CRC for
Water Sensitive Cities

Improving the ecological function of urban waterways:

A compendium of factsheets

Leah Beesley, Jennifer Middleton, Belinda Quinton, Peter M. Davies

Australian Government
Department of Industry, Innovation and Science

Business
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Water Sensitive Cities

Improving the ecological function of urban waterways:
A compendium of factsheets
Protection and restoration of urban freshwater ecosystems: informing management and planning (Project B2.23) B2.23-1-2018

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How to use the urban waterway factsheets

How to use the urban waterway factsheets

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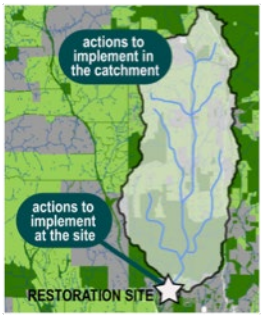
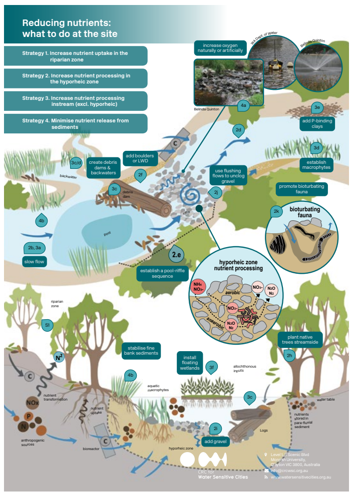
We have designed these factsheets to guide the repair or design of a living stream site on a flowing urban waterway. The site may be associated with a creek/stream channel, a constructed drain, a lowland river or a living stream built in a new urban development. The factsheets refer to the repair or design of nine different ecological components of flowing waterways: flow, geomorphology, riparian, connectivity (longitudinal, lateral, vertical), water quality (nutrients, physico-chemistry including toxicants) and biota (see next page for a description of components). For most components there are two factsheets: one for what to do at the site scale and the other for what to do at the catchment scale. We encourage practitioners to work at both spatial scales.



The factsheets summarise various actions for improving a given ecosystem component. Many, but not all of the actions are illustrated in the factsheets (see example right), with all actions listed in an adjoining table. How each action may improve the site is briefly discussed in the table, alongside a list of relevant scientific references for further information. Some of the actions may be important for your restoration site, others may not. The factsheets do not provide prescriptive advice about what actions your restoration activity should focus on (i.e. what will improve ecosystem health the most) because countless factors will dictate this. Nevertheless, the tables do provide advice on the likely effectiveness and suitability of any action given environmental factors and urban constraints. However, the information provided is general and we encourage practitioners to consult local scientific experts where possible.



The factsheets direct readers to specific technical guidelines. We also strongly encourage practitioners to seek out any technical guidelines created or adapted for their local environmental setting, before going ahead with any actions.

Prioritising factsheets

We provide a total of 13 factsheets, but which ones should you focus on, given your restoration site? A decision-support tool called RESTORE has been created to aid this process. The tool asks practitioners a range of questions about the environmental and urban setting of their restoration site and identifies the ecosystem components (i.e. factsheets) likely to be most relevant to your site or catchment.

The factsheets can also be used as a standalone product. Where this is done, we encourage practitioners to prioritise the ecosystem components that are most influential – i.e. start with flow and geomorphology and work upwards (see diagram on the next page).

"Urban waterway: a waterway whose ecology and geomorphology is primarily influenced by urbanisation."

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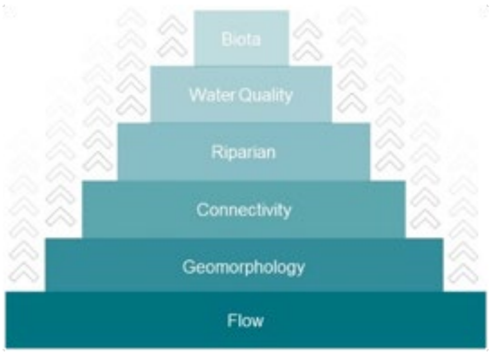
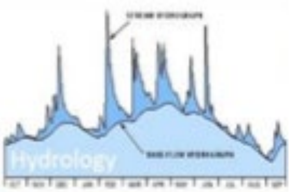
Ecological components

The factsheets describe nine ecological components. A brief description of each component is provided below. Note: overlap in ecological role or function occurs to some extent among components.



Modified from Harmanet al., 2012

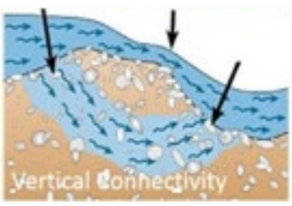


Flow – describes the volume, velocity, frequency of flow pulses, the rate of flow rise and fall, and low-flow conditions within the channel. It affects the depth and permanence of aquatic habitat, physical disturbance in the waterway and influences all of the components presented below.

Geomorphology – describes channel shape (width, depth, sinuosity), bed material and instream features (beds, bars, pools) and sedimentation. It affects the complexity of instream physical habitat, and the depth, velocity and turbidity of instream flows. It also influences lateral and vertical connectivity.

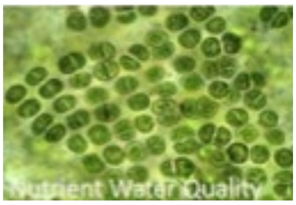
Longitudinal connectivity – describes the connectedness of flow from small headwater streams to large lowland riverine sites. It influences the movement of food along the length of the river, as well as the movement of biota both instream and on riparian land.

Lateral connectivity – describes the connectedness of flow between the main channel of the waterway and riparian land. It influences the velocity of instream flow, energetics, and nutrient and sediment trapping. It also influences riparian health and functionality.



Vertical connectivity – describes the connectedness of surface and subsurface water in the channel. It influences the processing of nutrients and other pollutants, and the depth of water during periods of low flow. It can also influence water temperature and biota.

Riparian – describes the land that runs adjacent to streams and rivers along their length. It influences food inputs to the waterway and water temperature, as well as nutrient filtration, sediment trapping and instream habitat. It also influences longitudinal and lateral connectivity.



Nutrient water quality – describes the amount of nitrogen and phosphorus in the water. These influence the growth of algae and plants instream, as well as the likelihood of algal blooms and oxygen crashes.

Physico-chemical water quality – describes the temperature, oxygen, clarity, pH and conductivity of water. It influences how suitable the water is for different forms of life.

Biota – describes the number and type of species living in the waterway. It indicates the overall health of the waterway and influences its resilience to perturbations. Biota affect how energy created in the waterway is moved up the food web and can influence water quality and nutrient-processing ability.

Note:
These factsheets are generic and outline a range of potential issues and responses in urban waterways within and outside of Australia.

Supporting documents

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Repairing flow: what to do at the site

CRC for Water Sensitive Cities

Strategy 1. Reduce the velocity of instream flow

Suitability of strategy: this strategy will be most effective where catchment-wide stormwater management has already been implemented.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
1a. Encourage the channel to naturally self-adjust See Repairing geomorphology: what to do at the site and in the catchment factsheet, Strategy 3	Natural self-adjustment to flow helps to slow instream flows because high-energy water loses some of its power when it transports sediments.	Where the soil surrounding the stream is erodible (e.g. sand, clay, gravel) – not bedrock. Where there is sufficient buffer space for channel adjustment. If the waterway is lined with concrete there must be sufficient space for earthmoving machinery to access the site without doing substantial damage to riparian vegetation.		See associated factsheet
1b. Reconfigure the channel to promote sinuosity and widening	Reconfiguring the channel so that it is wider and more sinuous will increase the area available to transport water – slowing flow. Wider, sinuous channels also increase the contact between instream water with rough (turbulent) surfaces (i.e. the channel edge) which help to slow instream flow.	When rapid change in channel form is desired (i.e. waiting for natural channel adjustment is not feasible), and where earthworks will not create substantial damage to riparian vegetation (e.g. new developments or highly degraded urban sites).	[1, 2]	See river restoration manuals
1c. Add large woody debris (LWD) to the channel	LWD creates roughness and turbulence, leading to a reachscale reduction in flow velocity.	Where streams would naturally have contained wood. Where earthmoving machinery can access the site. Where the channel is narrow (< 10 m) and where a large amount of wood is being added. Where urban scouring flows have been repaired such that LWD will not be swept away and damage downstream infrastructure. Note, LWD is unlikely to increase flood risk unless wood occupies > 10 per cent of the channel cross-section. Take care with LWD placement so bank stability is not undermined. If concerns exist about the risk to urban infrastructure, we recommend using the Large Wood Structure Stability Analysis Tool <http://www.fs.fed.us/ biology/nsaec/products-tools.html> [3]. The associated resource [4] describes the process and may also be useful.	[5-8]	[2-4, 8-12]

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
1d. Use engineering structures (cross vane, w-weir, j-hook vane, check dams or side-cast weirs). See Repairing riparian function: what to do at the site, action 2g	Numerous engineered structures can be constructed instream to reduce flow velocity.	Novel waterways in new urban developments. Pre-existing urban drains where actions 1a or 1b are not appropriate – e.g. where there is no room or funding available for channel adjustment or redesign, or LWD is likely to be swept away by scouring urban flows. Care should be taken to ensure that these structures do not impact in-stream connectivity (e.g. fish movement), particulary in lower stream reaches.	[1, 7, 13]	See associated factsheet
1e. Roughen channel lining using rocks and macrophytes See Repairing riparian function: what to do at the site factsheet, action 2ce	As the roughness of the channel increases it creates more turbulent flow, which slows overall water velocity	Most sites. Rocks are most suited to sites where very scouring urban flows occur. Macrophytes should be supported during the establishment phase using geofabric, but may not be suitable at some sites.	[2, 6]	See associated factsheet
1f. Improve hydrologic connectivity between the waterway and its riparian floodplain by grading the bank, lowering the floodplain/ raising the channel, removing levees and unblocking wetland feeder creeks	Urban channels are typically incised: lowering the floodplain, grading the bank or raising the channel bed will improve the overbank flow of water from the main channel to the floodplain. This transfer of water will reduce the velocity of instream flows.	Where a series of natural floodplain wetlands or lakes exist on the urban river network. Where floodplain inundation does not pose a threat to people or urban infrastructure. Where earthworks do not create substantial damage to riparian vegetation (i.e. new development).	[14-16]	[9]
1g. Create ponds, wetlands and other topographical depressions on the riparian floodplain	The creation of wetlands and other depressions on the floodplain will increase the capacity of the riparian land to store floodwaters, slowing instream flow.	Where few wetlands and depressions currently exist. Where enough floodplain space is available for wetland creation. Where floodplain inundation does not pose a threat to people or urban infrastructure. Where earthworks do not create substantial damage to riparian vegetation (i.e. new development).	[15]	[9]
1h. Repair riparian vegetation	Revegetating the riparian buffer will increase flow roughness and slow the velocity of overbank flow.	Sites where hydrologic connectivity is good (i.e. the channel is not very incised or action 1h has been done). Where the vegetative buffer is wide > 30 m so it can absorb a large volume of flow.	[6, 9, 14]	

Strategy 2. Repair stream baseflow

Suitability of strategy: the height of the local watertable is likely to be controlled by larger off-site processes; hence actions to repair baseflow at the site scale are likely to be less effective than catchment-scale strategies.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
Where urbanisation has led to a decrease in baseflow				
2a. Remove impermeable channel lining	An impermeable channel lining (e.g. concrete, compacted clay) prevents the inflow of groundwater.	Where the channel is lined with an impermeable material (e.g. concrete, clay).		Not applicable
2b. Lower channel to reconnect the stream with shallow groundwater (i.e. excavate a pool to create a low-flow refuge)	Lowering the channel will increase contact with a falling watertable.	Where earthmoving equipment can access the site without causing too much ecological damage. Lowering the channel could lead to further drainage and exacerbate the falling of the watertable. We recommend this approach only be undertaken in patches – i.e. to create pools that provide low-flow refuges. When creating a pool, take care to ensure the upstream end does not create a knick point that leads to upstream erosion.		
Where urbanisation has led to an increase in baseflow				
2c. Plant native deep-rooted trees in high density, particularly species with high water consumption	Deep-rooted trees that have a high evaporative demand, such that some eucalypts (e.g. blue gums) may cause a local lowering of the watertable.	Where the riparian buffer is wide enough to support a large number of trees. Where riparian vegetation would naturally have been forested.		

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River restoration manuals

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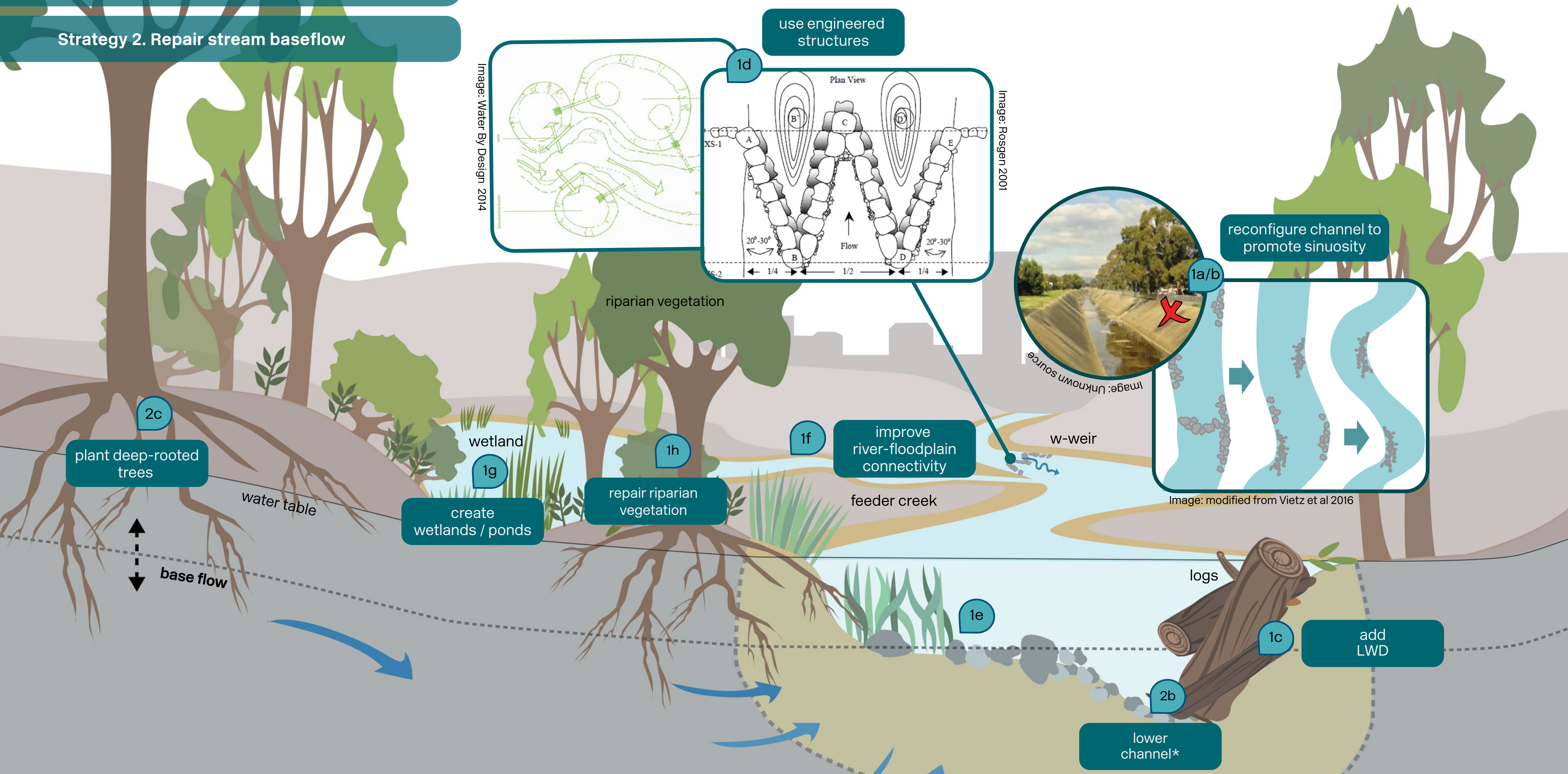
Repairing flow: what to do at the site

Strategy 1. Reduce the velocity of instream flow

Strategy 2. Repair stream baseflow



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* only where urbanisation has caused the water table to fall

Repairing flow: what to do in the catchment

Repairing flow: what to do in the catchment

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Strategy 1. Reduce flow volume

Suitability of strategy: most readily achieved where the catchment is small with relatively low imperviousness (< 10 per cent), such as in peri-urban areas, because there are fewer impervious surfaces and therefore less stormwater that needs to be attenuated. That said, we recommend this strategy be implemented whenever possible across an urban area, because stormwater initiatives associated with infill development can lead to improvements in the long-term.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
1a. Harvest rainwater at the lot scale using rainwater tanks and roof gardens	Local consumption of rainwater reduces stormwater runoff or excessive infiltration rates, such as those associated with the localised infiltration of roof runoff below houses in Perth.	Water tanks most efficiently collect water in climates where rainfall is relatively uniform throughout the year. Green roofs are more effective where plants are not exposed to protracted periods of drought – hence this action is more appropriate for urban areas in coastal eastern Australia than for Perth or Adelaide.	[1-6]	[1, 4, 7-9] See relevant WSUD guidelines and MUSIC tool
1b. Infiltrate stormwater at the lot scale using soakwells and permeable paving. Discourage the use of fake lawn	Local infiltration of roof, driveway and garden runoff reduces the volume of water entering stormwater drainage.	Stormwater infiltration is most effective where soils are highly permeable (e.g. sand).	[1-3, 5]	[8, 10] See relevant WSUD guidelines and MUSIC tool
1c. Infiltrate stormwater at the street scale using rain gardens, swales and tree pits	As per action 1b.	As per action 1b.	[1, 3, 5, 11, 12]	[8, 13] See relevant WSUD guidelines and MUSIC tool
1d. Increase overland flow paths between stormwater sources and urban drainage	Extending the flow path between a stormwater source (e.g. a road) and stormwater drainage (e.g. a pipe or a creekline) increases the opportunity for infiltration. This can be done in many ways, such as using flush-kerbing or a kerbless design on the road adjacent to a waterway, or by terminating stormwater pipes into riparian swales rather than directly into the waterway.	Where soils are permeable (clay, sand, gravel). Where the land slope is moderate to low. Where there is enough overland distance for infiltration. It can still be achieved when permeability is low and slopes are high – but greater distances are needed for infiltration.	[14]	

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
1e. Remove (daylight) pipes and remove channel hard-lining	Stormwater pipes and hard-lined drainage channels prevent the infiltration of stormwater. Removing these hard-linings increases the potential for water to infiltrate along its flow path.	Most sites, particularly where the substrate below the hard-lined channel is highly permeable (e.g. sand, gravel).		
1f. Infiltrate stormwater at the precinct scale using biofiltration basins	Infiltrating stormwater at the precinct scale reduces the volume of stormwater entering downstream receiving waters during wet weather, and recharges local groundwater to improve flow during dry periods.	Most catchments, particularly where soils are highly permeable (sand, sandy/clay mixture).	[2, 3, 5, 12]	[8, 10] See relevant WSUD guidelines and MUSIC tool
1g. Detain stormwater at the precinct scale using detention basins	Detaining stormwater in clay-lined basins reduces stormwater volume by trapping and evaporating stormwater.	Most catchments, particularly where soils are low permeability (clay) and evaporative demand is high due to the climate and/or plant biomass. Where basins have smaller multi-level offtakes.	[15, 16]	See relevant WSUD guidelines and MUSIC tool
1h. Strategically place biofiltration basins and stormwater wetlands in locations that receive the most stormwater	Not all infiltration basins are as effective as one another.	Where space permits the placement of the basin.	[17]	
1i. Redirect or retrofit subsurface drainage so it empties into wetland basins or riparian swales – not directly into waterways (see also action 5m)	Subsurface drainage may also deliver stormwater inputs into the stream. While subsurface drainage water cannot be infiltrated at the site where it is gathered, it can be infiltrated on the edge of a riparian buffer (i.e. swale) or into a low-lying wetland.	Where the riparian swale/wetland has highly permeable soils. Where some level of geologic disconnection occurs between the site of groundwater collection (drain input) and the swale/wetland – otherwise the drainage system will fail.		

Strategy 2. Reduce the velocity of instream flow, particularly peak flows

Suitability of strategy: as per Strategy 1, but see action 2b for the specific suitability of this strategy.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
2a. Harvest, infiltrate and detain stormwater. See all actions in Strategy 1	Minimising the volume and timing of stormwater inputs into the waterway helps reduce the velocity of instream flows.	See Strategy 1 this factsheet.	See Strategy 1	See Strategy 1
2b. Use existing dams and weirs to trap water	Man-made structures such as weirs can be used to trap flashy urban flows and moderate outflow spikes, reducing the velocity of downstream flows.	Where there are significant inputs of stormwater upstream of the dam or weir and relatively few stormwater inputs downstream of the weir – at least for some way. Where the regulating structure has capacity to store high flows behind it. Not suitable where dams and weirs act as barriers to biota (e.g fish). This action does NOT advocate for the creation of new dams or weirs.		Few instructions, but flows need to be slowly released during dry periods to create storage room to trap fast-moving flows when they occur. Storages should also be managed to reinstate natural components of the flow regime, such as minimum flows and freshes.

