive rock lining (i.e. RIP RAP) of the banks. While it is unlikely that conflicts will arise, we encourage managers to select actions that favour 'natural' remedies rather than engineering fixes, because they are likely to promote broader ecological repair.

Step 9. Continue to monitor and statistically evaluate success

We will not know if our on-ground actions have been successful until we have collected enough post-intervention data, at both control and restoration sites, to allow us to perform a rigorous statistical appraisal. Numerous studies examining waterway restoration stress the long time frames for recovery, both for physical factors such as water quality (Meals et al. 2010), and particularly for biota (Becker and Robson 2010, Parkyn and Smith 2011). Given this we need to give considerable thought to the expected time frame of recovery of our indicator and sample it accordingly. For example, we might assess water temperature maximums every second year during the height of summer over a period of 10-15 years to assess if tree planting at the site and in the upstream corridor has cooled the stream. In contrast, we might assess chemical pollutants every month over a 2 year period (one year before and one after intervention) to assess the extent to which disconnected a polluting stormwater drain and infiltrating it through a riparian biofilter has improved water quality.

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Appendix 1. A modified version of the Rapid Appraisal of Riparian Condition (RARC) version 2

Below we present a table that guides the scoring of riparian indicators. This table has been taken from Jansen et al. (2005) and modified for an urban setting. Practitioners should use this table to assist them to complete Table 2 in the main document. Those seeking assistance classifying bank condition in Table A1 should consult p10 of Galvin et al. (2009) River Health Assessment Scheme for the sub-catchments of the Swan Canning, User's manual, Water Science Technical Series Report No. 8, Department of Water, Western Australia.

Table A1. RARC Indicators and their associated scoring modified from Jansen

Sub-Index	Indicator	Range	Scoring
HABITAT	Longitudinal continuity of riparian vegetation (≥ 5m wide)	0-4	0 = < 50%, 1 = 50–64%, 2 = 65–79%, 3 = 80–94% 4 = 95% vegetated bank; with 1/2 point subtracted (5m wide) for each significant discontinuity (≥ 50m long)
	Width of riparian vegetation (scored differently for channels ≤ or > 10m wide)	0-4	Channel ≤ 10m wide: 0 = VW < 5m, 1 = VW 5–9m, 2 = VW 10–29m, 3 = VW 30–39m, 4 = VW ≥ 40m Channel > 10 m wide 0 = VW/CW 0.5, 1 = VW/CW 0.5–0.9, 2 = VW/CW 1–1.9, 3 = VW/CW 2–3.9, 4 = VW/CW 4, where CW = channel width and VW = vegetation width
	Proximity to nearest patch of intact native vegetation > 10 ha	0-3	0 = > 1 km, 1 = 200m–1 km, 2 = contiguous, 3 = contiguous with patch > 50 ha
COVER	Canopy streamside zone (i.e. trees >5m tall within 5m of bank)	0-3	0 = absent, 1 = 1–30%, 2 = 31–60%, 3 = > 60% cover
	Canopy (>5m tall)	0-3	0 = absent, 1 = 1–30%, 2 = 31–60%, 3 = > 60% cover
	Understorey (1-5m tall)	0-3	0 = absent, 1 = 1–5%, 2 = 6–30%, 3 = > 30% cover
	Ground (<1m tall)	0-3	0 = absent, 1 = 1–30%, 2 = 31–60%, 3 = > 60% cover
	Number of layers	0-3	0 = no vegetation layers to 3 = ground cover, understorey and canopy layers
NATIVES	Canopy (>5m tall)	0-3	0 = absent, 1 = 1–30%, 2 = 31–60%, 3 = > 60% cover
	Understorey (1-5m tall)	0-3	0 = absent, 1 = 1–5%, 2 = 6–30%, 3 = > 30% cover
	Ground (<1m tall)	0-3	0 = absent, 1 = 1–30%, 2 = 31–60%, 3 = > 60% cover
DEBRIS	Leaf litter	0-3	0 = absent, 1 = 1–30%, 2 = 31–60%, 3 = > 60% cover
	Native leaf litter	0-3	0 = absent, 1 = 1–30%, 2 = 31–60%, 3 = > 60% cover
	Standing dead trees (>20cm dbh)	0-1	0 = absent, 1 = present
	Hollow-bearing trees	0-1	0 = absent, 1 = present
	Fallen logs (>10 cm diameter)	0-2	0 = none, 1 = small quantities, 2 = abundant
FEATURES	Native canopy species regeneration (<1m tall)	0-2	0 = none, 1 = scattered, 2 = abundant; with 1/2 point subtracted for grazing damage
	Native understorey regeneration	0-2	0 = none, 1 = scattered, 2 = abundant; with 1/2 point subtracted for grazing damage
	Large native tussock grasses	0-2	0 = none, 1 = scattered, 2 = abundant
	Reeds	0-2	0 = none, 1 = scattered, 2 = abundant
	Floodplain wetlands & topography	0-4	0 = no wetlands or topographical depressions, 1 = wetlands/depressions occupy < 5% of the riparian buffer, 2 = wetlands/depressions occupy 5 – 10% of the riparian buffer, 3 = wetlands/depressions occupy 11 – 25% of the riparian buffer,

