Repairing riparian function: what to do at the site

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CRC for Water Sensitive Cities

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)		

Supporting documents

1. Bunn, S. and P. Davies (1990) Why is the stream fauna of south-western australia so impoverished? Hydrobiologia, 194(2): p. 169-176.
2. Davies, P.M., et al. (2007) Temperature and light. Principles for riparian lands management: p. 33-46.
3. Beesley, L., et al. (2017) Riparian design guidelines to repair urban waterways. Cooperative Research Centre for Water Sensitive Cities. Melbourne Australia.
4. Bunn, S., et al. (1999) Temperature and light. Riparian Land Management Technical Guidelines Volume One: Principles of Sound Management: p. 17-24.
5. DeWalle, D.R. (2010) Modeling stream shade: Riparian buffer height and density as important as buffer width1. JAWRA Journal of the American Water Resources Association, 46(2): p. 323-333.
6. Rutherford, J.C., et al. (2004) Effects of patchy shade on stream water temperature: How quickly do small streams heat and cool? Marine and Freshwater Research, 55(8): p. 737-748.
7. Rutherford, I.D., et al. (2000) A rehabilitation manual for australian streams: Volume 2. Cooperative Research Centre for Catchment Hydrology. Land and Water Resources Research and Development Corporation. Available from: http://www.engr.colostate.edu/~bbledsoe/CIVE413/Rehabilitation_Manual_for_Australian_Streams_vol2.pdf.
8. Price, P. and S. Lovett (2002) Streambank stability. Fact sheet 2. Land & Water Australia, Canberra.
9. Kondolf, G.M. (2013) Setting goals in river restoration: When and where can the river "heal itself"?, In: Stream restoration in dynamic fluvial systems. American Geophysical Union. p. 29-43. Available from: http://dx.doi.org/10.1029/2010GM001020.
10. Vietz, G.J., et al. (2016) Thinking outside the channel: Challenges and opportunities for protection and restoration of stream morphology in urbanizing catchments. Landscape and Urban Planning, 145: p. 34-44.
11. Miller, J.R. and C.R. Kochel (2010) Assessment of channel dynamics, in-stream structures and post-project channel adjustments in north carolina and its implications to effective stream restoration. Environmental Earth Sciences, 59(8): p. 1681-1692.
12. Rutherfurd, I., et al. (1999) Stream erosion. Riparian land management technical guidelines: volume one, principles of sound management. Land and Water Resources Research and Development Corporation, Canberra, Australia: p. 61-78.
13. Abernethy, B. and I.D. Rutherfurd, Guidelines for stabilising streambanks with riparian vegetation. 1999: Cooperative Research Centre for Catchment Hydrology Victoria.
14. Finkenbine, J.K., et al. (2000) Stream health after urbanization. JAWRA Journal of the American Water Resources Association, 36(5): p. 1149-1160.
15. Rutherford, I.D. (2007) The influence of riparian management on stream erosion, In: Principles for riparian lands management, S. Lovett and P. Price, Editors. Land and Water Australia Canberra, ACT.
16. Fischer, R.A. and J.C. Fischenich (2000) Design recommendations for riparian corridors and vegetated buffer strips. Army Engineer Waterways Experiment Station. E.R.a.D. Centre. Vicksburg, Massacheuttus.
17. Shields, J., F Douglas, et al. (2000) Large woody debris structures for incised channel rehabilitation. In: Joint conference of Water Resources Engineering and Water Resources Planning and Management. Minneapolis.
18. Cottingham, P., et al. (2003) Managing wood in streams. L.a.W. Australia. Canberra, ACT.
19. Brooks, A.P., et al., Design guideline for the reintroduction of wood into australian streams. 2006: Land & Water Australia Canberra.
20. Treadwell, S., et al. (2007) Wood and other aquatic habitat. Principles for riparian lands management. Edited by S. Lovett and P. Price. Land and Water Australia, Canberra, AUS: p. 117-140.
21. Erskine, W., et al. (2007) River restoration based on natural channel characteristics: How to develop restoration designs for different rivers and riparian plant communities. Australian rivers: Making a difference: p. 85-90.
22. Rafferty, M. (2017) Computational design tool for evaluating the stability of large wood structures. F.S. Department of Agriculture, National Stream and Aquatic Ecology Centre. Fort Collins, Colorado, USA. Available from: https://www.fs.fed.us/biology/nsaec/assets/rafferty_usfs_nsaec_tn-103-2_stabilitylargewoodstructurestool.pdf.
23. Wohl, E., et al. (2016) Management of large wood in streams: An overview and proposed framework for hazard evaluation. JAWRA Journal of the American Water Resources Association, 52(2): p. 315-335.
24. Hughes, R.M., et al. (2014) A review of urban water body challenges and approaches: (1) rehabilitation and remediation. Fisheries, 39(1): p. 18-29.
25. Rosgen, D.L. (Year) A hierarchical river stability/watershed-based sediment assessment methodology. In: Proceedings of 7th Federal Interagency Sedimentation Conference, March, Reno, Nevada.
26. Dosskey, M.G., et al. (2010) The role of riparian vegetation in protecting and improving chemical water quality in streams1. JAWRA Journal of the American Water Resources Association, 46(2): p. 261-277.
27. Osborne, L.L. and D.A. Kovacic (1993) Riparian vegetated buffer strips in water-quality restoration and stream management. Freshwater Biology, 29(2): p. 243-258.
28. Hoffmann, C.C., et al. (2009) Phosphorus retention in riparian buffers: Review of their efficiency. Journal of Environmental Quality, 38(5): p. 1942-1955.
29. Groffman, P.M. and M.K. Crawford (2003) Denitrification potential in urban riparian zones. J. Environ. Qual., 32(3): p. 1144-1149.
30. Prosser, I.P. and L. Karssies, Designing filter strips to trap sediment and attached nutrient. 2001: Land & Water Australia.
31. Roberts, W.M., et al. (2012) Phosphorus retention and remobilization in vegetated buffer strips: A review. Journal of Environmental Quality, 41(2): p. 389-399.