Strategy 3. Reduce the frequency of flow pulses

Suitability of strategy: as per Strategy 1.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
3a. Harvest, infiltrate, detain and disconnect stormwater. See all actions in Strategy 1 this factsheet	Harvesting, infiltrating and disconnecting stormwater across the catchment will reduce the likelihood that small rain events turn into instream flow pulses.	See all actions in Strategy 1.	See all actions in Strategy 1	See all actions in Strategy 1

Strategy 4. Slow the rate of flow rise and fall

Suitability of strategy: as per Strategy 1.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
4a. Infiltrate, detain and disconnect stormwater.	Infiltrating, detaining and disconnecting stormwater across the catchment increases the time for water to travel from the catchment to the stream via surface or subsurface pathways, which will slow the instream rate of flow rise and fall.	See Strategy 1, actions 1b–1h.	See Strategy 1, actions 1b–1h	See Strategy 1, actions 1b–1h
4b. Use existing dams and weirs to trap water – as per action 2b this factsheet	Trapping excess urban flows behind a dam or weir and slowly releasing it will moderate the speed of flow rise and fall in the downstream waterway.	Where there are significant inputs of stormwater upstream of the dam or weir and relatively few stormwater inputs downstream of the weir – at least for some way. Where the regulating structure has capacity to store high flows behind it.		Few instructions, but see action 2b this factsheet

Strategy 5. Repair stream baseflow

Suitability of strategy: The height of the local watertable is likely to be controlled by larger off-site processes; hence actions to repair baseflow at the site scale are likely to be less effective than catchment-scale strategies.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
Where urbanisation has led to a decrease in baseflow				
5a. Infiltrate stormwater throughout the catchment – see Strategy 1, actions 1b, 1c, 1d, 1f and 1g this factsheet	Stormwater runoff over hard surfaces and its direct piping to streams/drains reduces natural infiltration, lowering the local shallow watertable and reducing baseflow.	Where infiltration occurs or is focused on groundwater recharge areas.	[18-20]	See actions 1b–1d, 1f and 1g
5b. Repair leaks from wastewater and storm drainage infrastructure	Old infrastructure (sewers, stormwater drains, water pipes) that has cracked can drain the local watertable and reduce baseflow. Urban infrastructure (e.g. sewer trenches) can also intercept infiltrated water and may affect sub-surface flow paths to waterways.	Where significant leakage of groundwater into piped infrastructure occurs (old infrastructure).	[18]	

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
5c. Reduce groundwater pumping	Pumping of groundwater for residential use (e.g. bores) or industrial use can cause the watertable to fall, hence decrease baseflow.	When pumping occurs predominantly during low-flow periods. When bores are close to the stream. When large volumes of water are being removed.	[18]	
5d. Buy back, limit or suspend water pumping from the waterway	Water pumping out of the waterway reduces instream flow and should be restricted or suspended during periods of extreme low flow.	Where legislative powers exist to suspend water abstraction. Where the sites of water abstraction are located at or upstream of the river reaches experiencing reduced baseflow. Where critical flow refuges have been identified.	[21]	
5e. Use environmental water releases during pronounced low-flow periods	A controlled water release from an upstream dam/weir or large detention basin can be used to supplement low flows, creating a more natural baseflow.	Where a flow regulating structure (dam, weir) exists upstream. Where water pipelines run alongside the waterway so that scour releases can easily deliver water.	[21-24]	[21, 25, 26]
5f. Controlled water release	The slow release of water (i.e. treated effluent) from a wastewater discharge plant can supplement low baseflows.	Where wastewater treatment plants discharge water into the catchment – especially catchments where the discharge point is high in the catchment. This should be done with caution and appropriate environment risk assessments as it could cause unintended impacts.	[27, 28]	
5g. Use the periodic release of flushing flows to reduce the clogging of coarse bed sediments	Flushing flows from dams/weirs, water supply pipes, wastewater treatment plants or fire hydrants can remove fine sediments that are preventing subsurface water (groundwater) from entering the stream. If upstream flow regulating structures are available they can be used to send down flushing flows to improve local groundwater input.	Where the site has silt deposited over naturally porous bed material (e.g. gravel, coarse sand). Where an upstream water release point is available and produces enough flow to move sediment. Where flows can move fine sediment onto the floodplain rather than just transporting it downstream.	[29, 30]	
5h. Avoid urban development in areas with naturally shallow groundwater	Waterways that run through areas with naturally shallow groundwater – such as wetlands, swampland or floodplains – will be more affected by falling watertables associated with urbanisation. For this reason, development should not occur in these areas.	All areas		
Where urbanisation has led to an increase in baseflow (e.g. south-eastern Perth)				
5i. Harvest rainwater at the lot scale using rainwater tanks and roof gardens	Stormwater harvesting for domestic use reduces the amount of water available to recharge the groundwater.	As per action 1a.	[18, 19, 31, 32]	As per action 1a

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
5j. Lined bioretention with controlled outlet, or distributed 'trickle tanks'	Controlled infiltration from detention wetlands can be used to ensure infiltration takes place at suitable times of the year to create appropriate baseflow.	Where detention basins sit in groundwater recharge areas.	[18]	[33]
5k. Catchment-wide planting of native trees	Tree planting will promote evapotranspiration of groundwater, reducing watertable height and unnaturally high baseflow.	Where trees have long-enough roots to reach the shallow watertable. Where evaporative demand on trees is high (e.g. warm, dry conditions).	[18]	
5l. Irrigation using stormwater up to, but not above, evaporative demand	Watering residential gardens or playing fields using just enough stormwater, such that the vast majority of water is transpired, will minimise groundwater recharge.	Where automated smart technology is available to link watering with climatic conditions. Where information on plant water use is known.	[18, 32]	
5m. Irrigation using pumped groundwater during periods of high evaporative demand	None known	Areas that receive the majority of annual rainfall during the cool months.	[18, 34]	
5n. Treat and reuse local groundwater for drinking rather than import water into the catchment	Importing water from outside the catchment brings in excess water that can raise the watertable – particularly where drinking water is used to irrigate residential gardens. Treating and using local groundwater can repair the natural water balance.	Where groundwater treatment technology is available and economically viable.	[18]	Not applicable
5o. Repair leaks from water supply or wastewater infrastructure	Leaks from water supply pipes or wastewater infrastructure can recharge local groundwater. Efforts should be made to reduce this unnatural input of water.	Where significant leakage of groundwater into piped infrastructure occurs (old infrastructure).	[18]	
5p. Avoid urban development in areas with naturally shallow groundwater	Waterways that run through areas with naturally shallow groundwater – such as wetlands, swampland or floodplains – will be more affected by rising watertables associated with urbanisation. For this reason, standard development should not occur in these areas. Alternative development, such as houses on stilts, may be appropriate.	All areas		

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Other useful tools

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Repairing flow: what to do in the catchment

Strategy 1. Reduce flow volume

Strategy 2. Reduce the velocity of instream flow, particularly peak flows

Strategy 3. Reduce the frequency of flow pulses

Strategy 4. Slow the rate of flow rise & fall

Strategy 5. Repair stream baseflowrise

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Repairing geomorphology: what to do at the site and in the catchment

Repairing geomorphology: what to do at the site and in the catchment

CRC for
Water Sensitive Cities

Strategy 1. Reduce flow volume and velocity

Suitability of strategy: in general, this strategy is most appropriate for small- and medium-sized streams rather than large lowland rivers.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
1a. Reduce flow volume by harvesting, infiltrating, detaining and disconnecting stormwater in the catchment See *Repairing flow: what to do in the catchment* factsheet. Strategy 1 all actions	Minimising the volume of stormwater inputs into the waterway will reduce the volume and velocity of instream flows, reducing their erosive force on the waterway channel and reducing unnatural incision and widening.	Most effective where the catchment is small with relatively low imperviousness (< 10 per cent), such as in peri urban areas, because there are fewer impervious surfaces and therefore less stormwater that needs to be attenuated. See *Repairing flow: what to do in the catchment* factsheet for the suitability of specific actions.	[1-7]	See associated factsheet
1b. Use exsisting dams and weirs to trap water	Man-made structures such as weirs can be used to trap flashy urban flows and moderate outflow spikes, reducing the scouring of downstream flows and their erosive force on channel beds and banks.	Where there are significant inputs of stormwater upstream of the dam or weir and relatively few stormwater inputs downstream of the weir – at least for some way. Where the regulating structure has capacity to store high flows behind it.	[1-7]	[8, 10] See relevant WSUD guidelines and MUSIC tool
1c. Reduce the velocity of instream flow at the site See *Repairing flow: what to do at the site* factsheet, Strategy 1 all actions	Changing the shape of the channel and using instream structures (logs, w-weirs) can all slow the flow at a given site and reduce erosive forces on the channel. Note, these actions have much less influence than actions implemented at the catchment scale (i.e. action 1a this strategy).	Where catchment-wide implementation of water saving urban design (WSUD) has already occurred.		See associated factsheet

Strategy 2. Reduce fine sediment and promote coarse sediment

Suitability of strategy: most suitable for established urban catchments that are starved of coarse sediments (e.g. there are few bars or benches made of sand or gravel in the channel).

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
2a. Ensure that construction sites use sediment control measures	Urban construction can cause instream sedimentation to increase three-fold. Ensuring that developers put measures in place (e.g. sediment traps) to reduce sediment runoff from construction sites into stormwater drains will reduce the un-naturally high levels of fine sedimentation that during urban construction phases typically smother gravel beds, infill pools and create sediment slugs.	Where considerable construction activity is occurring in the upstream catchment, such that the urban waterway is in a state of sediment accumulation. Where roadside stormwater drains are directly connected to the waterway. Where fine sediments (silt, sand) are smothering the channel.	[8]	[8] and WSUD manuals
2b. Encourage the channel to naturally self-adjust See Strategy 3 all actions this factsheet	Many urban waterways are starved of coarse sediment. Channel banks can be a good source of coarse sediment for the channel. If the channel is allowed to naturally migrate across the floodplain then bank sediments can be transported downstream where they contribute to the construction of geomorphic units (riffles, banks, bars).	Where there is little construction in the upstream catchment, such that the urban waterway is in a state of sediment depletion. Where there is sufficient space in the riparian buffer for channel migration and/ or widening. See Strategy 3 for the suitability of specific actions.	[3, 9]	See Strategy 3 this factsheet
2c. Protect headwater sources of coarse-grained sediment	Headwater streams in relatively undeveloped catchments can provide a natural supply of coarse-grained sediments for downstream reaches and should be protected from development. If they are developed they should have wide riparian corridors and be allowed to adjust naturally so they can continue to deliver sediment downstream.	For waterways with relatively undeveloped headwaters (e.g. greenfield sites, or peri urban areas). Where headwaters sit in sloped landscapes – i.e. their flows have enough power to mobilise coarse sediment downstream.	[3]	
2d. Re-engage headwater sources of coarse sediment by removing stormwater pipes and removing instream barriers	Daylighting small streams (first order) will provide a source of coarse sediments for downstream receiving waterways. Similarly, removing barriers (such as weirs) should improve the delivery of coarse sediments to downstream sites.	Daylighting is most suitable for small brownfield waterways. Removing instream barriers is most suitable for lowland sites located downstream of an instream barrier that is preventing the passage of coarse sediment. Note that barrier removal may also increase stream power and exacerbate scouring and thus should be considered with caution. Decisions to remove barriers must be viewed holistically and consider the consequences for geomorphology, flow and biota.	[3]	

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
2e. Redesign GPTs or manage them so that coarse sediments are returned to the stream	Gross pollutant traps (GPTs) are designed to trap sediment; however, this contributes to sediment problems in streams. While fine sediments bond to pollutants and should be removed, coarse sediment (sand, gravel) should be put back into the channel to support the construction of geomorphic units (i.e. riffles, banks, bars).	Where the channel is starved of course-grained sediment – evidence of this is where the channel bed has been actively eroding. Where scouring urban flows have been managed by catchment-wide WSUD (otherwise gravel additions will be lost downstream).	[10-12]	
2f. Manually add coarse sediment (clean gravel) to stream	Many urban waterways are starved of coarse sediment. If clean coarse fill (e.g. gravel) is available it can be directly added to the channel.	In high value locations where the channel is starved of coarse sediment and modification by GPTs is not possible or insufficient to repair the coarse-sediment load. Where scouring urban flows have been managed by catchment-wide WSUD (otherwise gravel additions will be lost downstream).	[3, 10, 11]	Gravel can be added in one location and flow can naturally redistribute it [11]

Strategy 3. Allow the channel to naturally self-adjust to altered flow

Suitability of strategy: suitable for sites where enough space exists to allow channel migration in relation to altered flows, where the bed and bank material is erodible (i.e. gravel, clay, sand, NOT bedrock). Note, this strategy may result in wider, shallower waterways that may exacerbate water temperature increases, thus it is recommended that natural channel adjustment is combined with riparian restoration to limit temperature rises.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
3a. Remove channel hard-lining	Removing the hard surface of urban channels, such as concrete lining and various forms of revetment, is a prerequisite to allowing the channel to self-adjust. Many geomorphologists consider that simply removing hard linings is a more efficient and cost-effective approach to channel self-adjustment than channel reconfiguration.	Where the channel is lined with hard surfaces (e.g. concrete).	[3, 13, 14]	
3b. Recreate channel sinuosity	If the urban channel is very straight and has uniform bank sediment, it may be necessary to give channel self-adjustment a helping hand by using earth-moving equipment to add some sinuosity. This man-made sinuosity will support the channel to create patches of erosion and deposition and start to adjust in a more natural fashion.	Creating sinuosity is inappropriate where the waterway slope is > 2 per cent.	[15]	[15-18]

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
3c. Increase the width of the riparian buffer	For natural adjustment to succeed, there must be enough land on either side of the waterway for the channel to migrate or widen into. Increasing the width of the riparian buffer ensures there is sufficient space for lateral channel migration.	Where there is sufficient available land surrounding the waterway. Where the development is greenfield and in the planning stage. In brownfield areas where it is difficult to widen riparian buffers, it may be possible to widen the buffer in discrete patches.	[3, 9, 13, 19]	[20]

Strategy 4. Mitigate erosion caused by urban infrastructure or head-cutting

Suitability of strategy: suitable for most sites, particularly sites where stormwater pipes or roads are present. Most effective if scouring flows have already been repaired at the catchment scale. The strategy is not appropriate if the channel is hard-lined with concrete.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
4a. Relocate/ redesign stormwater drainage inputs	Stormwater pipes that feed directly into the waterway create a hotspot of bank and bed erosion. Stormwater pipes should be disconnected from the waterway. They should terminate at swales or biofilters on the distal edge of the riparian zone.	All sites, particularly where the riparian buffer is wide enough to facilitate retrofitting and the establishment of a biofilter or swale.	[2, 3]	See WSUD manuals
4b. Redesign culverts	Culverts (i.e. pipes beneath road crossing) concentrate stream flow and often cause localised incision downstream. Open-bottom culverts can prevent this.	Where the site includes a road crossing with a culvert.	[21]	[21]

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
4c. Employ grade control structures (boulder weirs – cross vane, w-weir, j-hook; rigid weirs)	Knick points are abrupt changes in the slope of a stream caused by erosion. These geomorphic features typically erode upstream (i.e. head cutting) and can exacerbate incision problems in urban waterways. Grade control structures can be used to protect these areas and limit incision from spreading upstream.	At the downstream end of a restoration site. Where knick points exist downstream of the restoration site. Where natural changes in channel profile are causing unwanted scouring of the stream bed. Care needs to be taken so that grade-control structures do not reduce connectivity, i.e fish passage.	[22]	[22]

Strategy 5. Stabilise the bank, particularly erosion hotspots

Suitability of strategy: typically this strategy will be suitable where the stream bed is no longer undergoing marked adjustment to urban flow; that is, where the channel has already self-adjusted (Strategy 1 this factsheet) or where catchment hydrology has been repaired (see *Repairing flow: what to do in the catchment* factsheet, all strategies). The strategy is not appropriate if the channel is hard-lined with concrete.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
5a. Plant deep-rooted trees and a range of vegetation in the stream-side zone	Deep-rooted vegetation (e.g. trees) reduce the likelihood of bank collapse because they anchor the riverbank to the surrounding land. Trees also reduce the chance of the bank collapsing because they intercept rain and improve soil drainage, which keeps the bank drier and lighter and less likely to collapse. Grasses and sedges reduce the likelihood of bank collapse because their roots and rhizomes increase the tensile strength of soil matrices.	Most suitable when bank material is erodible (e.g. sand, clay) but relatively unimportant when it is non-erodible (e.g. bedrock). Trees are less effective for bank stabilisation if the watertable is very shallow as the tree roots are unlikely to be deep. Importantly, stream-side vegetation will exert relatively little influence on bank stability when channel width is > 50 m and when banks extend beyond the root zone (i.e. bank > 2 m depth).	[23-25]	[23, 24] – and see summary in [19]

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
5b. Line the stream bank with macrophytes (i.e. semi-aquatic plants such as sedges)	Macrophytes and other groundcover vegetation reduce bank erosion during high flows by flattening against the bank and reducing the scouring of bank material.	Where the stream bank is low (< 1 m high) and the bank slope is low (< 45° angle with stream). Where the macrophytes are planted in areas not subject to highly scouring flows; that is, they aren't likely to be just washed away. Macrophyte establishment will be more successful in some areas if the plants are supported by geofabric.	[23, 26, 27]	[19, 24]
5c. Add large woody debris (LWD) to the channel	LWD can deflect scouring flows away from the bank.	Most effective where the channel is narrow. Where LWD is placed in the correct location; that is, downstream of meander bends or on the toe of eroding banks. Most effective for bank stabilisation where density of LWD placed into the channel is large and where the logs are complex (rootwads, branches attached). If concerns exist about the risk to urban infrastructure, we recommend using the Large Wood Structure Stability Analysis Tool <http://www.fs.fed.us/ biology/nsaec/ products-tools.html> [28]. The associated resource [29] describes the process and may also be useful.	[24, 30, 31]	[31-34] See synthesis by [19]
5d. Use bank-hardening techniques (revetment)	Bank hardening techniques, such as RIP RAP, tree revetment, geotextiles, gabions or retaining walls can be used to stabilise stream banks or parts of stream banks susceptible to erosion or exposed to scouring flows.	Where the site is still subject to highly scouring urban flows. Where earth moving machinery can access the site. Where urban infrastructure is at risk from channel migration/erosion. This action should be used with caution because these techniques can accelerate bed and bank erosion downstream.	[3, 35]	[14, 36, 37] See summary in [19]
5e. Use engineering structures (e.g. cross-vanes, w-weirs or j-hooks)	Cross-vanes, w-weirs, j-hooks and other similar structures can stabilise stream banks by reducing near-bank shear stress, stream power and water velocity.	Where earth moving machinery can access the site, and can do so without causing undue damage to riparian vegetation. Care needs to be taken so that grade-control structures so not reduce connectivity, i.e fish passage.	[38]	[19, 38]
5f. Construct check dams	Check dams are small, sometimes temporary dams constructed across a waterway to counteract erosion by reducing water velocity.	In novel or severely-modified waterways where these dams are unlikely to limit the dispersal of native biota (e.g. fish).	[39]	See river restoration manuals
5g. Fence-off riparian land	Fencing riparian land restricts access to people and animals and prevents them from contributing to bank erosion.	In peri urban areas, particularly on agricultural land where cattle have access to the waterway.	[24]	

Strategy 6. Increase geomorphic complexity

Suitability of strategy: where the waterway is straight and has little to no geomorphic complexity (e.g. channelised drain, incised creekline with little habitat complexity), and where some attempt to repair scouring urban flows has been made – either via WSUD in the catchment or the presence of a flow-regulating structure upstream. If scouring flows have not been repaired, any instream improvements are unlikely to last for long.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
6a. Recreate channel sinuosity	Channel reconfiguration is often used to undo the damage caused by man-made channel straightening (channelisation)	Where earth moving machinery can access the site and where the riparian buffer is wide enough for sinuosity to be created.	[15, 40]	[15-18] See also RVR Meander tool
6b. Create pool-riffle sequence	Pool-riffle sequences are natural recurring geomorphic units in meandering gravel-bed streams.	Suitable in gravel-bed streams. Unsuitable for sand-bed streams, unless the sand is underlain by gravel. Where earthmoving machinery can access the site and where rapid restoration is required.	River restoration manuals	[41] and river restoration manuals
6c. Add logs (LWD) or boulder clusters	Logs alter the flow of water in the channel, creating patches of erosion (scour) and deposition which promote the formation of pools and bars.	Where the channel is narrow (< 10 m). Where earthmoving machinery can access the site. Where scouring urban flows have been repaired such that LWD inputs will not be lost. If concerns exist about the risk to urban infrastructure, we recommend using the Large Wood Structure Stability Analysis Tool <http://www.fs.fed.us/ biology/nsaec/products-tools.html> [28]. The associated resource [29] describes the process and may also be useful.	[17, 19, 31, 33, 42-44]	[17, 19, 28, 29, 31, 32, 45, 46]
6d. Add gravel to the channel (sediment augmentation)	Many urban waterways are starved of coarse sediment. Adding gravel back to the channel can replace these missing sediments and support the construction of geomorphic units (i.e. riffles, banks, bars)	At high value locations where the channel is starved of course-grained sediment – evidence of this is where the channel has been actively eroding. In most locations respairing sources or coarse sediment (action 2d) and allowing the channel to naturally adjust will be more effective over the longer term.	[3, 10]	Gravel can be added in one location and flow can naturally redistribute it [12]
6e. Encourage the channel to naturally self-adjust See Strategy 3 all actions this factsheet	Many urban waterways are starved of the coarse sediment that builds riffles, bars and banks. Channel banks can be a good source of coarse sediment for the channel. If the channel is allowed to naturally self-adjust, then bank sediments can be transported downstream where they contribute to the construction of geomorphic units (riffles, banks, bars).	Where there is little construction in the upstream catchment, such that the urban waterway is in a state of sediment depletion. Where there is enough space in the riparian buffer for channel migration and/or widening. See Strategy 3 for the suitability of specific actions.	[3, 9]	See Strategy 3 this factsheet

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
6f. Remove fine sediment from the channel manually or by using a controlled flushing flow	Fine sediment associated with urban development can smother riffles and infill pools. These fine sediments can be manually removed or controlled flushing flows (e.g. environmental flows) can be used to transport the fine sediments onto the floodplain.	Where urban construction or agricultural development has occurred in the upstream catchment but has now largel y ceased (otherwise the benefits of this action will be short lived). Flushing flows will only be successful if they are able to mobilise fine sediments onto the floodplain. If flushing flows will exacerbate channel erosion then this action is not recommended. Manual removal of sediment should be done with caution as it may cause unintended damange to the stream bed and to riparian vegetation.	[47]	
6g. Promote/ protect trees and native vegetation along the bank	Tree roots stabilise the bank and encourage non-uniform erosion and promote the formation of different geomorphic units.	Most sites.	[40]	

Strategy 7. Restore connection to the floodplain

Suitability of strategy: most suitable where channel incision, levees or regulators have disconnected the river from its floodplain. This strategy is particularly important for stream health where the floodplain is well developed (i.e. lowland river sites) and supports diverse productive aquatic habitats (i.e. permanent and temporary wetlands/ponds). Suitable only where overbank flows do not pose a significant risk to people or urban infrastructure.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
7a. As per *Repairing lateral connectivity: what to do at the site and in the catchment* factsheet, Strategy 2 all actions	Enhanced river/ floodplain connectivity reduces the volume and velocity of streamflow in the main channel during flood periods. Reducing the power of these flood flows should help the recovery of geomorphic units, such as bars and benches, which would otherwise be washed downstream.	See associated factsheet.	[3]	See associated factsheet