Sub-Index	Indicator	Range	Scoring
			4 = > 25 % of the riparian buffer is occupied by wetlands (permanent or ephemeral)
OTHERS	Channelisation & hard-lining	0-3	0 = channelization (i.e. very straight) and concrete lining (e.g. drain), 1 = channellisation with revetment (e.g. drain), 2 = the channel meanders but there is revetment in patches, 3 = the channel has irregular or regular meanders and no revetment.
	Bank condition	0-2	0 = highly eroded as evidenced by a vertical or undercut bank and an unstable bank toe, many exposed woody roots. 1 = moderately eroded as evidenced by some bank instabilities that extent to the toe of the bank, discontinuous woody vegetation and some exposure of woody roots. Banks maybe gentle or vertical slope. 2 = relatively stable as evidenced by little eroding of bank, gentle slope, continuous cover of riparian vegetation and few exposed woody roots Undercut banks, bank stabilisation works (RIPRAP)
	Channel incision	0-2	0 = deeply incised channel, high width to depth ratio 1 = moderately incised channel 2 = no evidence of channel deepening, low width to depth ratio
	Levees present	0-1	0 = absent, 1 = present

dbh = diameter at breast height, revetment = engineering methods to stabilise the bank (e.g. rocks, wood boards, geofabric)

Note. The RARC (v2) can be found at https://arrc.com.au/wp-content/uploads/2015/05/The%20Rapid%20Appraisal%20of%20Riparian%20Condition%20assessment%20tool.pdf

The River Health Assessment Scheme User's Manual can be found at http://www.water.wa.gov.au/__data/assets/pdf_file/0011/5015/84253.pdf

Appendix 2. A summary of riparian buffer widths recommended to promote nutrient filtration and sediment trapping

Table A2. Recommended buffer and filter strip widths for nutrient filtration and sediment trapping

Attribute	Guideline	Reference	Country and land use
Buffer width	10 m width should trap 65% of sediments transported in overland flow, 30 m width should trap 85%	Sweeney and Newbold (2014) review	USA & International; forested and grass
	5 to 30m width depending on slope, soil type and nutrient load	Hawes and Smith (2005) review	USA
	>50m width consistently removed more nitrogen than 0-25m width. 75% removal for 50m buffer, 90% removal 150m buffer	Mayer et al (2007) meta-analysis	International, but predominantly USA
	10 – 60m width for steep sloped (> 8%) riparian land	Nigel et al (2013) single study	Canada; agriculture
	60m if adjacent to high intensity landuse	Hansen et al. (2010) guidelines	Australia (Victoria); agriculture
Grass, sedge or herb filter strip width	5 m wide grass or sedge filter strip at distal end of riparian zone. Vegetation must be able to tolerate periods of inundation and drying	Fischer and Fischenich (2000) review	USA, mixed landuse (forested, urban, agriculture)
	5m wide strip of varying vegetation types sufficient to reduce > 70% sediment on very steep slopes (25-35%)	Ding et al. (2011) single study	China; agriculture

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