32. Schipper, L., et al. (1991) Mitigating nonpoint-source nitrate pollution by riparian-zone denitrification, In: Nitrate contamination. Springer. p. 401-413.
33. Hill, A.R. (1996) Nitrate removal in stream riparian zones. Journal of environmental quality, 25(4): p. 743-755.
34. Gift, D.M., et al. (2010) Denitrification potential, root biomass, and organic matter in degraded and restored urban riparian zones. Restoration Ecology, 18(1): p. 113-120.
35. O'Toole, P., The functionality of riparian zones in flat sandy catchments. 2014, Murdoch University.
36. Lyons, J., et al. (2000) Grass versus trees: Managing riparian areas to benefit streams of central north america. JAWRA Journal of the American Water Resources Association, 36(4): p. 919-930.
37. Prosser, I., et al. (1999) The delivery of sediment and nutrients to streams, In: Riparian land management technical guidelines, S. Lovett and P. Price, Editors. Land and Water Resources Research and Development Corporation Canberra, ACT.
38. Rassam, D.S., et al. (2006) The hydrology of riparian buffer zones: Two case studies in an ephemeral and a perennial stream. Journal of Hydrology, 325(1): p. 308-324.
39. Groffman, P.M., et al. (2003) Down by the riverside: Urban riparian ecology. Frontiers in Ecology and the Environment, 1(6): p. 315-321.
40. Bhaskar, A., et al. (2016) Will it rise or will it fall? Managing the complex effects of urbanization on base flow. Freshwater Science, 35(1): p. 293-310.
41. Bernhardt, E.S. and M.A. Palmer (2007) Restoring streams in an urbanizing world. Freshwater Biology, 52(4): p. 738-751.
42. Newcomer Johnson, T., et al. (2016) Nutrient retention in restored streams and rivers: A global review and synthesis. Water, 8(4): p. 116.
43. Kaushal, S.S., et al. (2008) Effects of stream restoration on denitrification in an urbanizing watershed. Ecological Applications, 18(3): p. 789-804.
44. Duncan, J.M., et al. (2015) Mechanisms driving the seasonality of catchment scale nitrate export: Evidence for riparian ecohydrologic controls. Water Resources Research, 51(6): p. 3982-3997.
45. Duncan, J.M., et al. (2013) Towards closing the watershed nitrogen budget: Spatial and temporal scaling of denitrification. Journal of Geophysical Research: Biogeosciences, 118(3): p. 1105-1119.
46. Johnston, C.A., et al. (1990) The cumulative effect of wetlands on stream water quality and quantity. A landscape approach. Biogeochemistry, 10(2): p. 105-141.
47. Schipper, L.A., et al. (2010) Denitrifying bioreactors—an approach for reducing nitrate loads to receiving waters. Ecological Engineering, 36(11): p. 1532-1543.
48. Barron, O., et al. (2010) Determining the effectiveness of best management practices to reduce nutrient flows in urban drains managed by the water corporation. Part 2-literature review. Water for a Healthy Country National Research Flagship Report.
49. Cui, Z., et al. (2016) Use of a three-dimensional reactive solute transport model for evaluation of bioreactor placement in stream restoration. Journal of Environmental Quality, 45(3): p. 839-846.
50. Robertson, W.D., et al. (2000) Long-term performance of in situ reactive barriers for nitrate remediation. Ground Water, 38(5): p. 689-695.
51. Fahrner, S. (2002) Groundwater nitrate removal using a bioremediation trench. BEng (Hons) Thesis, Department of Environmental Engineering, University of Western Australia, Crawley, W. Aust.