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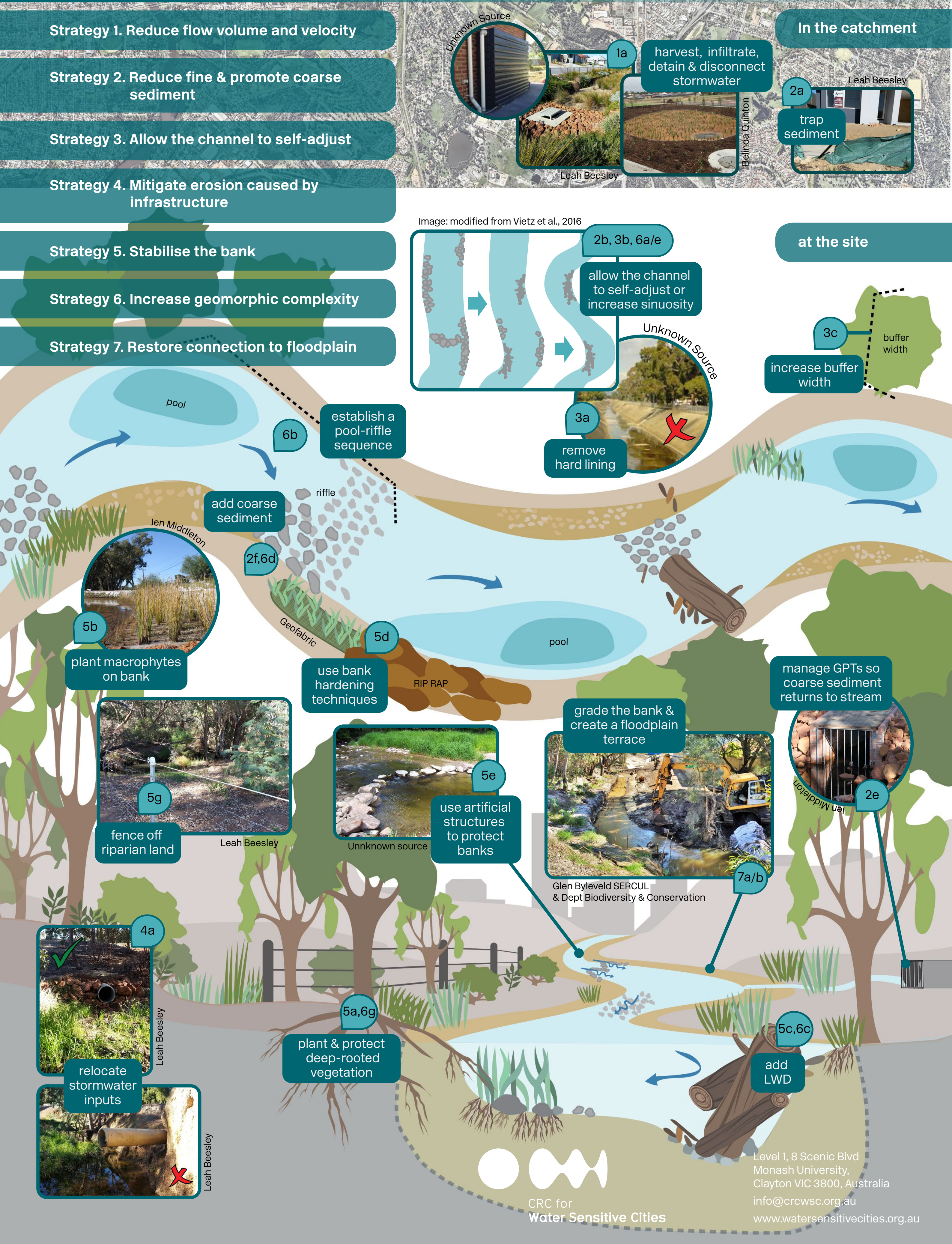
Repairing geomorphology: what to do at the site and in the catchment

- Strategy 1. Reduce flow volume and velocity
- Strategy 2. Reduce fine & promote coarse sediment
- Strategy 3. Allow the channel to self-adjust
- Strategy 4. Mitigate erosion caused by infrastructure
- Strategy 5. Stabilise the bank
- Strategy 6. Increase geomorphic complexity
- Strategy 7. Restore connection to floodplain



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Repairing longitudinal connectivity: what to do at the site and in the catchment

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Strategy 1. Assist the in-stream movement of water and biota

Suitability of strategy: most appropriate where aquatic biota require high rates of dispersal for ongoing persistence, and where there are important small, isolated populations of biota. Particularly recommended where a desired native aquatic animal is present downstream, but missing from the site due to barriers or poor functional connectivity between the restoration site and the site where the species is present.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
1a. Daylight or remove piped streams	Small streams in urban areas are typically piped or paved over, removing connectivity between the top of the stream network and lower reaches.	Where small headwater streams have been piped. Where daylighting is not prohibited by urban constraints.	[1]	[2-4]
1b. Remove or modify artificial instream barriers (e.g. rock dams, weirs)	Barriers prevent the passage of fish and other biota. The removal of barriers or the creation of fishways improves the passage of fish and biota along the length of the river.	Where the barrier is large (i.e. weir, dam) such that it prevents movement year round – even during high flows. Where migratory or diadromous species exist (i.e. fish need to move between fresh water and the estuary/ ocean to complete their life cycle). Where diadromous species are present, the removal of barriers downstream in the river network is particularly important. Caution: barriers should not be removed if their absence will increase the spread of non-native invasive species.	[5-7, but see 8 as a caution]	See fishway manuals
1c. Minimise or retrofit road crossings (i.e. use flyovers, minimise roads crossings, use fish-friendly culverts)	Road crossings can reduce the dispersal of aquatic (fish) and semi-aquatic biota (insects, turtles); hence reduce the potential for these species to recolonise restored sites. Where possible, road flyovers should be used in place of normal roads. Planning for new developments should prevent roads from bisecting riparian corridors as much as possible.	For fish – where the road crossing culvert is non-fish friendly. For semi-aquatic biota - where the road crossings are upstream in the catchment – i.e. they are blocking dispersal from a relatively healthy peri urban population of insects. Where the road crossing prevents connection of a riparian corridor to a wetland or a large remnant parcel of bushland.	[6, 9-11]	See fishway manuals

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Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
1d. Repair stream baseflow See *Repairing flow: what to do in the catchment* factsheet, Strategy 5, for specific actions	Unnatural reductions in baseflow associated with urbanisation (e.g. Melbourne, and water extraction, strand fish in pools during low flow periods, reducing their dispersal capacity and increasing their risk of mortality. Unnatural rises in baseflow associated with urbanisation (e.g. south-east Perth) can turn intermittent streams permanent and make them susceptible to invasion by non-native species.	Where the urban change to baseflow is marked. Stream baseflow is easier to repair when the catchment is small because there is not as much land to retrofit with water sensitive urban design (WSUD). Similarly, sites with a catchment that has a relatively low percentage of imperviousness will be easier than those with a catchment that has a high percentage. Increasing baseflow may be difficult to achieve in a drying climate.	[12-15]	See associated factsheet
1e. Improve instream cover Repairing riparian function: what to do at the site factsheet, actions 5a–5c and 5e	Instream cover (e.g. logs, pools, macrophytes, overhanging vegetation) supports particular life stages of, and provides shelter for, dispersing or migrating species.	Where little instream cover exists. Where scouring urban flows have been repaired by catchment-scale stormwater management or by flow regulation via an instream structure (e.g. weir).	[16]	See *Repairing riparian function: what to do at the site* factsheet, actions 5a–5c and 5e
1f. Repair streamside vegetation	Streamside vegetation provides shading and structural cover that protects instream biota, such as fish, from aerial predators (i.e. birds).	Where the natural vegetation is tall (i.e. trees are present) and the stream channel is relatively narrow (< 10 m wide). Where there are aerial predators.	[17]	
1g. Cold-water release from base of dam or other infrastructure	Water temperature can limit the movement of fish along the length of a river. Cold-water releases from dams may be used to facilitate fish migration by reconnecting thermal refuges.	Where valued fish species have thermal limitations and are restricted to deep, cool water refuges, or where life history migrations (e.g. spawning migrations) are cued by temperature changes (e.g. Australian grayling). This action should be monitored and used with caution as it could have unintended negative consequences for biota or life stages that require warm water.	[18]	Little information available, but see [18] for a discussion of the pros and cons
1h. Attenuate or remove urban point-source pollution	Point source pollution that is discharged into an urban stream can cause a chemical (toxic) barrier to movement.	Where point-source industry discharges into the waterway and causes unnatural conditions (e.g.toxic chemicals, low oxygen, altered pH or conductivity, macrophyte overgrowth) that deter or prevent the passage of animals.		See best practice documents on industrial release into waterways

Strategy 2. Support the terrestrial movement of semi-aquatic biota

Suitability of strategy: most appropriate where the urban catchment is fragmented by roads and when semi-aquatic biota have large home ranges, use riparian vegetation as movement corridors and are not adapted to edge environments.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
2a. Connect riparian corridors	Fragmentation, or breaks, in riparian corridors associated with the loss of riparian vegetation prevent the longitudinal movement of semi-aquatic and terrestrial biota.	Where relatively few road crossings exist, such that reconnection of a corridor puts large unfragmented pieces of riparian land together (i.e. peri urban areas).	[6, 9-11]	
2b. Minimise or retrofit road crossings (i.e. use flyovers, minimise roads crossings)	As per action 1c this factsheet	As per action 1c this factsheet	As per action 1c this factsheet	As per action 1c this factsheet
2c. Increase buffer width	Increasing the width and density of riparian vegetation will create a better movement corridor for wildlife.	Where pre-existing space is available for buffer expansion (e.g. greenfield development).	[19]	[20]
2d. Increase the structural complexity of riparian vegetation	For riparian land to function as an effective wildlife corridor, it should contain vegetation that has enough structural complexity so that animals feel protected as they move through it.	Where the current vegetation is very sparse.		Little known, but see [20]

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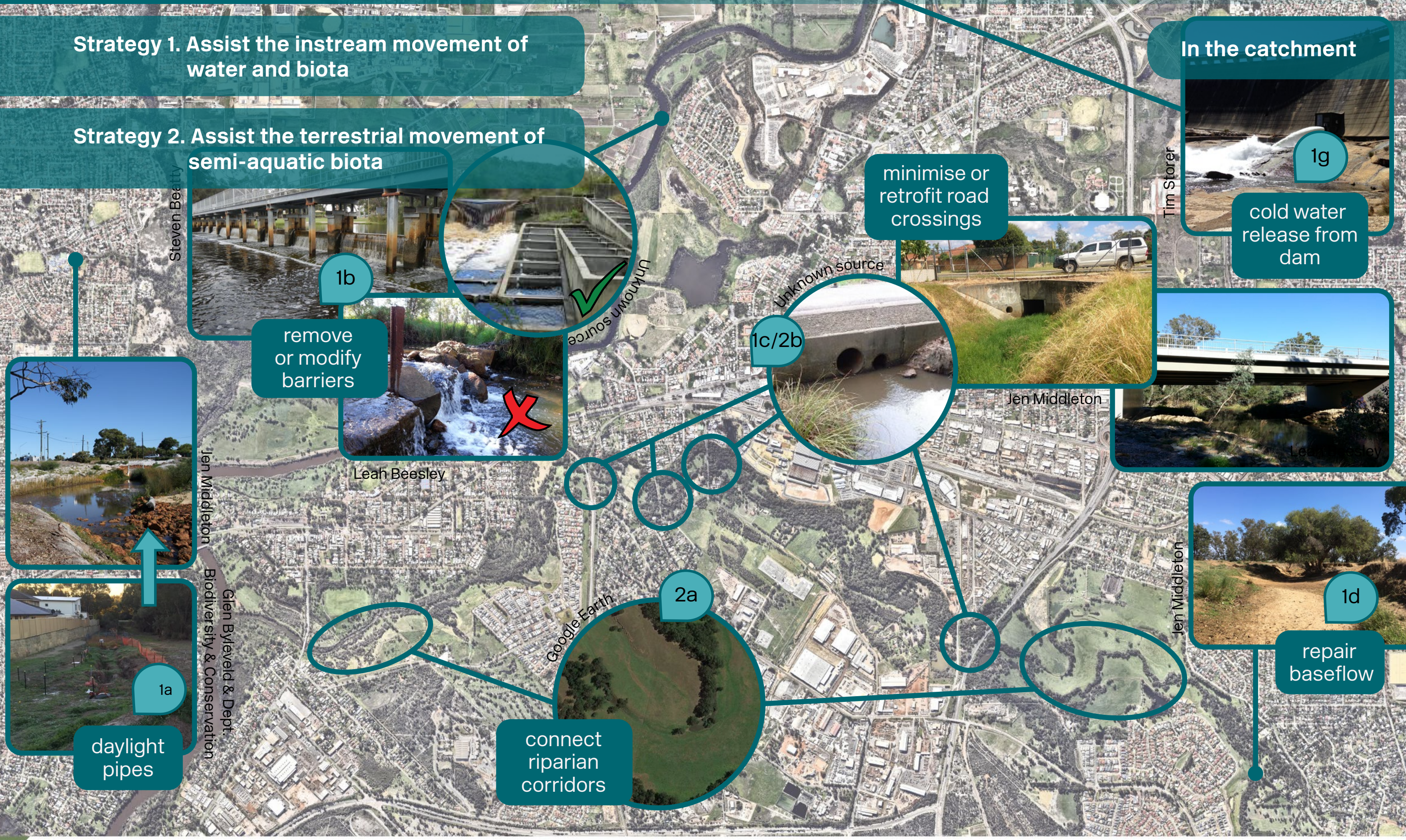
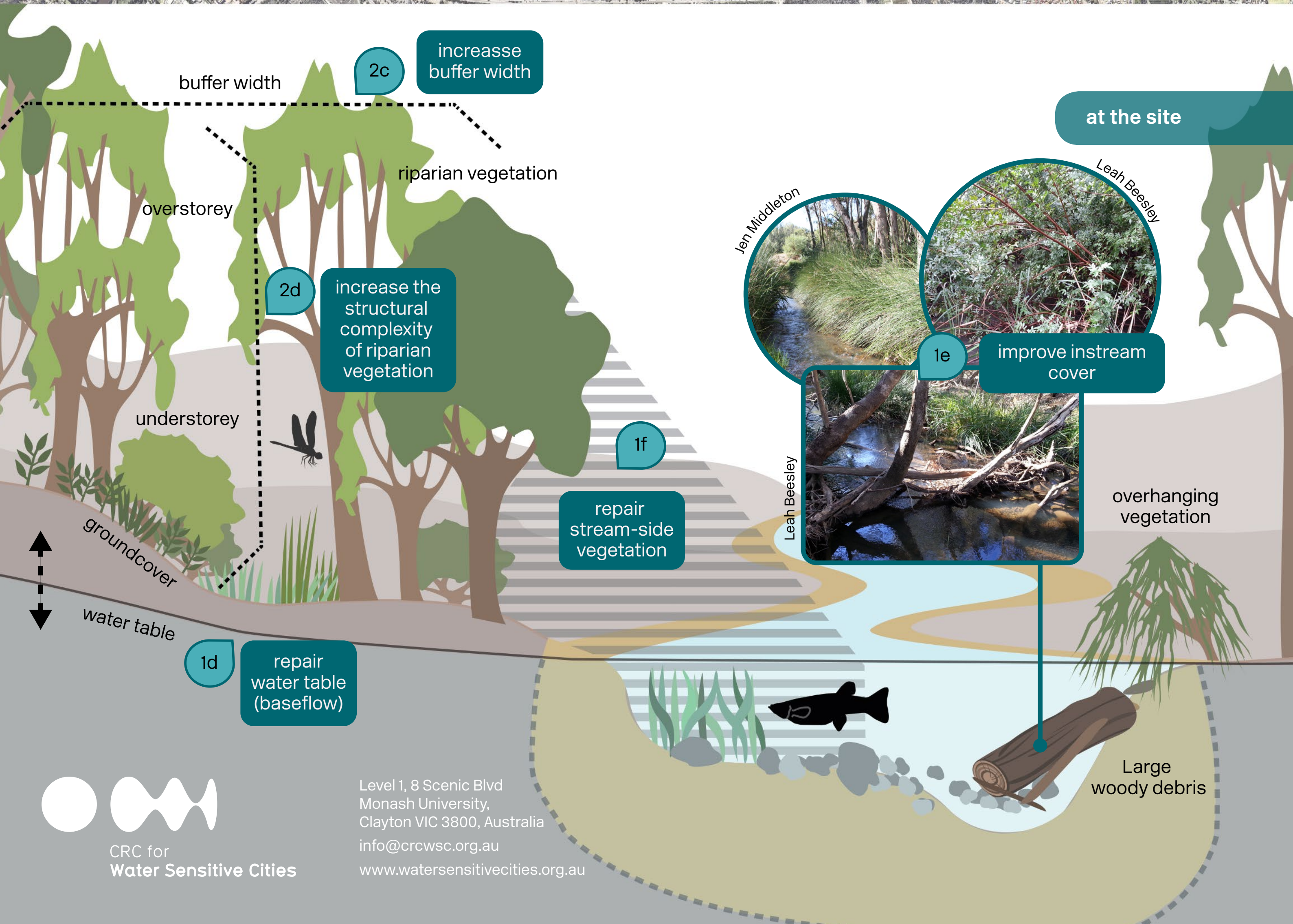
Repairing longitudinal connectivity: what to do at the site and in the catchment





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Repairing lateral connectivity: what to do at the site and in the catchment

Repairing lateral connectivity: what to do at the site and in the catchment

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Strategy 1. Protect floodplain land and riverine wetlands

Suitability of strategy: suitable where the catchment includes low-lying land with a meandering channel.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
1a. Protect low-lying floodplain areas from development	Low-lying parcels of land adjacent to the waterway are important sites of lateral connectivity. These sites should be protected from urban development.	All areas	[1]	None
1b. Protect/ create floodplain wetlands and other depressions	Floodplain wetlands and other depressions are important habitats for biota, and important sites of nutrient processing on the floodplain. Protecting and creating these habitats is important for the ecological health of the waterway.	Low-lying parcels of land that are prone to flooding. This action is most important to waterway health where floodplains are highly productive and are generally sinks rather than sources of nutrients.	[2-5]	

Strategy 2. Improve water flow between the channel and floodplain

Suitability of strategy: most suitable where channel incision, levees or regulators have disconnected the river from its floodplain. This strategy is particularly important for stream health where the floodplain is well developed (i.e. lowland river sites) and supports diverse productive aquatic habitats (i.e. permanent and temporary wetlands/ponds). Suitable only where overbank flows do not pose a significant risk to people or urban infrastructure.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
2a. Daylight a buried stream	Buried (piped) streams are totally disconnected from their surrounding environment. Daylighting these streams by removing the pipe and exposing them to the light allows water in the channel to interact with the surrounding land.	Where the channel is buried inside a stormwater pipe. Where the channel is heavily incised. Where grading the bank won't destroy valuable shade trees or other important habitat features.	[1, 6]	[7] See WSUD manuals

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Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
2b. Grade the bank	Grading the bank to create a gentle slope between the riparian land and the urban waterway will improve the likelihood of high flows going out into the riparian buffer.	Where the channel is heavily incised. Where grading the bank won't destroy valuable shade trees or other important habitat features.	[8-10]	[11]
2c. Lower the floodplain	Channel incision associated with urbanisation prevents river/floodplain hydrologic interaction. Reconfiguring the channel and lowering the floodplain can improve the lateral hydrologic connection. Note: the new floodplain can be shaped as a terrace (narrow or wide) below the current floodplain.	Where the channel is heavily incised. Where urbanisation has caused the watertable to fall. Where scouring urban flows persist – given these are likely to detrimentally affect action 2c of this factsheet. Where earthworks don't pose a significant risk to the existing riparian vegetation (e.g. new greenfield development or highly degraded brownfield site).	[6, 9, 12, 13]	
2d. Raise the channel by adding coarse sediment (e.g. cobbles, gravel)	Channel incision associated with urbanisation prevents river/floodplain hydrologic interaction. Adding coarse sediment (gravel) can raise the floor of the channel and improve lateral hydrologic connection.	Where the channel is heavily incised. Where urbanisation has caused the watertable to rise. When scouring urban flows have been repaired so as not to wash the added bed material downstream and out of the site. Where gravel is a natural bed substrate. Where the addition of gravel or cobbles won't lead to a noticeable unnatural reduction in baseflow. Take care that the addition of gravel does not smother important instream habitats. Most suitable for high value sites.	[6, 13-15]	
2e. Create artificial structures (e.g. pond and plug, cross-vanes, w-weirs, check dams)	Artificial instream structures can be created that partially block flow and promote overbank flow.	Where the channel is highly incised. Where scouring urban flows persist. Where actions 2a, 2b or 2c are inappropriate. Where the ecology of the site is highly modified. Where overbank flows do not pose a significant risk to people or urban infrastructure. Care needs to be taken so that artifical srtructures do not reduce connectivity, e.g. fish passage, or cause other environmental issues downstream.	[15, 16]	[17]
2f. Reroute the waterway	Rerouting a heavily incised channel to an adjacent piece of land that is less erodible will reduce future incision and promote greater overbank flow. Rerouting may also be effective if the soil type is similar but urban flows have been managed. The abandoned segment may be used as a wetland.	Where there is enough space, such as in a greenfield development. Channel rerouting is encouraged if the new channel pathway contains soils that are significantly less erodible or if management has markedly reduced the velocity of instream flows.	[15]	

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
2g. Remove floodplain levees and regulators	Levees and regulators provide a barrier to the flow of water from the main channel to the floodplain. Barrier removal repairs natural flow paths.	Where levees and regulators exist. Where overbank flows do not pose a significant risk to people or urban infrastructure. Do not reconnect the wetland to the main channel if doing so would facilitate the spread of invasive species.	[10, 14, 18-20] but see [18, 21] for caution	[22]

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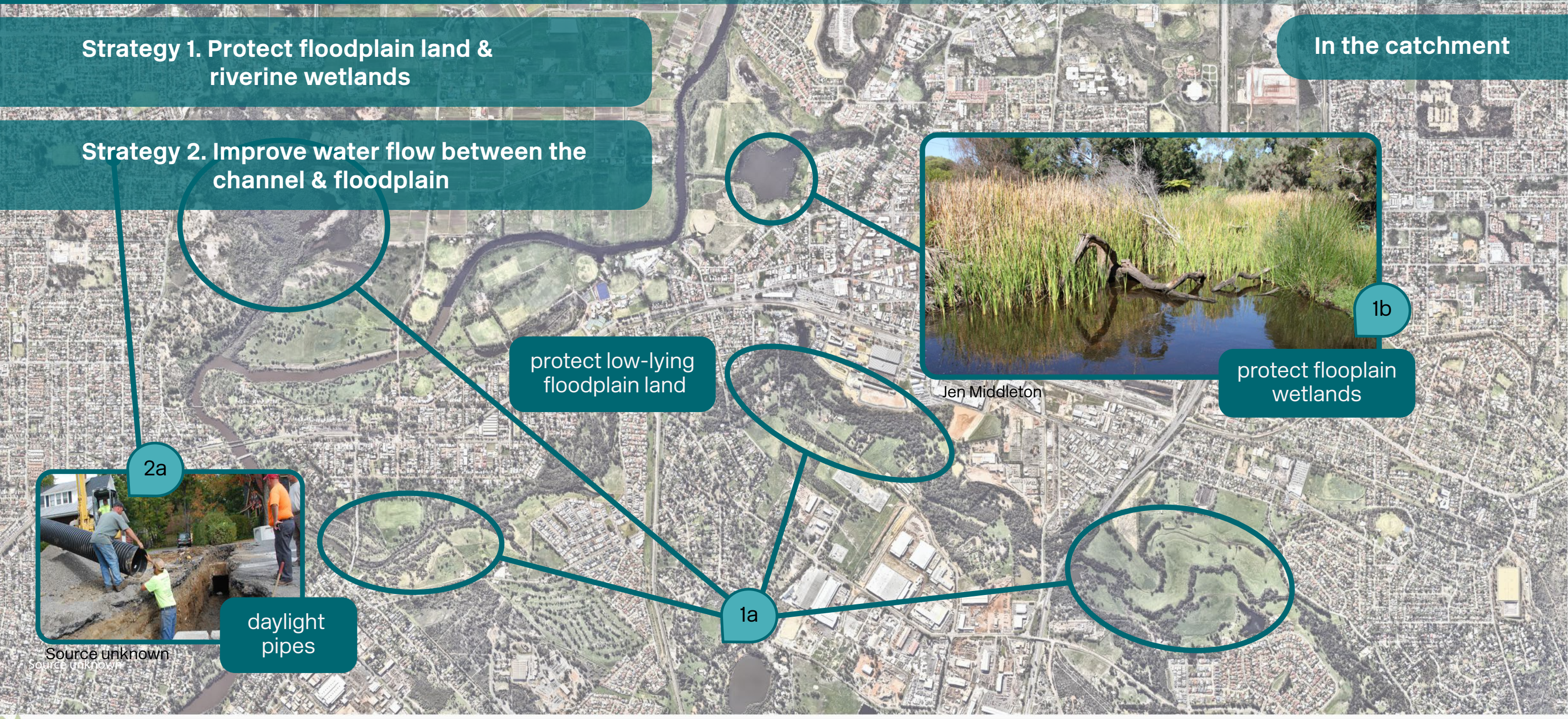
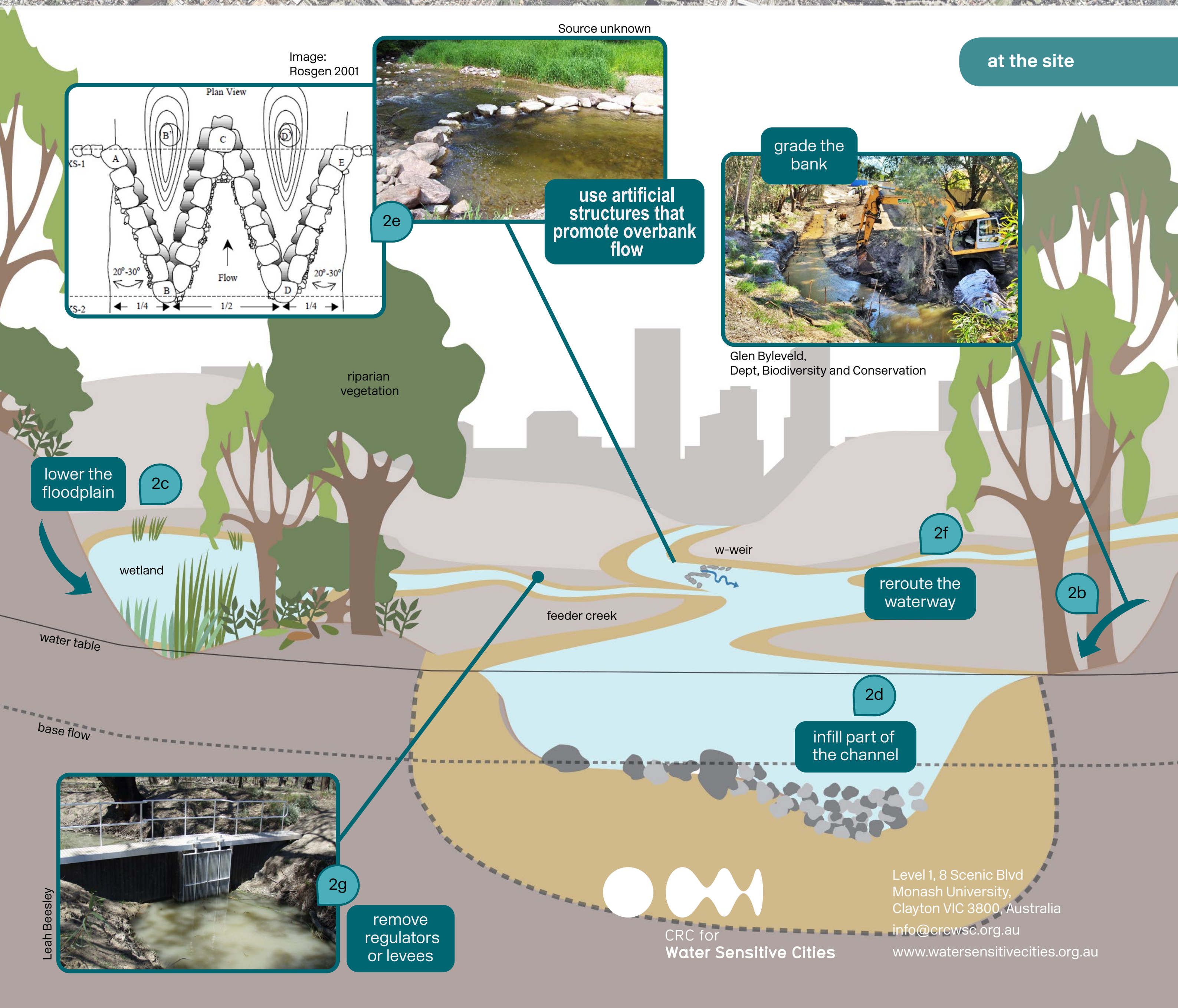
Repairing lateral connectivity: what to do at the site and in the catchment





Repairing vertical connectivity: what to do at the site and in the catchment

Repairing vertical connectivity: what to do at the site and in the catchment

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Strategy 1. Repair the height of the watertable

Suitability of strategy: most suitable for waterways where the watertable is shallow – at least during the wet season (baseflow index of site is high).

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
1a. Repair the height of the watertable See *Repairing flow: what to do in the catchment* factsheet, actions 5a–5h for falling watertable, actions 5i–5p for a rising watertable	The height of the watertable affects surface water/ groundwater interactions.	Suitable in most locations except where the groundwater is contaminated. See *Repairing flow: what to do in the catchment* factsheet for the specific suitability of specific actions.	[1, 2] but not where groundwater is contaminated [3]	See associated factsheet

Strategy 2. Slow flow

Suitability of strategy: all sites, except those where flow has already been slowed (e.g. downstream of a flow regulating structure or in a weir pool).

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
2a. Slow flow by catchment-wide harvesting, infiltration and detention of stormwater See *Repairing flow: what to do in the catchment* factsheet, Strategy 1	Minimising the volume of stormwater inputs into the urban drainage network helps reduce the velocity of instream flows and increases the potential for water to downwell into the hyporheic zone.	See *Repairing flow: what to do in the catchment* factsheet, Strategy 1, all actions.	[4]	See associated factsheet

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
2b. Slow flow using existing dams and weirs	Dams or weirs can be used to trap and store high flows, moderating the velocity of water flow downstream and increasing the potential for water to downwell into the hyporheic zone.	Where there are significant inputs of stormwater upstream of the dam or weir, but relatively few stormwater inputs downstream of the water storage facility. This action does NOT advocate for the creation of new dams or weirs.		

Strategy 3. Promote hydraulic diversity

Suitability of strategy: suitable only once scouring urban flows have been repaired or if low flows occur for a protracted period each year. Most effective where the bed material is highly permeable.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
3a. Allow the channel to adjust naturally See *Repairing geomorphology: what to do at the site and in the catchment* factsheet, Strategy 3	More geomorphic diversity (beds, bars) occurs in naturally adjusted channels than channelised waterways. The increased geomorphic complexity promotes hydraulic diversity (e.g. deep and shallow waters), which promotes the vertical exchange of water.	Where the waterway is channelised at present, particularly where it is constrained by hard-lining (e.g. concrete, RIP RAP). Where the bed material is highly porous. See associated factsheet for the suitability of specific actions.		See associated factsheet
3b. Increase channel sinuosity	Reconfiguring the channel to increase sinuosity will slow flow and increase instream hydraulic diversity – both of which will promote the vertical exchange of water.	Where the waterway has been channelised. Where there is sufficient land around the stream for channel redesign. Where earthworks don't pose a significant risk to existing riparian vegetation.	[3-5]	[6-10] See also RVR Meander tool
3c. Establish a pool-riffle sequence	Pool-riffle sequences increase variation in hydraulic head (water pressure) along the stream, stimulating the vertical upwelling and downwelling of water.	Where bed material is highly porous. Where stream depth is shallow so that riffles can create marked hydraulic diversity. Where the stream channel is stable such that riffles won't get washed away. Where sedimentation is low so that riffles won't be buried.	[4, 5, 11-13]	[14] and River restoration manuals

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
3d. Install boulders and large woody debris (LWD)	Boulders and LWD create localised increases in surface water elevation that promote the downwelling of water into the hyporheic zone.	Where instream habitat complexity has been drastically simplified by urbanisation. Where bed material is porous. Placement of LWD will be most successful where logs are able to stretch across the channel. If concerns exist about the risk to urban infrastructure, we recommend using the Large Wood Structure Stability Analysis Tool <http://www.fs.fed.us/biology/nsaec/products-tools.html> [2-5, 15-18] [8, 10, 19-23]	[2-5, 15-18]	[8, 10, 19-23]
3e. Create artificial structures	Artificial structures (e.g. cross vanes, J-hooks, sub-surface boxes) can create localised variation in water depth and therefore promote upwelling and downwelling.	Where actions 3b, 3c and 3d are inappropriate due to any number of constraints. Care needs to be taken so that artificial structures do not reduce connectivity, e.g. fish passage, or create other environmental impacts downstream.	[4, 24, 25]	[25, 26]

Strategy 4. Improve the permeability of bed material

Suitability of strategy: most suitable for waterways where the bed material is highly permeable (cobble, gravel, coarse sand).

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
4a. Remove impermeable channel lining	An impermeable channel lining (e.g. concrete, compacted clay) prevents the interaction of surface water with shallow groundwater – limiting the vertical exchange of water, i.e. both groundwater upwelling and local recharge of the watertable by stream water.	Where the channel is lined with an impermeable material (e.g. concrete, clay). Where concrete removal is coupled with other restorative works such that it does not exacerbate channel incision.	[4, 27]	
4b. Add coarse gravel to the channel	Adding coarse sediment will increase the porosity of the stream bed, facilitating hyporheic exchange. If gravel is added to a concreted drain it will allow the creation of a hyporheic zone for nutrient processing (see *Reducing nutrients: what to do at the site* factsheet), but still not facilitate groundwater/surface water interactions. If gravel is added to a non-concreted channel, it will improve the development of a hyporheic zone and enable groundwater/surface water exchange.	At high value lacations. Where scouring urban flows have been repaired so they won't just simply wash the added bed material out of the site. Where gravel is a natural bed material. In most locations repairing sources or coarse sediment (see *Repairing Geomorphology: what to do at the site and catchment* factsheet, Actions 2c and 2d) and allowing the channel to naturally adjust will be more effective over the longer term.	[4, 5]	

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
4c. Use flushing flows to clean gravel beds	High levels of sedimentation can clog the top layer of channel sediments, reducing the permeability of the bed and the development of a hyporheic zone. A flushing flow from a dam/weir, a wastewater treatment plant or other urban water infrastructure (e.g. fire hydrant, water pipeline) can flush fine sediment downstream or overbank, cleaning gravel beds or other permeable bed material.	Where stream bed sediments are naturally porous (e.g. gravel, coarse sand) and covered with fine sediment. Where catchment land management is advanced such that fine sediment inputs will not immediately compromise this action.	[2-4, 28]	
4d. Support bioturbation by native fauna	Stream fauna that dig tunnels into the substrate (e.g. chironomids, worms) enhance the movement of water into and out of the hyporheic zone.	Where bioturbating fauna are naturally abundant.	[4, 29, 30]	
4e. Repair streamside riparian vegetation	Streamside vegetation can promote the infiltration of surface water into the hyporheic zone because roots create macropores that act as subsurface flow paths.	Where streamside vegetation has been largely cleared. Where tree and macrophyte roots extend into the hyporheic zone.	[4, 31]	

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Other useful tools

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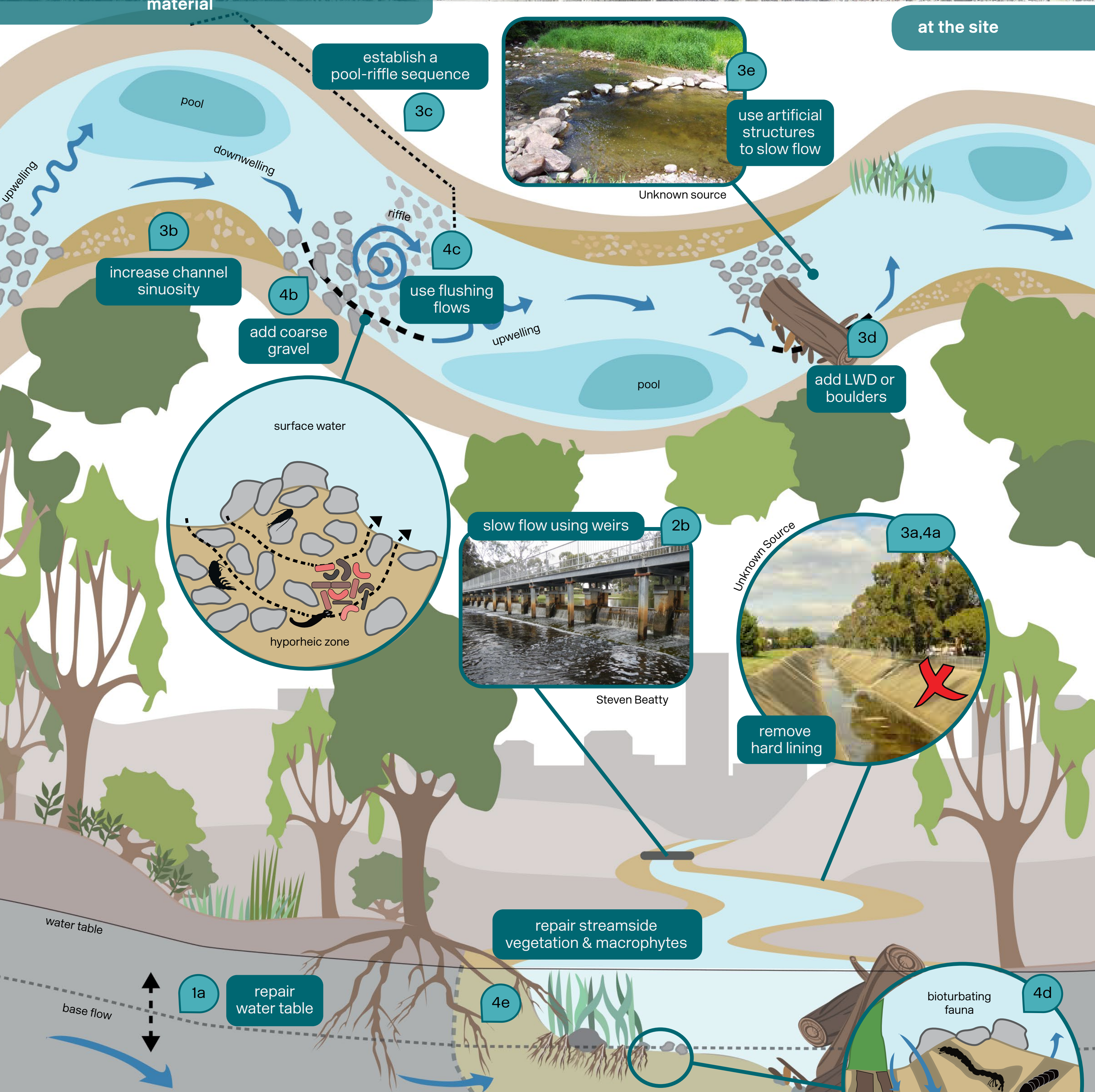
Repairing vertical connectivity: what to do at the site and in the catchment

Strategy 1. Repair the height of the water table

Strategy 2. Slow flow

Strategy 3. Promote hydraulic diversity

Strategy 4. Improve the permeability of bed material



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Repairing riparian function: what to do at the site

Repairing riparian function: what to do at the site

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Strategy 1. Shade the stream to regulate light and temperature

Suitability of strategy: most suitable where the stream channel is narrow (< 10 m wide), where the natural vegetation was once forest, shrubland, or grassland with riparian trees rather than pure grassland, and where the vegetation has been thinned or cleared.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
1a. Plant trees in stream-side zone	Tall vegetation adjacent to the stream shades the channel, reducing instream water temperature and light.	Where the stream channel is relatively narrow: < 10 m. Planting should focus on the north banks of E–W oriented channels, as this location is most effective at shading the channel. Not appropriate where natural riparian vegetation was grassland.	[1, 2]	[2-5]
1b. Increase buffer width	Increasing the width of treed land away from the channel can increase shading in the stream.	Where the treed buffer is very narrow at present: < 10 m. Particularly effective when the channel is N–S oriented. Not appropriate where severe space constraints exist.	[5]	[2, 4, 5]
1c. Install a shade structure	Installing a shade sail or shade cloth is an artificial way to reduce light and temperature.	Where space is too limited to allow tree planting. In highly urban areas where only a small length of waterway is present.	None	None
1d. Plant trees in the upstream corridor*	Water temperature at the site is also affected by upstream processes. Improving the shading of the upstream riparian corridor will reduce water temperature at the site.	Most sites. Not effective where the majority of water comes from groundwater upwelling.	[6]	[6, 7]
1e. Protect from fire	If the streamside tree canopy is burnt, it will not properly shade the channel.	Most sites. Protection from fire is less important for sites where riparian vegetation naturally provided little shade (e.g. grass).		

*catchment-scale action

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Strategy 2. Stabilise the bank

Suitability of strategy: most suitable where bank soils are highly erodible (e.g. clay, sand, gravel – not bedrock).

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
2a. Allow the channel to naturally self-adjust to flow See *Repairing geomorphology: what to do at the site and in the catchment* factsheet, Strategy 3	It is difficult to stabilise the stream bank using riparian vegetation if the stream bed is still adjusting to altered urban flows.	Where there is sufficient riparian buffer space for the channel to migrate. See associated factsheet for the specific suitability of specific actions.	[8-11]	[3] See associated factsheet
2b. Plant deep-rooted trees and a range of vegetation in the stream-side zone	Deep-rooted plants (e.g. trees) stabilise the stream bank by holding the soil together.	Where the stream bank is composed of erodible materials (sand, clay). Where urban flows have been managed so that the channel is not still adjusting. Where the channel has already been allowed to self-adjust to urban flows.	[12-14]	[3, 15]
2c. Plant macrophytes and other perennial vegetation as far down the bank as possible	Vegetation on the bank can protect the bank from scouring erosion during high flows.	When the bank is low (< 1 m high) and the bank slope is low (< 45° angle with the channel).	[15, 16]	[3, 15, 16]
2d. Add large woody debris (LWD) to the channel	Strategically-placed LWD can deflect scouring flows away from eroding stream banks.	Where LWD is placed on the outside and downstream of meander bends. Where scouring urban flows are not great enough to displace LWD. Where large amounts of LWD are added. Care should be taken with LWD placement, as incorrectly placed logs can exacerbate bank erosion.	[12, 17, 18]	[3, 7, 17, 19-23]
2e. Use bank-hardening or armouring techniques (revetment)	Bank hardening techniques, such as RIP RAP, logs, geotextiles, gabions or retaining walls can be used to stabilise stream banks, particularly parts of banks that are subject to scouring urban flows.	Where scouring urban flows are severe. Where limited space exists for channel adjustment and tree planting.	[12] but use caution as per [24]	[12, 15]

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
2f. Use geofabric socks on the bank and plant with macrophytes	Geofabrics reduce the erodibility of bank soils and can improve bank stability while natural methods (macrophytes, trees) are establishing.	When there is limited space for tree planting or if trees have been planted but are still too small to protect the bank. Where scouring urban flows are severe.	[3]	See WSUD manuals
2g. Use engineering structures (cross vane, w-weir, j-hook vane)	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.	In highly urban areas where flows are scouring and likely to displace LWD. Where there is little space for channel reconfiguration or self-adjustment. Where these structures will have no impact on connectivity, e.g., the passage of biota, and not cause environmental impacts downstream.	[3, 11, 25]	[11, 25]

Strategy 3. Improve nutrient filtration and sediment trapping

Suitability of strategy: most sites, refer to specific actions for specific suitability.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
3a. Relocate/ redesign stormwater and subsurface drainage inputs	Direct piping of road runoff or subsurface water to the stream via pipes bypasses riparian filtration. Stormwater and subsurface drainage outputs should be allowed to filter through riparian soils so that biogeochemical processes can transform and reduce nutrient levels. Flush road kerbing or kerbless roads should be used on the side of the road that drains to riparian land. 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.	Sites where stormwater pipes or subsurface drainage pipes are present and where a road borders the riparian land.	[3, 24]	See WSUD manuals
3b. Increase buffer width	Increasing the width of the riparian buffer increases the length of surface and subsurface flow paths, increasing the time for nutrient processing and uptake in surface or subsurface soils. An increase in buffer width also provides more land for nutrient and sediment deposition associated with overbank flows.	Where groundwater or surface stormwater flows into the riparian zone. Where the current vegetated buffer is very narrow, i.e. <10 m wide. Where there is enough space. This action will be less effective in very flat sandy landscapes where most nutrients are transported to the site by vertical movement of the watertable, as opposed to lateral movement of flow through the riparian buffer.	[26-28]	[3]

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
3c. Create a filter strip/ biofilter on the distal edge of the riparian buffer	Shallow-rooted plants such as grasses and sedges are particularly effective at stripping nutrients from surface flows. These plants are also very good at slowing flow so that sediment and associated nutrients are deposited.	Where the filter strip/ biofilter receives stormwater. Where excess nutrients in stormwater and subsurface drainage are inorganic (e.g. NOX, SRP) – i.e. readily taken up by plants.	[26, 29-31]	[3, 30]
3d. Revegetate the buffer (i.e. increase plant density)	Increasing the density of riparian vegetation increases the root mass available to take up nutrients. More vegetation will also increase the amount of organic matter which will, in turn, improve nutrient processing by improving P-binding capacity and increasing the carbon content of soils (promoting denitrification in subsurface water). Dense vegetation also slows the rate of overland flows, providing more time for biogeochemical transformation.	Where groundwater or surface stormwater flows into the riparian zone. Where vegetation density has been markedly reduced from natural levels. This approach will not be as effective in very flat sandy landscapes where most nutrients are transported to the site by vertical movement of the watertable, as opposed to lateral movement of flow through the riparian buffer.	[32-37]	[3]
3e. Reconfigure the slope of the riparian zone	Nutrient processing will be enhanced when water filters slowly through riparian soils – as there is more time for nutrient adoption to soils, uptake by plants or microbially-mediated transformation. Changing a steep or very flat slope to a gentle to moderate slope promotes the slow lateral movement of water.	Where stormwater flows into the riparian zone. Where the riparian land has a very steep (>25°) or a very flat (0–2°) cross-sectional profile.	[3, 28, 35, 38]	None
3f. Raise or lower the local watertable. See *Repairing flow: what to do in the catchment* factsheet, Strategy 5, for individual actions	Most of the nutrient processing in riparian zones happens in the subsurface water. Where urbanisation has lowered the watertable, the goal should be to raise it so that N-rich groundwater comes into contact with C-rich surface soils to promote denitrification. Where urbanisation has caused the watertable to rise, the goal should be to lower it to reduce the volume of nutrient-rich groundwater flowing into the stream.	Where a marked increase or decrease in watertable height has occurred. See decision support tool in Bhaskar et al. 2016. Actions to raise the watertable are suitable for most sites, except where the groundwater is rich in bioavailable nutrients. Raising or lowering the watertable will be ineffective if the waterway is concrete lined (or constrained by bedrock) as there will be no contact between subsurface flow and the waterway. For more details, see *Repairing flow: what to do in the catchment* factsheet, Strategy 5.	[34, 39-41]	See *Repairing flow: what to do in the catchment* factsheet, Strategy 5, and *Repairing flow: what to do at the site*, Strategy 2, for individual actions and their guidelines.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
3g. Promote hydrologic connectivity by grading the bank, lowering the floodplain (e.g. terracing), raising the channel or other methods See *Repairing lateral connectivity* factsheet, actions 2a–d	Floodplains are hotspots of nutrient processing. Increasing overbank flow by using one of several techniques will promote water and nutrient exchange and processing. The flow of main-channel water onto riparian land also promotes sediment and nutrient deposition on the floodplain.	Where the channel is heavily incised. Where overbank flows will not cause damage to infrastructure or people. Proceed with caution if the floodplain contains nutrient-rich stormwater biofilters. See associated factsheet for details.	[28, 34, 38, 42-45]	[3] See associated factsheet
3h. Reconnect main channel to adjacent wetlands by removing levees and regulators, digging out blocked creeks	Floodplain wetlands are hotspots of mineralisation and nutrient transformation: reconnecting the main channel to wetlands will promote nutrient processing.	Where wetlands exist and they are predominantly nutrient 'sinks' not 'sources'. Note, most wetlands shift temporally from source to sink – specific analysis may need to be done to determine the nutrient status of the wetland(s) at the site.	[42, 46]	
3i. Line the stream bank and riparian wetlands with wet-dry tolerant sedges	Shallow-rooted sedges efficiently take up nutrients from the main stream channel and from riparian backwaters/wetlands/ depressions.	Where scouring urban flows have been managed. Sedges are most likely to survive if planted in low-velocity areas such as the inside of meander bends.	[35]	See biofiltration guidelines
3j. Install permeable reactive barriers (bioreactors)	Permeable reactive barriers can adsorb nutrients (P04, NO3) or promote biologically-mediated nutrient transformation from laterally moving groundwater before it enters the waterway (e.g. denitrification). The media inside the barriers include iron oxide, calcium oxide, limestone or sawdust. Bioreactors help tackle localised source nutrient pollution (i.e. septic tanks, golf course) adjacent to streams and can be positioned so that subsurface drainage outputs filter through them.	Where localised nutrient pollution is entering the site from an adjacent land use (e.g. septic tanks, golf course) or from a subsurface drain or stormwater pipe. Where the watertable is high and soil carbon is low. Where nutrients are inorganic (e.g. NOX, SRP). Where restoration is occuring over a small area.	[47]	[47-51] Match bioreactor type with the biogeochemical need
3k. Remediate soil	Adding clay to sandy soils increases its ability to bind to nutrients, particularly phosphorus.	Where riparian soils are sandy, or have a low clay content. Where riparian soil receives stormwater. Where restoration is occuring over a small area.	[28, 35]	

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
3l. Harvest grass and sedges from filter strips and along the channel bank	Young, rapidly growing plants take up more nutrients than older, slower growing plants; thus harvesting grass and sedges in filter strips or along the stream bank can promote vigorous regrowth and nutrient uptake. The removal of plant matter can also prevent nutrients from being released back into the system when plants die.	When phosphorus is a particular management priority.	[52, 53]	
3m. Protect from fire	Fire in the riparian land will increase sediment and nutrient inputs into the waterway.	Most sites. Burning should be considered if the vegetation community needs fire for regeneration or recruitment.	[3, 54]	

Strategy 4. Improve leaf litter inputs and retention

Suitability of Strategy: most suitable where the food web of the site is naturally supported by leaf litter inputs or by a productive floodplain.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
4a. Plant native vegetation in the stream-side zone	Leaf litter that falls into streams is an important source of energy (carbon) that supports the food web. Native rather than non-native vegetation should be prioritised because its inputs are suitably timed and of appropriate quantity and quality.	Where the channel naturally had shrub or tree vegetation. Where the channel is narrow (< 10 m). Where urban scouring flows have been repaired such that leaves are not swept away – or the site is downstream of a flow regulating structure.	[3, 41, 55]	[3, 55]
4b. Increase channel sinuosity	Increasing channel sinuosity increases the area of exchange between the stream and the riparian zone, which increases the potential for leaf litter inputs.	Where the channel is narrow (< 10 m wide). Where the stream has been channelised.		[11]
4c. Increase buffer width	Increasing buffer width will increase leaf-litter inputs into small streams (channel width < 10 m).	Where the current vegetated buffer is very narrow (i.e. < 10 m). Not appropriate where there are space constraints.	[56]	[3, 56]
4d. Revegetate the riparian buffer	Increasing plant density increases the volume of litter fall into streams and the amount swept into streams during overbank flows.	Where high flows connect the riparian buffer vegetation with the main channel.	[3, 55]	[3, 55]

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
4e. Add large woody debris (LWD) to the channel	LWD traps leaves in the channel and increases their retention at the site. Bacteria and fungi are then able to condition the leaves and invertebrates can feed on them – supporting the food web.	Where the stream naturally had logs. Where the channel is narrow (< 10m). Where urban scouring flows have been repaired such that leaves are not swept away – or the site is downstream of a flow regulating structure. If concerns exist about the risk to urban infrastructure, we recommend using the Large Wood Structure Stability Analysis Tool <http://www.fs.fed.us/biology/nsaec/products-tools.html> (Rafferty, 2017). The associated resource, Wohl et al. (2016), describes the process and may also be useful.	[3, 55]	[3, 7, 17, 19-23]
4f. Promote hydrologic connectivity by grading the bank, lowering the floodplain, (e.g. terracing) raising the channel or other methods See *Repairing lateral connectivity* factsheet, actions 2a–d	Improving the transfer of water and other materials (organic matter, animals) between the riparian floodplain and the channel will improve leaf inputs into the stream.	Where channels are heavily incised. Where the site would naturally experience river/floodplain connectivity (this typically increases as you move down the river network). See associated factsheet for details.	[3, 57]	See associated factsheet
4g. Remove levees and other barriers	Regulators and levees disconnect the main river channel from the floodplain and its wetlands, preventing the flow of material (carbon). Levees/regulators should be removed if appropriate. If river wetland channels have become blocked with sediment they should be recut.	Where the site is a lowland river separated from productive floodplain wetlands.	[3, 58]	
4h. Manage or redesign gross pollutant traps (GPTs) so that leaves pass to the stream	GPTs often trap large amounts of leaves, preventing their passage into the urban waterway. Managing these traps so that leaves are allowed to move into the stream will improve terrestrial carbon input to the food web.	Where GPTs are trapping large quantities of native leaves and streamside vegetation is limited. This action may not be suitable where most roadside vegetation is non-native (deciduous), because high deciduous leaf loads in autumn may cause water quality (low oxygen) issues.		
4i. Protect from fire	Fire will destroy leaf litter and other vegetation inputs into streams.	Most sites. Burning should be considered if the vegetation community needs fire for regeneration or recruitment.		

Strategy 5. Improve aquatic habitat

Suitability of strategy: most suitable where the channel is narrow (< 10 m wide) and the natural vegetation is treed OR where the floodplain is wide with a low gradient (especially where wetlands are present).

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
5a. Add large woody debris (LWD) to the channel	LWD creates aquatic habitat in many ways. It acts as shelter for fish and a stable substrate for biofilm development and invertebrates. It also creates hydraulic variability instream (patches of slow and fast flow), promoting the creation of other geomorphic features such as step-pools, bars and benches. LWD can also trap finer organic matter, such as leaves and sticks, creating debris dams that can provide important habitat for fish and invertebrates.	Where the channel is narrow (< 10 m). Where earthmoving machinery can access the site. Where scouring urban flows have been repaired such that LWD inputs will not be lost. When rapid repair of LWD is required. If concerns exist about the risk to urban infrastructure, we recommend using the Large Wood Structure Stability Analysis Tool <http://www.fs.fed.us/ biology/nsaec/ products-tools.html> (Rafferty 2017). The associated resource, Wohl et al. (2016), describes the process and may also be useful.	[3, 14, 20, 21, 41, 59, 60]	[3, 7, 17, 19-23]
5b. Plant and maintain native vegetation in the streamside zone	Planting trees, particularly natives, adjacent to the channel provides long-term natural inputs (leaves, LWD) to the stream.	Where the channel naturally had shrub or tree vegetation. Where the channel is narrow (< 10 m). Where urban scouring flows have been repaired such that leaves are not swept away – or the site is downstream of a flow regulating structure.	[3, 14, 20]	[3]
5c. Line the stream bank with wet/ dry tolerant plants	Lining the streambank with sedges creates complex habitat that protects zooplankton, aquatic invertebrates and frogs. Fish may also use this complex habitat as a spawning site.	Where sedges are not dislodged by scouring urban flows. Most likely to be effective where macrophytes are placed in depositional areas (e.g. on the inside and downstream of meander bends).	[20]	[3]
5d. Install mesh cages or floating platforms	Steel cages containing wood can be anchored onto a heavily revetted urban channel at different heights to provide habitat for wet/ dry tolerant macrophytes. Alternatively, floating platforms can be anchored onto the bank of heavily revetted urban channels to provide a space for riparian vegetation to grow.	Revetted channels in lowland urban rivers, where more natural methods of habitat repair are not possible or likely to persist.	[61]	

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
5e. Create floodplain wetlands or depressions	Creating or protecting riparian wetlands and other depressions creates non-flowing water aquatic refuges for instream fauna during spates of high urban flows. These stillwater habitats may also provide important habitat for species that would otherwise fare poorly in the main channel, e.g. frogs, invertebrates.	Where enough floodplain space exists to create wetlands. Where earthworks do not create substantial damage to riparian vegetation.	[62-64]	
5f. Promote hydrologic connectivity between the main channel and the floodplain See *Repairing lateral connectivity* factsheet, actions 2a–d	Promoting overbank flow allows water to fill the habitats from 5e, creating stillwater aquatic habitats with a variety of hydroperiods (i.e. permanent to highly ephemeral). This diversity of aquatic habitats will be suitable for a variety of fauna.	Where floodplain wetlands exist. Where overbank flows do not pose a risk to people and urban infrastructure. See associated factsheet for details.	[63, 65]	See associated factsheet
5g. Protect from fire	Fire is likely to lead to a slug of sediment entering the waterway, which may bury instream habitat and cause oxygen levels to crash.	Most areas, particularly where stormwater filters over the riparian soils. Where the riparian buffer is moderate to steeply sloped > 10° and experiences high intensity rainfall (i.e. burnt riparian land will lose a significant amount of sediment to the site)		

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Repairing riparian function: what to do at the site

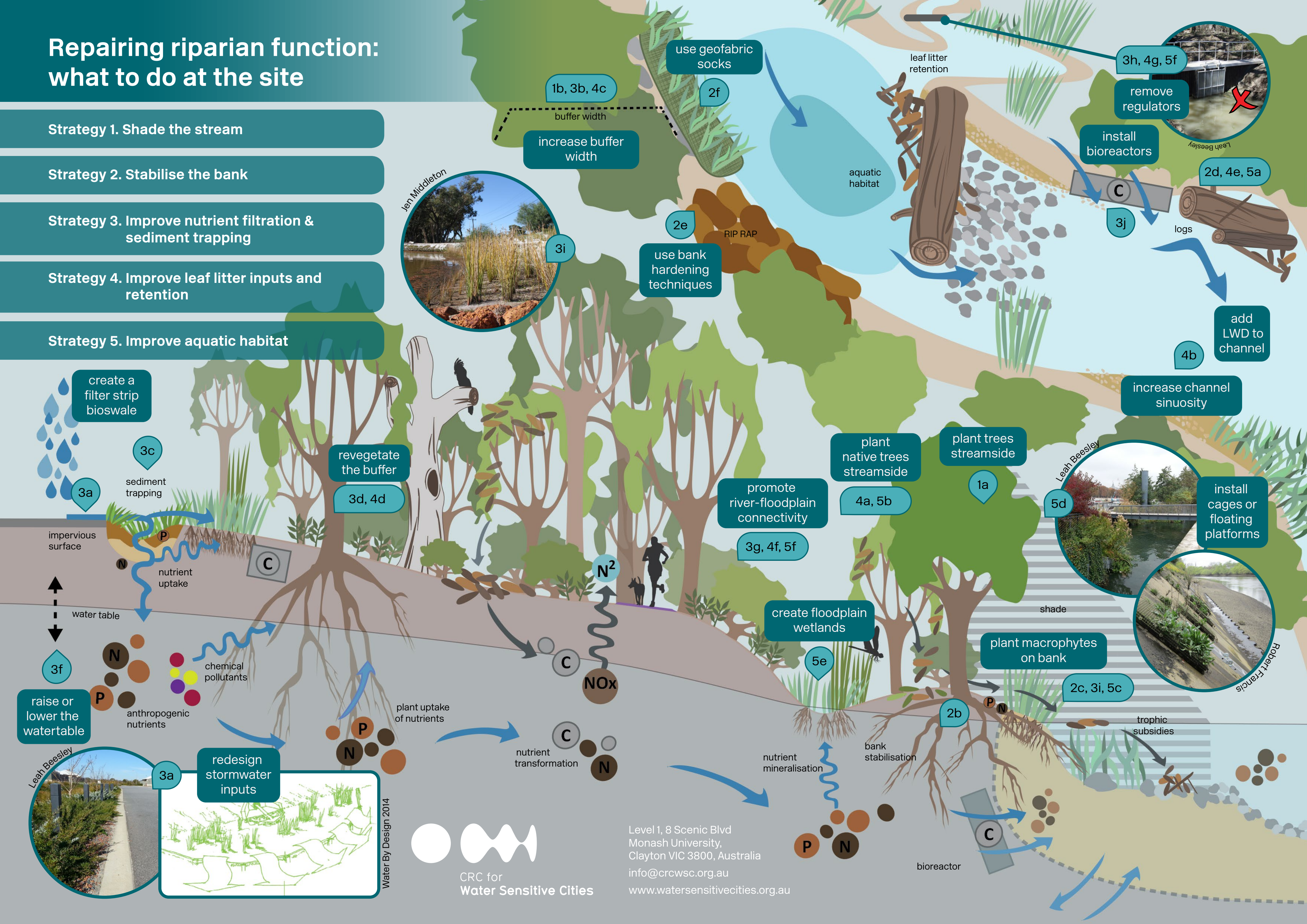
Strategy 1. Shade the stream

Strategy 2. Stabilise the bank

Strategy 3. Improve nutrient filtration & sediment trapping

Strategy 4. Improve leaf litter inputs and retention

Strategy 5. Improve aquatic habitat



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Reducing nutrients: what to do at the site

Reducing nutrients: what to do at the site

CRC for Water Sensitive Cities

Strategy 1. Increase nutrient uptake in the riparian zone

Suitability of strategy: most suitable where surface stormwater flows into or through the riparian zone; where a significant amount of groundwater flows laterally from the catchment to the stream; and/or where the floodplain is well-developed. Most effective where nutrient pollution occurs via overland or groundwater flow (e.g. septic tanks, golf course).

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
1a. See all actions in *Repairing riparian function: what to do at the site* factsheet, Strategy 3	The riparian zone is a naturally important nutrient filter: it cleans surface and subsurface water flowing laterally from the catchment towards the stream, as well as water that flows from the stream overbank into riparian land and associated wetlands.	See *Repairing riparian function: what to do at the site* factsheet, Strategy 3, actions 3a–3m.	[1-5]	See associated factsheet

Strategy 2. Increase nutrient processing in the hyporheic zone

Suitability of strategy: most suitable where natural bed material is highly porous (e.g. gravel, to a lesser extent sand) and where the climate creates periods of low flow.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
2a. Remove impermeable channel lining or daylight pipe	Impermeable channel lining (e.g. concrete) on an urban drain/ stream prevents interaction of surface water with shallow groundwater, thus limiting hyporheic activity.	Where natural material surrounding the concrete channel is porous.	[5, 6]	
2b. Reduce the velocity of instream flow See *Repairing flow: what to do at the site* factsheet, Strategy 2, for specific actions	Stream water is more likely to downwell into the hyporheic zone[1] when flows are relatively slow.	See *Repairing flow: what to do at the site* factsheet, Strategy 2, for the suitability and effectiveness of individual actions.	[4, 6-10]	See associated factsheet

[1] The wetted area among the sediments below and alongside rivers, inhabited by many animals (Boulton and Brock, 1999)

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Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
Reduce flow volume See *Repairing flow: what to do at the site* factsheet, Strategy 1, actions 1a –1g	As the volume of water in the channel gets smaller, a proportionally larger proportion of it will pass through the hyporheic zone and be exposed to nutrient transformation.	See *Repairing flow: what to do at the site* factsheet, Strategy 1, actions 1a–1g for the suitability and effectiveness of individual actions.	[6]	See associated factsheet
2c. Reconfigure the channel to improve sinuosity[2]	Reconfiguring the channel to increase sinuosity will slow flow (as per action 2b) and increase instream hydraulic diversity – both of which will promote the vertical exchange of water.	Where channel form is stable. Where bed material is highly porous. Where there is enough land around the stream for channel redesign. Where earthworks don't pose a significant risk to the existing riparian vegetation.	[11]	[12-17] See also RVR Meander tool
2d. Establish a pool-riffle sequence	Increases variation in hydraulic head to stimulate vertical exchange of water.	Where bed material is highly porous. Where stream depth is relatively shallow. Where the stream channel is stable such that riffles won't get washed away. Where sedimentation is low, such that riffles won't be buried. Where climate creates periods of low flow as the slower flows increase the capacity of the hyporheic zone to process nutrients.	[10, 11, 18-20]	[14]
2e. Install boulders and large woody debris (LWD)	Boulders and LWD increase instream hydraulic diversity and promote downwelling into the hyporheic zone. Debris dams (i.e. concentrations of leaves) often form around logs and boulders, creating carbon-rich anoxic environments that are hotspots for denitrification. The carbon from debris dams also supports microbial transformation of nutrients in the hyporheic zone.	Where logs and/or boulders would naturally have occurred but are now rare. Where bed material is highly porous. Where stream depth is relatively shallow such that boulders and LWD will create marked hydraulic diversity that will promote up/downwelling.	[9, 11, 20]	[14, 17, 21-26]
2f. Create many small habitat patches of 2e and 2f, rather than a few large patches	Nutrient processing typically occurs at the downwelling end of hyporheic flow paths. Therefore reach-scale nutrient processing will be enhanced by many small patches rather than a few large patches.	Streams where anoxic conditions (i.e. denitrification) occur within short subsurface flow paths. This action may not be appropriate where long subsurface flow paths are required for denitrification (e.g. highly porous bed sediments, high velocity flows).	[27]	
2g. Plant native trees in stream-side zone	Eucalypt leaves break down at a slower rate than non-native species. This allows carbon to persist in the system for longer and act as a source of C for microbial nutrient processing in the hyporheic zone.	Where the riparian vegetation has been cleared.	[11]	[25] See associated factsheet

[2] The extent of meandering of a body of water (Boulton and Brock, 1999)

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
2h. Add coarse sediment (i.e. gravel) to the stream bed	Adding coarse sediment will increase the porosity of the stream bed and facilitate hyporheic exchange, which can promote denitrification if flow paths are long enough such that water becomes oxygen depleted.	At high value locations. In systems where bed material has low permeability. Where peak streamflow will not wash away the coarse sediment. Where the coarse sediment will not be filled in by fine sediment (i.e. covered by silt or sand). In most locations repairing sources or coarse sediment (See *Repairing Geomorphology: what to do at the site and catchment* factsheet, Actions 2c and 2d) and allowing the channel to naturally adjust will be more effective over the longer term.	[11]	Gravel can be added in one location and flow can naturally redistribute it [28]
2i. Use flushing flows to clean gravel beds and other permeable bed material	Flushing flows remove fine sediment from gravel beds, increase the porosity of the stream bed and promote hyporheic exchange.	In depositional areas of the stream where fine sedimentation is a problem. Most readily implemented where an upstream flow control structure (dam, weir) allows manipulation of flow.	[29, 30]	
2j. Promote the presence of bioturbating fauna	Animals that burrow into the bed sediment (e.g. chironomids, worms, mussels) create small channels that promote the downward movement of water into the hyporheic zone.	Where bioturbating fauna are abundant. Care should be taken not to promote a midge outbreak, particularly in still backwater habitats.	[6]	

Strategy 3. Increase nutrient processing instream (excl. hyporheic)

Suitability of strategy: most suitable where the channel's surface area to volume ratio is relatively high (i.e. small channel as opposed to a large river).

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
3a. Reduce the velocity of instream flow See *Repairing flow: what to do at the site* factsheet, Strategy 2	The ability of biofilms to take up nutrients increases when water flows more slowly, because it increases the contact time between nutrients in the water column and the biofilm.	Where the site has a small catchment – i.e. where catchment-scale stormwater management is feasible. Where the waterway contains (or will contain) hard surfaces that biofilms establish on (e.g. cobbles, logs, leaves). See *Repairing flow: what to do at the site* factsheet, Strategy 2, for the suitability of specific actions.	[5, 31]	See associated factsheet

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
3b. Reduce flow volume See *Repairing flow: what to do at the site* factsheet, Strategy 1, actions 1a–1g	Reducing the volume of water in the waterway increases the proportion of the water that is in contact with surface biofilms – thus a proportionally larger amount of water can be cleaned by biofilms as waterway volume decreases.	Where the site has a small catchment – i.e. where catchment-scale stormwater management is feasible.	[4, 5, 7]	See associated factsheet
3c. Increase hotspots of microbial processing (i.e. create debris dams, backwaters, add LWD)	Carbon is essential for microbial processing of nutrients, thus it is important to create instream structures that trap leaves. This can be supported by adding logs or boulders or creating low-flow backwater areas.	Most sites, particularly small streams that naturally have high inputs of leaves – i.e. forested small- to medium-sized streams.	[4, 9, 11, 20]	
3d. Establish macrophyte beds	Macrophytes can be very efficient at taking up nutrients from stream water, as well as bed and bank sediments. Note, nutrients will be recycled within the system (i.e. no net loss) unless macrophytes are periodically harvested.	Where channel form is stable such that macrophyte beds won't get washed away. Where scouring urban flows have been managed. Sedges are most likely to survive if planted in low-velocity areas such as the inside of meander bends.	[32, 33]	[34, 35]
3e. Add clays that bind phosphorous	Clays have a strong ionic charge and can bond to charged dissolved nutrients, such as PO4 taking nutrients out of solution. Natural clays or specially designed clay (e.g. Phoslock) can be used.	At high value locations. In systems where phosphorus is a management priority (P-limited). Lowland sites where water velocity over sediments is low – i.e. clay won't just be washed downstream.	[36, 37]	[36, 37]
3f. Install floating wetlands	Floating add P-binding clays wetlands take up inorganic nutrients (NOX, PO4) from the river water.	In deep slow-flowing water (e.g. lowland river sites, weir pools). In highly modified systems only.	[38, 39]	[38, 39]

Strategy 4. Minimise nutrient release from stream bed and bank sediments

Suitability of strategy: most suitable where fine sediments are abundant and rich in nutrients, and where the nutrients stored in sediments are bioavailable.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
4a. Increase the oxygen concentration of the water using natural (e.g. riffles, plants/algae) or engineered approaches (e.g. aerators)	Increasing the oxygen concentration of instream water is beneficial because it promotes nutrient processing in general. It also creates oxidative conditions (high pH) that promote the binding of phosphorus to sediments.	In high value locations where oxygen levels are prone to crash (e.g. low flows during warmer months, history of algal blooms, high levels of dissolved organic carbon). Riffles are appropriate if water depth in the site is relatively shallow (i.e. a riffle can be constructed). Aerators are appropriate where the water is deeper.	[40, 41]	Aerator [42] Riffles [14, 43]
4b. Stabilise fine sediments on the bed and bank of the waterway using plants and controlling unwanted bioturbating fish species	Fine sediments, particularly clays, store large quantities of nutrients – particularly phosphorus. Stabilising sediments instream and on the stream bank by using macrophytes and by controlling bioturbating fish species (e.g. common carp) can reduce the release of nutrients into the water column.	Where the water is shallow and clear enough so that macrophytes can establish. Where scouring urban flows will not wash them away. Where common carp or goldfish or other non-native bioturbating species are present.	This factsheet	[25]

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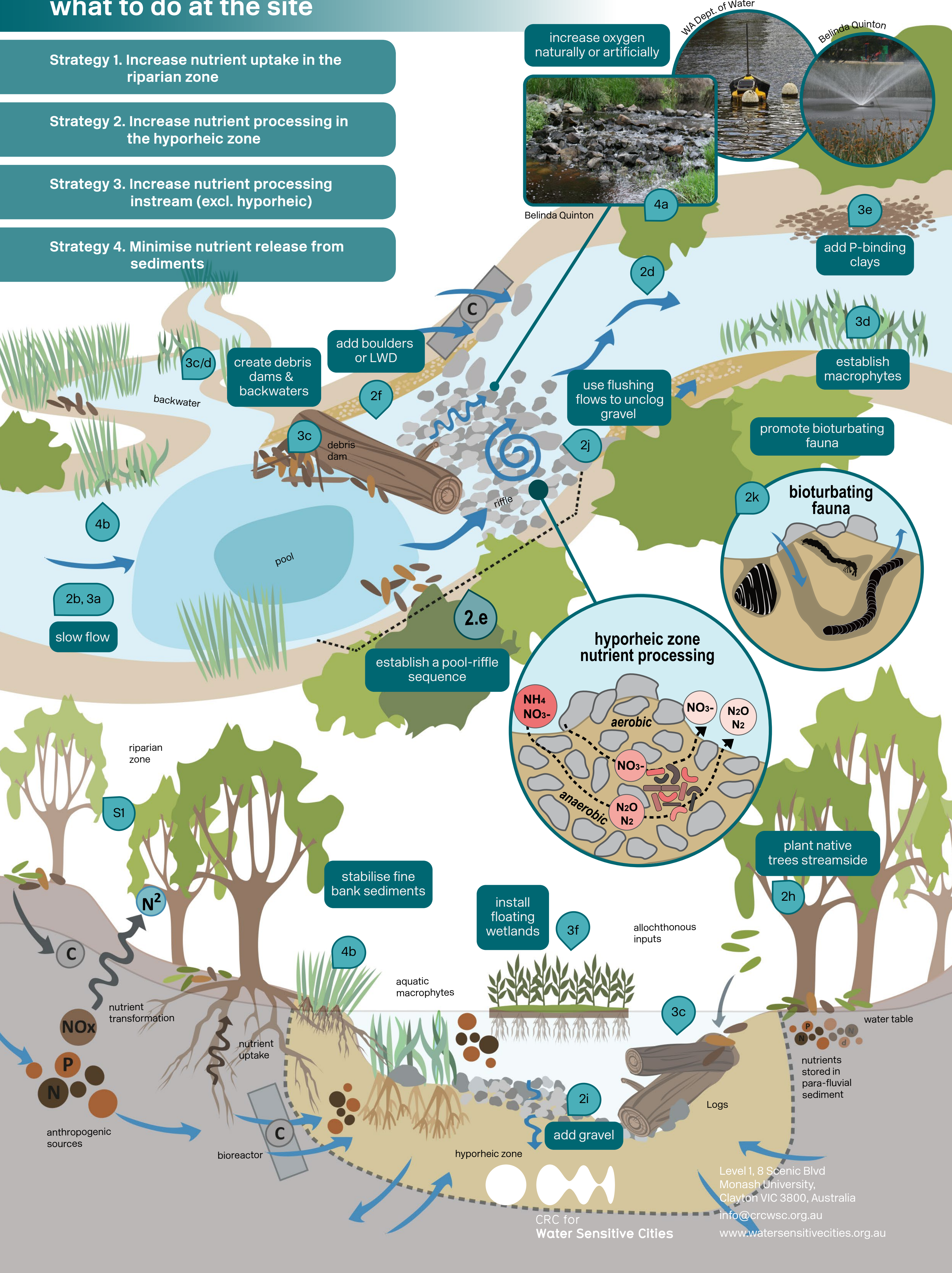
Reducing nutrients: what to do at the site

Strategy 1. Increase nutrient uptake in the riparian zone

Strategy 2. Increase nutrient processing in the hyporheic zone

Strategy 3. Increase nutrient processing instream (excl. hyporheic)

Strategy 4. Minimise nutrient release from sediments



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Reducing nutrients: what to do in the catchment

Reducing nutrients: what to do in the catchment

CRC for Water Sensitive Cities

Strategy 1. Reduce nutrient inputs

Suitability of strategy: no generic advice for this strategy. See individual actions for their suitability and effectiveness.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
1a. Educate residents to minimise their use of nutrients, especially fertilisers	Human use of fertilisers and detergents are a major source of the nutrients found in urban waterways. Educating residents so that they minimise fertiliser use, particularly during high rainfall months, will reduce the total nutrient load. Where wastewater treatment plants discharge into waterways, educating residents to use low-phosphorous detergents is also important.	Most areas, particularly on sandy soils where nutrients leach rapidly into the groundwater. Where the catchment has medium density residential housing (i.e. lots are large enough to allow gardens). Less effective where prior land use (e.g. agriculture) has left a legacy of high soil nutrients.	[1-3]	[1]
1b. Educate residents about pet manure	Dog and cat manure contains nitrogen and phosphorus and is easily washed into urban waterways.	All areas	[4]	
1c. Phase out septic systems	Septic systems leak nutrients into local groundwater, creating a diffuse source of nutrient pollution. Where possible these systems should be replaced by connected sewage. If this is not possible, we recommend they be maintained and monitored.	Where houses with septic tanks are close to a waterway (< 100 m).	[5-7]	Not applicable
1d. Relocate nutrient-exporting land uses (e.g. golf courses)	Nutrient exporting land uses, such as golf courses and other industry, should be relocated to areas remote from urban waterways.	New development areas where planning can prevent inappropriate land uses being established close to waterways or in areas with shallow groundwater susceptible to contamination.		WA: use UNDO tool in planning

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
1e. Permanently or seasonally disconnect wetlands that are nutrient sources	Wetlands containing a large amount of nutrients can export nutrients to the waterway rather than store them. These wetlands should not be connected to flowing waters as nutrient issues will be exacerbated.	Sites where wetlands are nutrient sources and are connected to the waterway year-round or during high flows. Note that wetlands are most likely to be sources if they have been receiving elevated nutrients from stormwater or agriculture for decades.		
1f. Avoid urban development on land with a legacy of high soil nutrients	The land surrounding urban areas often has an agricultural past and associated elevated soil nutrients. This land should be avoided for new urban development as soil nutrients are likely to find their way to waterways.	Sites where the watertable is high should be avoided, because subsurface drainage put in place to prevent local flooding will efficiently transport soil nutrients to waterways. DO NOT interpret this action as a recommendation to develop or clear remnant vegetation.	[8]	
1g. Improve nutrient retention in wastewater treatment plants	Wastewater treatment plants remove nutrients from the water they treat, however the process is not 100 per cent effective. Improvements in the treatment process will reduce nutrient loads to urban waterways.	Where wastewater treatment plants discharge into an urban waterway. Nutrients in the effluent of these plants has the greatest potential to cause problems if the waterway is naturally intermittent.	[9-11]	As per state and federal best management practice
1h. Preferentially select natives as street trees	Deciduous trees have higher leaf nutrient levels than native tree species and create unnaturally large inputs of nutrients into waterways during autumn.	New residential developments. Also older suburbs where old trees are dying and being replaced. Most appropriate for streets where stormwater pipes are directly piped into waterways.	[12]	

Strategy 2. Reduce the volume of stormwater directed to waterways

Suitability of strategy: this strategy will be easiest to implement in small catchments where relatively few impervious areas exist (i.e. not a lot of urban land needs to be retrofitted). However, we encourage the adoption of this strategy in all urban areas given that all efforts to reduce the volume of nutrient-rich water travelling to waterways will contribute to lowering nutrient loads in downstream receiving waters.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
2a. Reduce flow volume by harvesting rainwater and infiltrating; detaining and disconnecting stormwater. See *Repairing flow: what to do in the catchment* factsheet, Strategy 1, actions 1a–1g	Stormwater carries soluble nutrients to urban waterways. Reducing the volume of stormwater reaching the waterway will reduce the nutrient load being transported to the waterway.	See *Repairing flow: what to do in the catchment* factsheet, Strategy 1, actions 1a–g for advise on the suitability of specific actions.	[6, 13-17]	See associated factsheet

Strategy 3. Increase nutrient biofiltration of stormwater at the source (i.e. lot and street scale)

Suitability of strategy: this strategy is suitable for streets with wide verges that can accommodate swales/raingardens and where the residents are supportive. New residential developments should take this strategy into account at the design stage.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
3a. Install raingardens and vegetated swales along streets	The vegetation and soil in raingardens and vegetated swales takes up or binds nutrients, reducing the nutrient load of street stormwater.	Most sites, particularly streets with verges wide enough to accommodate the raingardens. Most effective where vegetation naturally has a high growth rate and is periodically harvested. Where raingardens have enough storage capacity to absorb a large fraction of overland flow before it is redirected into stormwater drainage. Where raingardens can be installed on most roads.	[18-21]	[22-25]

Strategy 4. Increase nutrient biofiltration of stormwater at the precinct scale

Suitability of strategy: this strategy is suitable for urban areas that have sufficiently large areas of low-lying land to accommodate the wetland biofilters, and where excess nutrients are predominantly inorganic and derived from stormwater. It is less suitable where most excess nutrients are inorganic and derived from groundwater.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
4a. Direct stormwater into wetland biofiltration basins	Biofiltration basins trap stormwater and create an artificial wetland-like environment that promotes nutrient uptake and transformation.	Where the precinct has large unused pieces of land in low-lying areas that can be transformed into biofiltration basins. Where excess nutrients are predominantly inorganic and from stormwater – less suitable where most excess nutrients are inorganic and derived from groundwater. Note, that the efficiency of basins is also likely to change with time (age of wetland, season).	[18, 26, 27]	[22-25, 28-32]
4b. Strategically place biofiltration basins	Biofiltration basins are most effective when placed in areas that receive large amounts of stormwater, particularly stormwater with high concentrations of nutrients (i.e. high nutrient load).	All areas	[33]	WA: use UNDO tool in planning
4c. Align water sensitive design features so they work cumulatively to protect the receiving waterway	The serial alignment of features, such as actions 3a and 4a, progressively reduce nutrients and result in greater nutrient attenuation and protection of the downstream waterway.	All areas	[34]	WA: use UNDO tool in planning

Strategy 5. Reduce the volume of nutrient-rich groundwater entering the waterway

Suitability of strategy: most suitable where the channel is narrow (< 10 m wide) and the natural vegetation is treed OR where the floodplain is wide with a low gradient (especially where wetlands are present).

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
5a. Avoid development on land with a shallow water table or build houses on stilts	If the water table is shallow and likely to cause seasonal flooding of the built environment, then the land should not be developed or houses should be constructed on stilts so they are protected from flooding.	Where urban development has not yet taken place, i.e. early in the planning process.	[35]	

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
5b. Lower the watertable. See all actions in *Repairing flow: what to do in the catchment* factsheet, Strategy 5, actions 5i–5p	If the groundwater is rich in nutrients, particularly bio-available forms, subsurface flows can contribute the majority of nutrients to urban waterways. Lowering the water table reduces the amount of nutrients delivered to urban waterways.	Where development has already occurred. See *Repairing flow: what to do in the catchment* factsheet, Strategy 5: actions 5i–5p for the suitability of individual actions.	[35, 36]	See associated factsheet
5c. Surround subsurface drains with amended soil	Certain soils, such as IMG a brown loamy soil that is rich in iron, can be effective in bonding to phosphorous and other dissolved organic nutrients and removing them from subsurface soil water.	Where urban development has not yet occurred – i.e. there is opportunity to lay the soil amendment around the subsurface drain. Where nutrients are predominantly organic and where the natural soil has a poor nutrient binding capacity, e.g. sandy soils of the Swan Coastal Plain, WA.	[36, 37]	[37]
5d. Redirect subsurface drains away from waterways and into biofiltration basins	The delivery of nutrient-rich groundwater from subsurface drainage exacerbates instream nutrient issues. Directing nutrient-laden groundwater into biofiltration basins may reduce nutrient loads.	Where there is unused land along the subsurface drainage path that may be used to create a detention basin. Where nutrients are predominantly inorganic. Where urban development has already taken place.	[38]	
5e. Disconnect subsurface drains from waterways and install bioreactors and P-sorbent soil at their outlet	Bioreactors promote nutrient transformation and sorbent soils bind to nutrients reducing nutrient loads exported from subsurface drainage into receiving waterways in the catchment.	Most sites, particularly where there is space adjacent to the receiving waterway to install the bioreactor and the sorbent soil. Where the existing soil adjacent to the receiving waterway is low in soil carbon and low in iron (e.g. sandy).	[36]	[39]
5f. Hard-line urban drainage channels	If the local groundwater is elevated and rich in nutrients, then any newly constructed urban drain will exacerbate nutrient issues downstream. In these circumstances a concreted or piped urban drain should be considered, as it prevents the inflow of nutrient-rich groundwater and its drainage downstream.	New developments, where no existing drainage channel (i.e. creek) exists. Where the groundwater is rich in nutrients that will flow into the newly created urban drain unless it is hard-lined. Where the nutrient load of the downstream receiving water is a management priority. Where the stormwater travelling along the hard-lined channel is relatively low in nutrients and/or will be treated by a biofiltration basin lower in the system.		As per standard techniques

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Other useful tools

Urban Nutrient Decision Outcomes (UNDO): a decision support tool that evaluates nutrient reduction decisions for urban developments on the sandy Swan Coastal Plain, WA. http://www.water.wa.gov.au/planning-for-the-future/water-and-land-use-planning/undo-tool

Reducing nutrients: what to do in the catchment

Strategy 1. Reduce nutrient inputs

Strategy 2. Reduce the volume of stormwater directed to waterways

Strategy 3. Increase nutrient biofiltration of stormwater at the source

Strategy 4. Increase nutrient biofiltration of stormwater at the precinct scale

Strategy 5. Reduce the volume of nutrient-rich groundwater entering the waterway

Repairing water quality: what to do at the site

CRC for Water Sensitive Cities

Strategy 1. Keep the water as cool as possible

Suitability of strategy: Most suitable for small streams with naturally cool water. Most likely to be effective where a small portion of the catchment is impervious and a sizeable tract of the upstream waterway is still relatively intact. Less achievable when the urban area is anticipating marked increases in temperature associated with climate change.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
1a. Shade the stream See *Repairing riparian function: what to do at the site* factsheet, Strategy 1, all actions	Increasing the shading of the stream will reduce the penetration of UV light into the waterway and reduce water temperature.	Where the stream channel is relatively narrow (< 10 m) and where the natural vegetation is trees rather than grassland. See *Repairing riparian function: what to do at the site* factsheet, Strategy 1, for the suitability of specific actions.	[1-4]	See associated factsheet
1b. Relocate stormwater inputs so they run stormwater through vegetated filter strips / riparian land	Stormwater should not be directly piped to waterways, instead it should be allowed to flow through vegetated filter strips or riparian land where it can cool before entering the stream via surface or sub-surface pathways.	Where the riparian land is shaded by trees. Where the vegetated buffer that the stormwater passes through is > 10 m wide.	[5]	[5]
1c. Promote groundwater upwelling See *Repairing vertical connectivity: what to do at the site and in the catchment* factsheet, all Strategies	Typically groundwater is considerably cooler than surface water, hence actions that improve the flow of groundwater into the waterway help to moderate elevated temperatures.	Where the site would naturally receive a significant proportion of its flow from groundwater – i.e. highly permeable bed sediment (gravel, coarse sand) and has a shallow watertable (< 4 m deep). Not appropriate if the groundwater is contaminated with pollutants (nutrient or non-nutrient).	[4, 6-8]	See associated factsheet

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Strategy 2. Keep oxygen levels high

Suitability of strategy: most suitable where the waterway experiences protracted periods of low flow, particularly during warm months, and where nutrient concentrations are elevated.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
2a. Increase turbulence instream using logs and riffles	Turbulent flow associated with instream structures such as logs and riffles promotes oxygenation of water.	Where the waterway has very little instream habitat complexity.	[9]	Riffles [10, 11] LWD [10, 12-18]
2b. Artificially aerate the waterway	Artificial aeration can either bubble air through the water or inject pure oxygen. In some cases, water low in oxygen is removed from the waterway, oxygenated, and then returned to the river.	In high value locations where the water is deep and prone to stratification, such as the lowland sections of urban rivers. River reaches downstream of flow regulating structures (e.g. weirs) are particularly susceptible to oxygen crashes.	[19]	Aerator [20]
2c. Use pumps to maintain flow	Water can be pumped from the downstream end of a site to the upstream end to maintain constant flow and aeration.	In high value locations where there is a differential in height between the upstream and downstream end of the waterway reach. Most appropriate for constructed or novel living streams in new urban developments.		
2d. Keep the water as cool as possible – as per Strategy 1	The solubility of oxygen in water decreases as the water temperature increases, therefore efforts to cool instream water will also improve oxygen levels.	Most suitable for small streams with naturally cool water. Most likely to be effective where a small portion of the catchment is impervious and a sizeable tract of the upstream waterway is still relatively intact. Less achievable when the urban area is anticipating marked increases in temperature associated with climate change.	[21]	As per Strategy 1 this factsheet

Strategy 3. Reduce non-nutrient pollutants (i.e. heavy metals, hydrocarbons, PCBs, pharmaceuticals and other personal care products)

Suitability of strategy: most suitable where the site has large quantities of fine sediments (e.g. mid to lowland river sites), given fine sediments bond to contaminants and increase the exposure of the site to pollutants. Particularly suited to sites adjacent to, or downstream of an industrial area.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
3a. Install gross pollutant traps (GPTs)	GPTs catch plastic and other rubbish in stormwater, preventing it from entering the waterway.	Where stormwater pipes discharge into the site. Care should be taken the GPT's do not prevent coarse sediment and leaf litter from entering the stream.	WSUD manuals	See WSUD manuals
3b. Relocate/ redesign stormwater inputs	Direct piping of stormwater into the stream bypasses riparian filtration. Stormwater outputs should be allowed to filter through riparian soils so that biogeochemical processes can transform pollutants. Flush road kerbing or kerbless roads should be used on the side of the road that drains to riparian land. Where stormwater pipes exist they should terminate at swales/ filter strips/biofilters on the distal (road side) edge of the riparian buffer.	Sites where stormwater pipes or subsurface drainage pipes are present and where a road borders the riparian land.	[22]	[23, 24] See WSUD manuals
3c. Promote hyporheic exchange See *Repairing vertical connectivity* factsheet, Strategies 3 and 4	The hyporheic zone is an active area of pollutant breakdown. Actions that increase downwelling and upwelling at the site, such as removing channel hard-lining, increasing channel sinuosity, adding logs, creating pool-riffle sequences or adding gravel will promote pollutant biodegradation.	Most effective where a large portion of flow occurs through the hyporheic zone – i.e. streams that experience protracted low flows and where bed permeability is moderate to high (sand, gravel). Less effective where high-volume scouring urban flows persist year round and where bed permeability is low (e.g. clay). See associated factsheet for additional advice on specific actions.	[9]	See associated factsheet

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
3d. Keep oxygen levels high – see Strategy 2 this factsheet	The biodegradation of many pharmaceuticals and most trace organic contaminants is accelerated under aerobic conditions.	Where oxygen levels are prone to fall below 4 mg/L.	[9]	As per Strategy 2 this factsheet
3e. Use aquatic macrophytes to stabilise fine sediment	Most metals and hydrophobic pollutants bind more readily to fine sediments than large sediments. Macrophyte roots are effective in stabilising these fine polluted sediments and preventing them from entering the water column where they can create stress for macroinvertebrates.	Where scouring urban flows have been managed. Where macrophytes (e.g. sedges) are planted in low-velocity, depositional areas such as the inside of meander bends, backwater habitats, and floodplain depressions or wetlands.	[25]	See biofiltration guidelines

Strategy 4. Improve water clarity

Suitability of strategy: suitable for most sites, particularly those with large quantities of fine sediments (e.g. clay, silt). May not be appropriate if improved water clarity will cause nuisance algal growth.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
4a. Establish macrophyte beds and plant streamside vegetation to stabilise banks	Macrophytes are known to improve water clarity because their dense fibrous roots stabilise bed and bank sediments – reducing the entrainment of these fine sediments by high flows.	Where channel form is stable such that macrophyte beds won't get washed away. Where scouring urban flows have been managed. Sedges are most likely to survive if planted in low-velocity areas such as the inside of meander bends.	[26, 27]	
4b. Control non-native bioturbating species	Species that feed by digging around in the mud stir up fine sediments and increase water turbidity. Removing these species should improve water clarity.	Where non-native bioturbating pest species are present. Where successful control or eradication is feasible (e.g. site is small).		[28-31]

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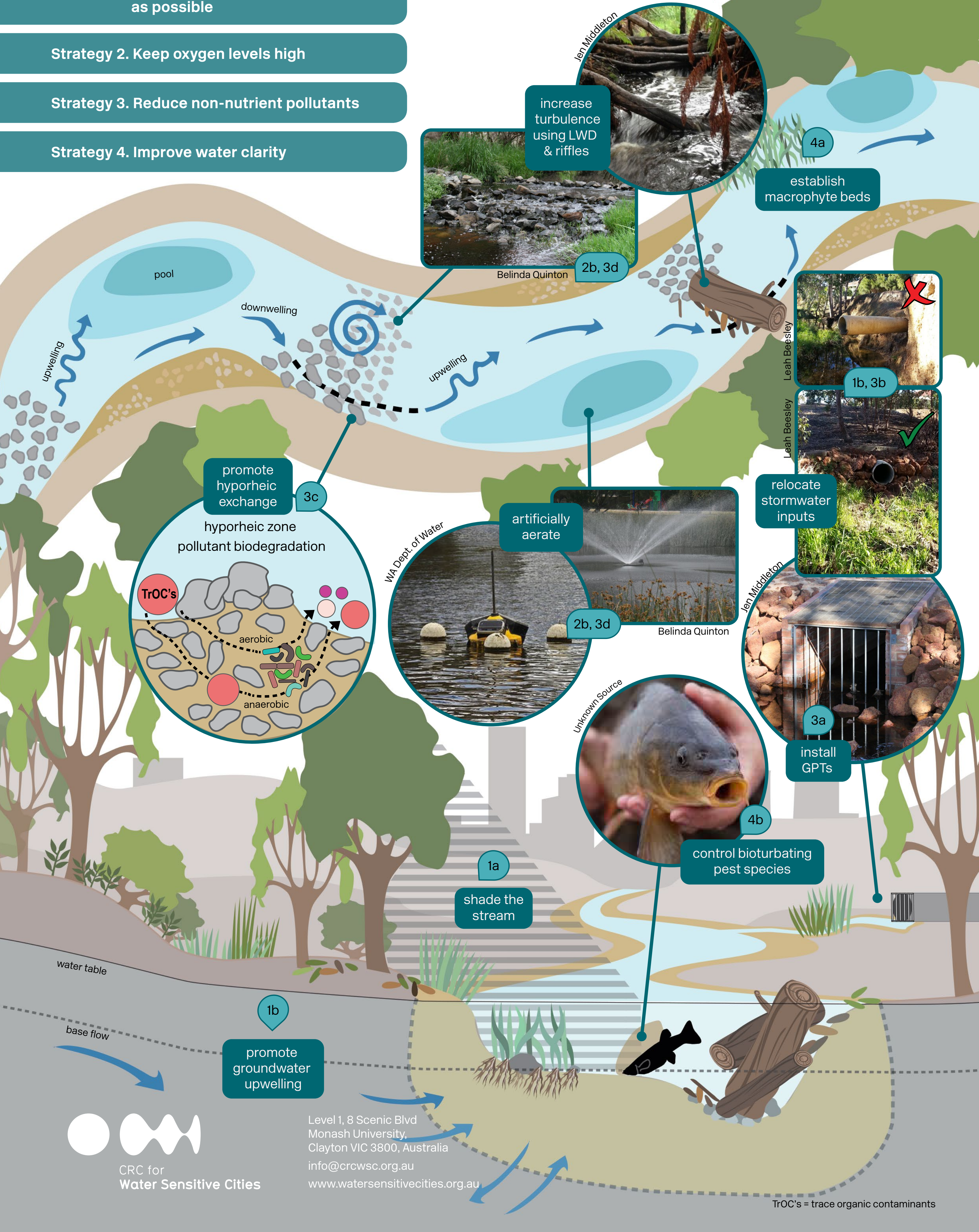
Repairing water quality: what to do at the site

Strategy 1. Keep the water as cool as possible

Strategy 2. Keep oxygen levels high

Strategy 3. Reduce non-nutrient pollutants

Strategy 4. Improve water clarity



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TrOC's = trace organic contaminants

Repairing water quality: what to do in the catchment

Strategy 1. Keep water cool

Suitability of strategy: most suitable for small streams with naturally cool water. Most likely to be effective where a small portion of the catchment is impervious and where a sizeable tract of the upstream waterway is still relatively intact. Less achievable when the urban area is anticipating marked increases in temperature associated with climate change.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
1a. Revegetate riparian land upstream of the site	Shading upstream of the site affects water temperature at the site. Ensuring the riparian zone is vegetated for the upstream 1 km will keep water cool at the site.	Where the channel is narrow (< 10 m wide). Where the upstream vegetation has been largely cleared. Where the buffer is wide enough to allow the establishment of two to three tree widths back from the channel.	[1-3]	[4]
1b. Manage the release of wastewater effluent into waterways	Wastewater effluent is typically several degrees warmer than stream water and can markedly increase instream water temperature. Wastewater should be held in shaded bioretention ponds until it cools (before release to waterways).	Where wastewater plants discharge effluent into waterways, particularly where the effluent makes up a large fraction of stream flow – e.g. where water is discharged into intermittent or low-flow streams. Where management actions cool effluent so that its temperature is similar (<0.5C of stream water) or slightly cooler than instream water. Use caution – this approach could exacerbate nutrient and pollution issues instream	[5, 6]	
1c. Use bioretention basins (biofiltration wetlands, raingardens, vegetated swales) to cool stormwater	Stormwater which runs off over hot paved surfaces should be held in bioretention basins and allowed to cool before being slowly released to waterways.	Most areas, particularly where rainfall and runoff from impervious surfaces occurs during the warmer months of the year. Most effective where the biorention area is large relative to the size of the catchment it is filtering.	[7, 8]	[8] Also see biofiltration guidelines
1d. Run stormwater through vegetated filter strips / riparian land	Stormwater should not be directly piped to waterways, instead it should be allowed to flow through vegetated filter strips or riparian land where it can cool before entering the stream via surface or sub-surface pathways.	Where the riparian land is shaded by trees. Where the vegetated buffer that the stormwater passes through is > 10 m wide.	[9]	[9]

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
1e. Cold-water release from base of dam	The release of cold water from the base of dams may be used to reduce the temperature of downstream urban waterways.	Where the capacity to shade the urban waterway is very limited. Where short-term weather forecasts predict upcoming severe hot weather. Where the addition of cold water will not create thermal shock for native species. Where environmental water allocations are available. Where dams have the capacity to release water from their hypolimnion. This action should be monitored and used with caution.	[3, 10]	Little information, but see [10] for a discussion of the pros and cons
1f. Environmental water release from alternative non-dam sources	Releasing water from non-dam water infrastructure (e.g. pipelines, fire hydrants) treatment facilities) can increase the volume of water in urban waterways, therefore reducing their susceptibility to changes in temperature.	Where environmental water allocations are available. Where instream flows are very low, such that the added water contributes a significant portion of flow or water in refuge pools.	[11]	
1g. Maintain baseflow See *Repairing flow: what to do in the catchment* factsheet, actions 5a to h	Water temperatures typically increase as waterways dry down. Maintaining flow and water volume in waterways assists to reduce temperature extremes.	Where urbanisation has caused baseflow to fall.	[3]	See associated factsheet
1h. Promote groundwater upwelling See *Repairing vertical connectivity: what to do at the site and in the catchment* factsheet, all Strategies	Groundwater is typically considerably cooler than surface water, hence actions that improve the flow of groundwater into the waterway help moderate elevated temperatures.	Where the site would naturally receive a significant proportion of its flow from groundwater – i.e. highly permeable bed sediment (gravel, coarse sand) and has a shallow watertable (< 4m deep). Not appropriate if the groundwater is contaminated with pollutants (nutrient or non-nutrient).	[3, 12, 13]	See associated factsheet

Strategy 2. Keep oxygen levels high

Suitability of strategy: most suitable where the waterway has protracted periods of low flow, particularly during the warmer months.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
2a. Reduce nutrients (N,P) concentrations See *Repairing nutrients: what to do in the catchment* factsheets, all Strategies	High levels of nutrients, particularly phosphorous, promote the development of algal blooms. The decomposition of these algal blooms by microbes causes high demand for oxygen – causing instream oxygen levels to fall.	Where nutrient levels are high. This is typically lowland rivers, but it can also be small urban waterways if they are adjacent to nutrient-rich landuse or if they receive water from wastewater treatment plants.	[14, 15]	See associated factsheet
2b. Reduce unnatural inputs of dissolved organic carbon by phasing out septic tanks and repairing leaky sewage networks	High levels of dissaolved organic carbon (DOC) fron septic tanks, and leaks in sewer networks, increase microbial demand for oxygen - causing instream oxygen levels to fall.	Where there are point source inputs of DOC that can be managed.		
2c. Keep the water as cool as possible – as per Strategy 1 this factsheet	The solubility of oxygen in water decreases as water temperature increases, therefore efforts to cool instream water will also improve oxygen levels.	Most suitable for small streams with naturally cool water. Most likely to be effective where a small portion of the catchment is impervious and where a sizeable tract of the upstream waterway is still relatively intact. Less suitable when the urban area is anticipating marked increases in temperature associated with climate change.		As per Strategy 1 this factsheet
2d. Maintain baseflow See *Repairing flow: what to do in the catchment* factsheet, actions 5a to h	Flow promotes the oxygenation of water. When flows cease, oxygen levels fall.	Where urbanisation has caused baseflow to fall.	[16, 17]	See associated factsheet

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
2e. Environmental water release to maintain flow	Releasing water from water infrastructure (e.g. weir/dam, pipelines, fire hydrants) can keep flow moving in waterways that would otherwise stop flowing. Maintaining flow promotes surface oxygenation, while slowing stratification and the establishment of algal blooms – all of which reduce the likelihood of an oxygen crash.	Where environmental water allocations are available. Where instream flows are very low, such that the added water contributes a significant portion of flow or water in refuge pools. This action is particularly important during years of drought and to protect high value assets (e.g. refuge pools). Care should be taken if water is released from the base of the dam (hypolimnion) as it may be low in oxygen. Caution should also be used where pools have already stratified (i.e. contain thermal layers) because high flow mixing could exacerbate low oxygen issues - seek expert guidance.	[11, 18, 19]	Little information about oxygen, but see [19] for general guidance

Strategy 3. Reduce non-nutrient pollutants (i.e. heavy metals, hydrocarbons, PCBs, pharmaceuticals and other personal care products)

Suitability of strategy: most suitable where the restoration site has large quantities of fine sediments, given fine sediments bond to contaminants and increase the exposure of the site to pollutants. Most appropriate for catchments that include industrial landuse.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
3a. Install gross pollutant traps (GPTs)	GPTs catch plastic and other rubbish in stormwater drains.	All areas.	WSUD manuals	[20]
3b. Relocate pre-exsisting industrial land use and strategic planning of industrial land use	Industrial land use creates significantly higher inputs of pollutants than residential land use. Polluting land uses should be strategically located or relocated to areas remote from waterways and WSUD elements such as biofiltration wetlands (constructed or natural).	Most urban areas. This action is best suited to new developments for inclusion in town planning.	[21]	
3c. Discourage pesticide/ herbicide use adjacent to the waterway and promote the use of lower risk chemicals	The use of pesticides and herbicides close to waterways should be discouraged, as these chemicals can make their way to the stream/river via overland or subsurface flow paths.	Where the riparian land is being actively managed for weeds. Where residential property is close to the waterway (< 30 m). Where residents grow vegetables on riparian land – more relevant to Asia than Australia.	[22]	

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
3d. Disconnect and infiltrate stormwater See *Repairing flow: what to do in the catchment* factsheet, actions 1b–1e.	Most chemical pollutants, such as heavy metals and hydrocarbons, are sourced from urban impervious surfaces (e.g. roads) and transported to streams via conventional stormwater drainage. Disconnecting and infiltrating stormwater will reduce the load of pollutants transported to urban waterways.	Most areas, particularly where stormwater drains roads or industrial land use. Where pollutant loads in the stormwater are high.	[7, 22]	See associated factsheet
3e. Direct stormwater through biofiltration basins See *Repairing flow: what to do in the catchment* factsheet, actions 1f and 1g	Wetland biofiltration basins and other specially designed biofiltration media adsorb or transform chemical pollutants – reducing the concentration of pollutants in stormwater.	Most areas, particularly where enough space exists to install biofiltration basins. Most effective when the appropriate biofiltration media is used and when biofiltration basins are strategically placed in areas of the catchment that receive the largest loads of pollutant-rich water.	[22-25]	See biofiltration guidelines
3f. Remove fine sediments in GPTs but allow coarse sediments to pass	Most pollutants bond to fine sediments (medium sand and smaller particles). Removing fine sediments from gross pollutant traps and transporting them to landfill can reduce the influx of pollutants to urban waterways.	If heavy metal contamination is a problem - where GPTs contain large quantities of fine sediment (< 500 µm). If PAHs are a problem – where GPTs contain large quantities of very fine particles (< 250 µm).	[26] but see [27] for a conflicting opinion	[26] Coarse sediments should be retained and returned to the urban waterway
3g. Improve practices on polluting land uses	Changes in behaviour, or the industrial process, can reduce the amount of pollutants released into the stormwater network or into the ground. Tackling illegal connections of industrial sewage to the stormwater network is key.	All areas		See best management practice guidelines
3h. Improve the treatment of wastewater	Wastewater is high in pollutants. Many treatment plants focus only on cleaning out nutrients and heavy metals, paying little attention to removing pharmaceuticals, such as hormones, anti-depressants and antibiotics. Updating onsite cleaning processes so that pharmaceuticals are also removed will reduce chemical stress to waterways.	Where wastewater plants discharge effluent into waterways, particularly where the effluent makes up a large fraction of streamflow – e.g. where water is discharged into intermittent or low-flow streams.	[5]	As per state and federal best management practice

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
3i. Keep oxygen levels high – see Strategy 2 this factsheet	The biodegradation of many pharmaceuticals and most trace organic contaminants is accelerated under aerobic conditions.	See actions 2a–2c this factsheet.	[28]	As per Strategy 2 this factsheet
3j. Promote hyporheic exchange See *Repairing vertical connectivity* factsheet, Strategy 2	The hyporheic zone is a biogeochemically active hotspot where many pollutants are broken down. Slowing streamflow by harvesting, infiltrating and disconnecting stormwater, or by using weirs, increases the likelihood that downwelling of surface water into the hyporheic zone will occur.	Where the catchment has waterways with permeable bed substrate. Where flashy urban flows have been managed.	[28]	See associated factsheet
3k. Prevent extreme low flows using environmental flow releases	Low flows increase contact between biota and sediment-bound pollutants. They also increase the concentration of water-borne pollutants. Releasing environmental water from weirs, dams, pipelines or fire hydrants may combat low-flow conditions that stress biota.	Where the climate and/or river regulation creates periods of protracted low flows.	[11, 29]	
3l. Disconnect or manage wetlands affected by acid sulfate soils (ASS)	Wetlands with pyritic soils (sulfide-rich sediments) that become exposed to air create sulfuric acid upon rewetting. This low pH environment promotes the release of heavy metals from sediments – increasing their availability in the waterway.	Where ASS-affected wetlands exist (note these may be pre-existing freshwater or coastal wetlands or constructed wetlands in new urban developments). Where ASS soils are likely to become exposed to air – i.e. either due to a falling watertable associated with urbanisation or due to climate change. Where the wetland inputs a large volume of low pH water into the receiving waterway.	[30]	[30]

Strategy 4. Maintain normal salinity and pH levels

Suitability of strategy: virtually all sites, except those that have naturally evolved under high conductivity, salinity or pH (likely to be very few places in Australia).

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
4a. Disconnect and infiltrate stormwater	Disconnecting stormwater pipes from waterways prevents the transfer of charged particles (metals, nutrients) from the built environment (roads, buildings) to waterways.	All areas.	[31]	See associated factsheet
4b. See *Repairing flow: what to do in the catchment* factsheet, actions 1b–1e.	Wetland biofiltration basins and other specially designed biofiltration media adsorb or transform ionised metals, repairing the ionic level of the receiving water.	Most areas, particularly where biofiltration basins are serially aligned along the drainage network to create a cumulative improvement in water quality.	[32]	See biofiltration guidelines
4c. Direct stormwater through biofiltration basins See *Repairing flow: what to do in the catchment* factsheet, actions 1f and 1g	In Australia, particularly in the south-west, agricultural clearing has caused the watertable to rise – bringing salt with it. If salt-affected land is developed it can cause salt to be transported by urban drainage to waterways.	In regions of south-western Australia that were formerly agricultural and now have a high soil salt content. Where the watertable is shallow (< 4 m) such that subsurface drainage will be used to prevent flooding of houses and other urban infrastructure.	[33]	
4d. Avoid development on agricultural land with a legacy of high soil salt levels	Urban development can accelerate the creation of ASS if the soils are highly pyritic because aggressive dewatering and stockpiling of peat soils allows oxygenation of the pyrite – priming the system for sulfuric acid creation upon rewetting. Subsurface drains can then mobilise low pH water from ASS-affected soils and transport this acidic water to urban waterways.	Where the catchment contains pyritic soils (e.g. parts of Perth) and where subsurface drainage has been installed. This action is particularly relevant where ASS soils are likely to become exposed to air – i.e. either due to construction, a falling watertable associated with urbanisation or climate change. Where the receiving waterway gets a large portion of its water from the subsurface drains (i.e. where dilution by water in the channel cannot overcome acidic inputs).	[30, 34]	[30]

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
4e. Avoid urban development in areas with significant risk of Acid Sulfate Soils (ASS) and shallow groundwater	Urban or agricultural drains (surface or subsurface) that are cut into historically water-logged pyritic soils are likely to leach sulfuric acid into the drain and then into the receiving waterway. Lining portions of these drains with soils high in lime (e.g. limestone) can neutralise the acidic water. Alternatively, shallow drains should be constructed so that ASS materials are not intersected. Permeable reactive barriers containing organic matter or iron filings can also be used to treat acidic water exiting from sub-surface drains before it reaches waterways.	Where the catchment contains ASS. Where the receiving waterway gets a large portion of its water from acid-affected drains (i.e. where dilution by water in the channel cannot overcome acidic inputs).	[30]	[30]
4f. Disconnect wetlands with ASS	Wetlands with pyritic soils (sulfide-rich sediments) that become exposed to air create sulfuric acid upon rewetting, which can compromise the pH of receiving waters.	Where ASS-affected wetlands exist (note these may be pre-existing freshwater or coastal wetlands or constructed wetlands in new urban developments). Where ASS soils are likely to become exposed to air – i.e. either due to a falling watertable associated with urbanisation or due to climate change. Where the wetland inputs a large volume of low pH water into the receiving waterway (i.e. where dilution by water in the channel cannot overcome acidic inputs from the wetland).	[30]	[30]
4g. Do not use salt to de-ice roads	Salt lowers the freezing point of water and is used in many countries, particularly in the northern hemisphere, to make roads more driveable. However, the salt makes its way via stormwater to urban waterways and creates severe salinity stress to these freshwater systems.	Where roads freeze over during winter and where salt is used as a de-icer. This does not occur anywhere in Australia.	[35]	Not relevant for Australia
4h. Prevent extreme low flows using environmental flow releases	Low flows, particularly drought conditions, increase daily fluctuations in pH. Maintaining flow can mitigate against extreme pH conditions.	Where the pH of the catchment is at the edge or beyond what is considered acceptable for water quality guidelines.	[36]	

Strategy 5. Improve water clarity

Suitability of strategy: suitable for most sites, particularly those with large quantities of fine sediments (e.g. clay, silt). May not be appropriate if improved water clarity will cause nuisance algal growth.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
5a. Slow the flow of water See *Repairing flow: what to do at the catchment scale* factsheet, Strategy 2, all actions	As flow velocity increases so does its ability to suspend particles in the water column and increase turbidity. Slowing the flow of water allows fine particles to drop out of suspension and improve water clarity.	Where the substrate of the site is fine sediment (e.g. silt, clay).	[37]	See associated factsheet
5b. Ensure that construction sites use sediment control measures	Urban construction can cause instream sedimentation to increase three-fold. Ensuring that developers put measures in place (e.g. sediment traps) to reduce sediment runoff from construction sites into stormwater drains will improve waterway turbidity.	Where considerable construction activity is occurring in the upstream catchment. Where roadside stormwater drains are directly connected to the waterway.	WSUD manuals	[38, 39] And WSUD manuals
5c. Run stormwater though biofiltration basins/media	Biofiltration basins that detain stormwater and allow sediment to settle out will reduce the load of fine sediments into the receiving waterway and improve water clarity.	Where catchment and waterway soils (bed and bank sediments) have a high clay or silt content.		See biofiltration guidelines

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Repairing water quality: what to do in the catchment

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Strategy 1. Keep water cool

Strategy 2. Keep oxygen levels high

Strategy 3. Reduce non-nutrient pollutants

Strategy 4. Maintain normal ionic & pH levels

Strategy 5. Improve water clarity

Repairing biota: what to do at the site

Repairing biota: what to do at the site

CRC for Water Sensitive Cities

Strategy 1. Create/protect refuges from high and low flows within the site

Suitability of strategy: most sites, particularly sites where high, scouring urban flows are thought to the major stressor to native fauna. Less suitable at sites where pollution is very high and considered to be the major stresso.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
1a. Create/protect slow-flow habitats in the main channel and on the floodplain See *Repairing lateral connectivity: what to do at the site and in the catchment* factsheet, Strategies 1 and 2, all actions	Slow flow or stillwater habitats provide a place for mobile aquatic animals (e.g. fish, turtles, amphibians) to retreat to during high velocity urban flows in the main channel. Slow-flow habitats in the main channel include bays, backwaters, in-channel wetlands or islands. Slow-flow habitat on the floodplain include natural or constructed wetlands (could be biofilters), ponds/depressions, or secondary channels (e.g. anabranch) that only connect during high flows.	In-channel slow-flow features are suitable for most sites, as long as scouring urban flows are unlikely to destroy them. Floodplain slow-flow habitats are most suitable in mid order streams and lowland rivers where the floodplain is well developed. Where floodplain wetlands do not support high loads of chemical pollutants and pose a threat to biota (e.g. ecological traps). See *Repairing lateral connectivity* factsheet for the suitability of specific actions.	[1, 2]	See associated factsheets
1b. Create/protect the hyporheic zone See *Repairing vertical connectivity* factsheet, all strategies	Spaces between coarse substrate particles can provide refuge for bacteria, algae and invertebrates during high flows, as well as very low flows.	Where the substrate is highly porous (e.g. gravel, cobbles). Where porous substrate is unlikely to be filled with sediment. See *Repairing vertical connectivity* factsheet for the suitability of specific actions.	[3-8]	See associated factsheet
1c. Improve instream habitat complexity See *Repairing riparian function: what to do at the site* factsheet, actions 5a–f	Large woody debris (logs), macrophytes and other complex habitat can provide some protection from scouring urban flows.	Where catchment scale repair of flow has occurred. Where there is little complex habitat instream. See *Repairing riparian function: what to do at the site* factsheet, actions 5a–f, for the suitability of specific actions.	[9, 10]	See associated factsheet
1d. Create deep pools	Deep pools provide an aquatic refuge for larger bodied fauna, such as fish, during low flow periods.	For reaches that cease to flow and where larger-bodied fish species are present.	[11, 12]	

Strategy 2. Improve the quality of instream habitat

Suitability of strategy: suitable for most sites, except those facing ongoing habitat modification/degradation. Most likely to succeed where flow has been repaired at the catchment scale.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
2a. Repair flow See *Repairing flow: what to do at the site* and *Repairing flow: what to do in the catchment* factsheets, all strategies	The flow regime has a strong overarching effect on the survival and persistence of instream biota. In an urban setting, high-velocity scouring flows create a physical disturbance that stresses instream animals (e.g. invertebrates and fish are dislodged from their homes). Scouring flows also indirectly stress biota by disrupting food production/retention, reducing instream habitat complexity and increasing sedimentation. Severe low flow periods also exacerbate water quality stress to instream animals, and magnify predation and competitive interactions.	Most likely to be successful if flow has already been repaired at the catchment scale or if the site is downstream of a flow-regulating structure. See actions in the associated factsheet for specific advice.	[5, 13, 14]	See associated factsheet
2b. Repair geomorphic complexity See *Repairing geomorphology: what to do at the site and in the catchment* factsheet, all strategies	Geomorphic complexity (e.g. bars, benches, pools, riffles) affects the abundance and complexity of instream habitat available for biota.	Where the channel form has been markedly altered by urbanisation. Where flow has or is being repaired (unless the channel is going to be allowed to naturally adjust). See actions in the associated factsheets for specific advice.	[15]	See associated factsheets
2c. Repair water quality See *Repairing water quality: what to do at the site* and *Repairing water quality: what to do in the catchment* factsheet, all strategies	Poor water quality (e.g. high temperatures, high levels of toxic pollutants, low levels of oxygen) is a significant cause of mortality to instream life in urban waterways. Improving water quality so that it doesn't cross thresholds is critical for the protection of instream biota.	Where water quality poses a serious threat to species persistence – i.e. oxygen falls below 4 mg/L, particularly if it falls below 2 mg/L. Or if temperature or pH exceeds the tolerance of species. See actions in the associated factsheet for specific advice.	[1, 15-22]	See associated factsheet

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
2d. Repair leaf litter inputs See *Repairing riparian function: what to do at the site* factsheet, Strategy 4, all actions; and see *Repairing nutrients: what to do in the catchment* factsheet, all strategies	Leaf litter underpins the food web of many flowing waterways. Increasing the input and retention of leaf litter is therefore important to the return/ persistence of many animals, particularly shredder invertebrate species. It is important to recognise that high nutrient levels can undermine the food web of streams because they accelerate the breakdown of leaves - reducing the amount of food available for macroinvertebrates.	Where the food web is supported by terrestrial litter – typically streams that are narrow (< 10 m wide). Where the stream would naturally have been forested. Where riparian vegetation has been largely cleared. See actions in the associated factsheets for specific advice.	[23-26]	See associated factsheets
2e. Repair aquatic habitat See *Repairing riparian function: what to do at the site* factsheet, Strategy 5, all actions	Macrophytes and logs are important habitat for many animals, providing places to hide and a stable substrate on which to live for some invertebrates. Reinstating complex habitat is important for the recovery of biota.	Where instream habitat complexity has been severely simplified by urbanisation. This action is unlikely to succeed unless scouring urban flows have already been repaired. See actions in the associated factsheet for specific advice.	[2, 14, 15, 27]	See associated factsheet
2f. Ensure the habitat requirements for all life history stages of valued species are present at the site	Some urban restoration efforts have failed to recover biota because restored sites do not contain appropriate habitat to allow species to complete their life history. For example, sites may not recover certain insect species because they are missing suitable habitat for oviposition (e.g. boulders or logs that extend into and out of the water). Alternatively, intermittent waterways may not support certain species (e.g. frogs) if the hydroperiod is not sufficient to allow larval survival and metamorphosis.	Suitable where the biota of management interest can complete their life history within the site (e.g. semi-aquatic insects). Not appropriate for species of fish that need to migrate for breeding.	[28-31]	
2g. Ensure that the banks of the waterway have a gentle slope	Urban waterways should have gentle slopes, at least in some areas, so that semi-aquatic animals such as frogs and turtles can easily leave the waterway. Steeply sloped waterways may become ecological traps for some biota.	Where the waterway is channelized or canalised.	[32]	

Strategy 3. Reduce negative interactions with non-native species

Suitability of strategy: where non-native species are present and are invasive. Not appropriate for highly novel sites where native species are unlikely to survive.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
3a. Control non-native species by removal or exclusion	The removal or exclusion of non-native species that are highly aggressive or are habitat modifiers (e.g. common carp, mosquito fish, redfin perch, pearl cichlid, dogs, cats, foxes) can improve the survival of sensitive species. Removal can occur via physical or chemical means. Fences can be used to exclude non-native predators from riparian habitat.	Removal should be attempted where aggressive non-native species are present but have recently invaded (i.e. low abundance), or at relatively isolated sites (e.g. certain floodplain wetlands) where recolonisation of the non-native species is unlikely. Removal should not occur if it puts other valued biota at risk. Exclusion via instream barriers (e.g. weirs) should be used if the invasive species is not yet at the site. Fences are suitable for most sites but can compromise human amenity.	[27, 33, 34]	[34-36]
3b. Increase the complexity of instream habitat	Complex instream habitat creates places for vulnerable species and individuals to hide – reducing their interaction with aggressive non-native species and increasing their ability to persist in the long-term. See actions 2e and 2f this factsheet for specific actions.	Where instream habitat complexity has been severely simplified by urbanisation. This action is unlikely to succeed unless scouring urban flows have already been repaired.		
3c. Repair baseflow See *Repairing flow: what to do in the catchment* factsheet, Strategy 5, actions a–h where baseflow has fallen, actions i–p where it has risen	Falling baseflow will reduce water depth during low-flow periods and exacerbate negative interactions with non-native species. Rising baseflow will facilitate the invasion of non-native species into previously intermittent river reaches where they would normally not survive.	Falling baseflow – where pools undergo severe contraction during low flow periods. Rising baseflow – where the site naturally had an intermittent flow. See associated factsheet for suitability various actions to repair baseflow given conditions in the catchment.	[12, 37]	See associated factsheet

Strategy 4. Translocate fauna

Suitability of strategy: most suitable for sites in small streams, less suitable for lowland rivers. Only likely to succeed where flow, geomorphology, water quality and riparian ecosystem components have already been repaired to some extent, such that translocated animals are likely to survive. Unlikely to suceed if invasive competitors or predators are present.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
4a. Translocate fauna	In highly fragmented urban environments natural recolonisation may not be possible. In these instances, managers should consider translocating healthy individuals from nearby refuge sites. Urban wetlands – natural or newly created – can also be used as arks for native species of conservation risk, but should be treated with caution.	Where the species of management interest has very low recolonisation potential (e.g. mussels, crustaceans, gastropods as opposed to fish or semi-aquatic insects) or where the fragmented urban fabric makes colonisation very difficult (e.g. frogs, fish, turtles). Where translocation does not pose a disease risk or a threat to genetic diversity.	[38-41]	See state and federal translocation guidelines

Strategy 5. Protect from fire

Suitability of strategy: suitable for most sites.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
5a. Protect from fire	Fire in the riparian zone of a restoration site will exacerbate the stresses to biota caused by urbanisation, and should therefore be prevented whenever possible.	All sites.	[42]	

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Repairing biota: what to do at the site

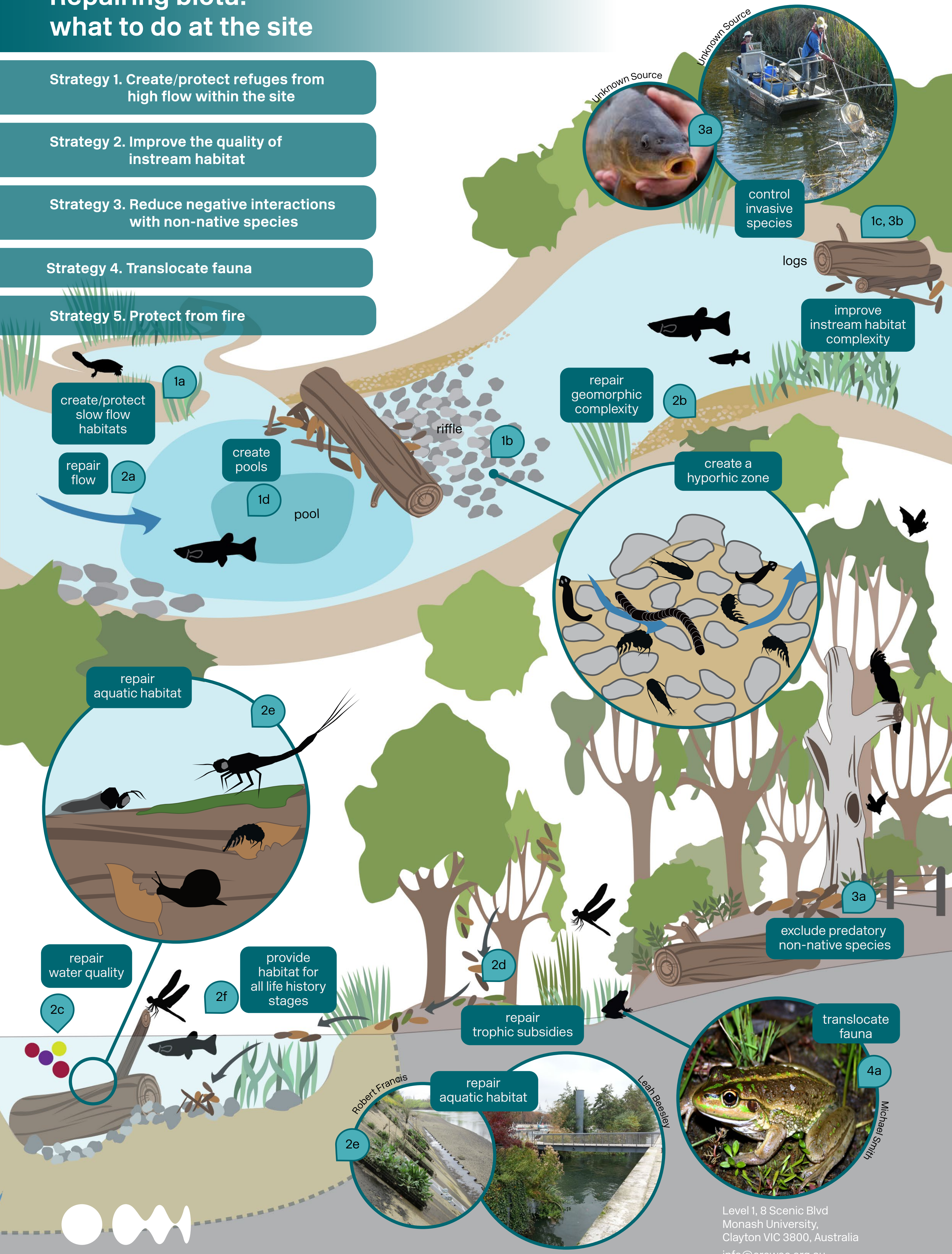
Strategy 1. Create/protect refuges from high flow within the site

Strategy 2. Improve the quality of instream habitat

Strategy 3. Reduce negative interactions with non-native species

Strategy 4. Translocate fauna

Strategy 5. Protect from fire



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Strategy 1. Identify biodiversity refuges

Suitability of strategy: suitable for all urban areas.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
1a. Catchment and system-wide survey of biota	Surveys of instream fauna are essential to identify waterway refuge sites. Refuges may not only be within the site's catchment, but also downstream of the site. Ideally, hundreds of sites should be surveyed across the urban network – including anthropogenic waterways; however, it is possible to use species distributional models to predict sites where biodiversity will be high (e.g. zonation).	All areas. Note, biodiversity refuges are most likely to occur in peri urban areas, but some refuge sites need to be located in lowland areas because these are likely to contain a different suite of species. Stormwater detention ponds may be refuges for adult biota or may be ecological traps - i.e. locations where reproduction and survival of young are low. Biodiversity refuge (definition) - A site of high native diversity (animals or plants). These are areas where adults or juveniles are protected from urban stressors. They are often sites of high breeding success and individuals move out of these sites to recolonise other less healthy sites. Refuges are critical to the resilience of the system.	[1, 2]	There are numerous system-wide surveys across Australia, e.g. the Sustainable Rivers Audit. SEQ Healthy Waterways, EPA Vic Rapid assessment. Surveys can be used to identify refuges and also to determine key threats.

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Strategy 2. Create/protect refuge stepping stones across the urban landscape

Suitability of strategy: suitable for most urban metropolitan areas, but most likely to be successful where a city's peri urban areas are relatively pristine. Less successful where prior agricultural land use has caused the loss of many species from the wider landscape.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
2a. Create/protect instream refuges (e.g. reaches of the stream/river with gentle flow and good water quality) See *Repairing biota at the site* factsheet, all strategies	Many freshwater animals spend 100 per cent of their life in the water (e.g. fish, mussels, many crustaceans). The long-term persistence of these animals across the urban landscape (i.e. meta-community) requires numerous healthy pools or river reaches where species can survive, breed and disperse out to the wider river network.	Protecting lotic refuges will be most easily achieved in parts of the catchment/urban landscape where stormwater has been managed at the catchment scale. Refuges can also be created around flow regulating structures (weirs) and in anabranches with little flow connection to the river. In general, intermittent refuges are easiest to create/protect in peri urban areas. See the associated factsheet for the specific suitability of individual actions.	[1, 3, 4]	See associated factsheet
2b. Create/protect wetland refuges (e.g. wetlands with good water quality, macrophytes and intact riparian vegetation	Many of the obligate aquatic animals can live in still, as well as flowing water habitats. Thus, creating and protecting healthy wetlands can support their long-term persistence in urban areas. Wetlands (floodplain and non-floodplain, natural or man-made – e.g. wetland biofilters) can be particularly important for protecting these aquatic animals from disruptive high velocity urban flows.	Newly created wetland refuges will be most successful if they are located relatively close to the waterway network (i.e. floodplain wetlands) – so that biota can easily colonise the area, as well as disperse from the refuges to newly repaired sites. Most successful in areas where soil and groundwater is not highly contaminated with nutrients or other chemical pollutants.	[1, 2, 5]	Refer to wetland restoration manuals
2c. Create/protect remnant bushland	Many freshwater animals are semi-aquatic (e.g. turtles) or have a terrestrial life stage (e.g. insects, frogs). These species, particularly aerial insects, often use remnant bushland as habitat. Protecting or creating patches of bushland can help them move through the urban fabric. Remnant bushland is likely to support more species and higher numbers of animals than restored parkland and should be protected as a priority.	Where the biota of management interest are aerial dispersers – i.e. move easily between terrestrial green patches.	[6-11]	

Strategy 3. Improve connectivity among refuges

Suitability of strategy: most suitable where Strategy 2 (this factsheet) has already been implemented. Actions that promote dispersal may not be suitable if they accelerate the spread of invasive non-native species.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
3a. Protect and repair riparian vegetation and address instream barriers See *Repairing lateral connectivity* and *Repairing longitudonal connectivity* factsheets, all strategies	The ability to move effectively along the length of a river, along a riparian corridor or between the riparian zone and remnant parcels of bushland is fundamental to the dispersal and recolonisation ability of biota. Without this ability animals are unlikely to reappear at restored sites. Care must be taken not to establish connectivity to a site where survival is low (e.g. ecological traps).	Where the biota of interest are species that are prone to suffer local extinction. This is often species that are found in low abundance, such as large species, predators and habitat specialists. Note that landscape connectivity is not as important for birds that can travel long distances through the air. Care should be taken that enhancing connectivity does not create ecological traps or allow predators (e.g. fish) to access sites where they naturally would not be present. See associated factsheet for specific advice.	[1, 5-8, 12, 13] but see [14-16] for caution	See associated factsheets

Strategy 4. Limit the invasion and spread of non-native species

Suitability of strategy: where non-native species are not present within the urban area, or they are present but have a restricted distribution, i.e. they are not present at the restoration site.

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
4a. Educate residents about the impacts of non-native species	Many people in urban areas release pet animals (fish, newt, turtles) into waterways. Educating people about the negative effects these non-native species is an important component of alien species management.	All areas, particularly where there is evidence of aquarium fish in waterways.		
4b. Intensive removal of non-native species	Eliminating non-native species once they have arrived is the only sure way to guarantee that they won't spread.	Where the non-native species is in low abundance and constrained to a small area (i.e. recent invasion). Or in high value isolated systems where re-invasion is less likely (e.g. certain floodplain wetlands).	[17, 18]	[19]
4c. Use barriers (existing) to limit the dispersal of invasive non-natives	Existing barriers, such as weirs, causeways and dams typically prevent fish passage and can be used to limit the spread of non-native species.	Where the non-native species has increased its abundance and distribution (i.e. created a self-sustaining population); but where the non-native species are located downstream of the restoration site (i.e. upstream sections of the river do not contain the alien species).	[14]	

Action	Explanation	Conditions where action is most likely to be suitable andeffective	Other references recommending action	Guidelines for implementation
4d. Use biocontrol or other methods	Specially designed viruses and genetic modifications (e.g. daughterless carp, cyprinid herpesvirus) can be used to control some invasive species.	Where the technology is available. This approach should be used with extreme caution to ensure that it does not put other biota at risk.	[17, 18]	

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Repairing biota:
what to do in the catchment
Strategy 1. Identify biodiversity refuges
Strategy 2. Create/protect refuge stepping stones across the urban landscape
Strategy 3. Improve connectivity among refuges
Strategy 4. Limit the invasion & spread of non-natives
protect remnant bushland
2c
catchment wide survey of biota
1a
improve longitudinal connectivity
3a
Stephen Beatty
Unknown Source
Unknown source
Leah Beesley
4b
David Morgan
use barriers to limit the dispersal of invasives
Leah Beesley
Jen Middleton
protect high quality wetlands
2b
Peter Robertson
4b
intensive removal of non-natives
create / protect instream refuges
2a
Belinda Quinton
Leah Beesley
Michael Smith
Belinda Quinton
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Water Sensitive Cities
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Monash University,
Clayton VIC 3800, Australia
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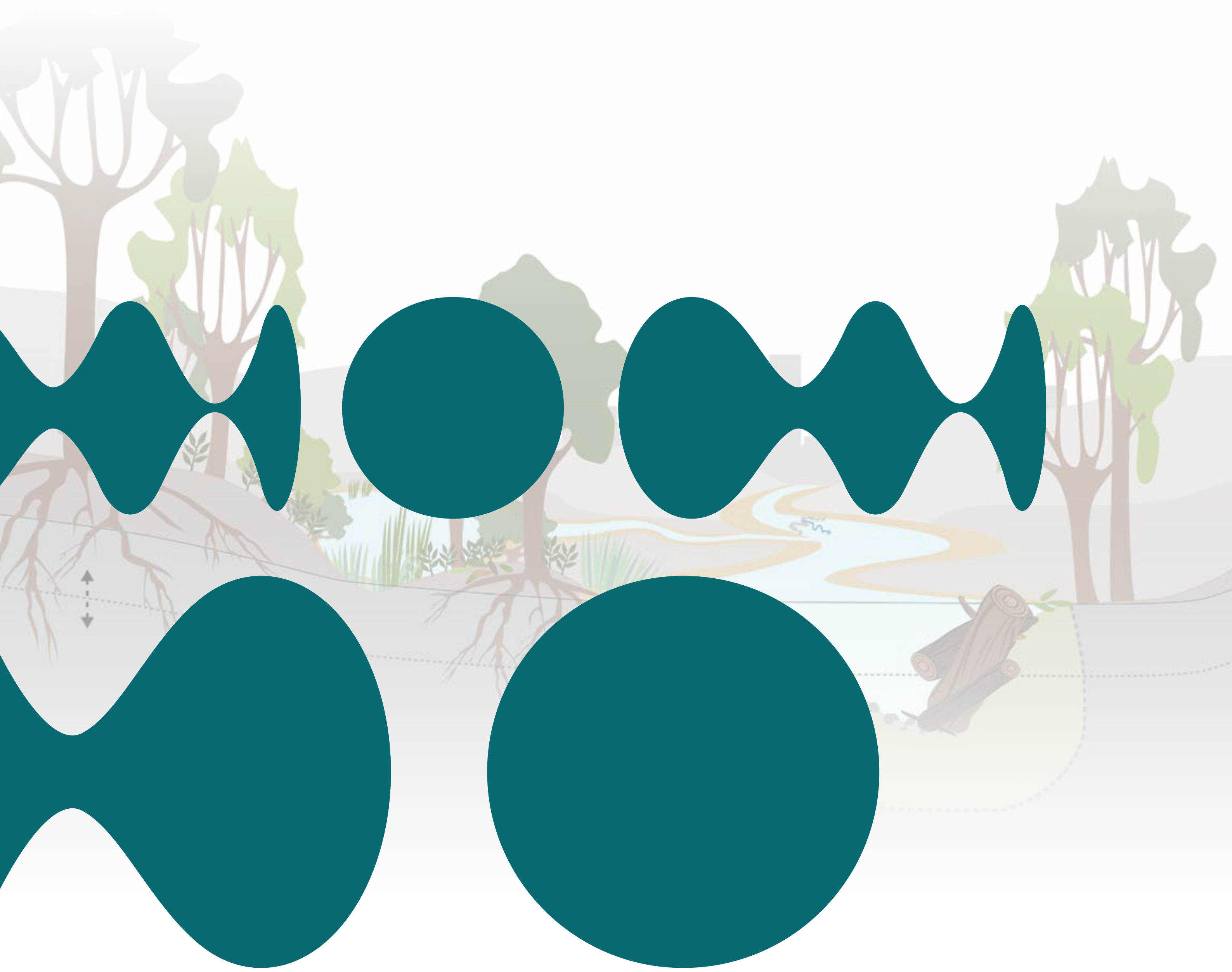
www.watersensitivecities.org.au
Legend
Sampling site
Refuge



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