52. Bentrup, G., Conservation buffers: Design guidelines for buffers, corridors, and greenways. 2008: US Department of Agriculture, Forest Service, Southern Research Station Asheville, NC.
53. Quilliam, R.S., et al. (2015) Can macrophyte harvesting from eutrophic water close the loop on nutrient loss from agricultural land? Journal of Environmental Management, 152: p. 210-217.
54. Beesley, L., et al. (2017) Are our urban streams on fire? Using studies on fire to learn about the urban stream syndrome. In: 8th Australian Stream Management Conference. Blue Mountains, NSW, Australia.
55. Bunn, S.E., et al. (2007) Aquatic food webs, In: Principles for riparian lands management, S. Lovett and P. Price, Editors. Land and Water Australia Canberra, ACT.
56. Price, P. and S. Lovett. Managing riparian widths, fact sheeet 13. L.a.W. Australia 2004.
57. Jansson, R., et al. (2007) Restoring freshwater ecosystems in riverine landscapes: The roles of connectivity and recovery processes. Freshwater Biology, 52(4): p. 589-596.
58. Sardi-Caromile, K., et al. (2004) Stream habitat restoration guidelines: Final draft. Co-published by the Washington Department of Fish and Wildlife and Ecology and the U.S. Fish and Wildlife Service. Olympia, Washington. Available from: http://wdfw.wa.gov/publications/00043/wdfw00043.pdf.
59. Booth, D.B., et al. (1997) Large woody debris in urban streams of the pacific northwest. In: Engineering Foundation Conference. Snowbird, Utah, USA.
60. Larson, M.G., et al. (2001) Effectiveness of large woody debris in stream rehabilitation projects in urban basins. Ecological Engineering, 18(2): p. 211-226.
61. Francis, R.A., et al. (2008) Meeting the challenges of urban river habitat restoration: Developing a methodology for the river thames through central london. Area, 40(4): p. 435-445.
62. Ward, J., et al. (1999) Biodiversity of floodplain river ecosystems: Ecotones and connectivity. Regulated rivers: research & management, 15(1): p. 125-139.
63. Pess, G.R., et al. (2005) Monitoring floodplain restoration. Monitoring stream and watershed restoration. American Fisheries Society, Bethesda, Maryland: p. 127-166.

64. Lawrence, J.E., et al. (2013) Hyporheic zone in urban streams: A review and opportunities for enhancing water quality and improving aquatic habitat by active management. Environmental Engineering Science, 30(8): p. 480-501.

65. Paillex, A., et al. (2009) Large river floodplain restoration: Predicting species richness and trait responses to the restoration of hydrological connectivity. Journal of Applied Ecology, 46(1): p. 250-258.

Water Sensitive Urban Design (WSUD) guidelines

Australia Wide

CSIRO, Urban stormwater: Best practice environmental management guidelines. 1999, Collingwood, Victoria: CSIRO Publishing.

Allen, M.D., et al. (2004) Water sensitive urban design: Basic procedures for'source control'of stormwater: A handbook for australian practice.

New South Wales

URS (2003) Water sensitive urban design technical guidelines for western sydney. Available from: http://www.richmondvalley.nsw.gov.au/icms_docs/138067_Development_Control_Plan_No_9_-_Water_Sensitive_Urban_Design.pdf.

South Australia

South Australian Government (2010) Water sensitive urban design greater adelaide region: Technical manual. Available from: https://www.sa.gov.au/__data/assets/pdf_file/0003/7770/WSUD_contents_and_glossary.pdf.

South Australian EPA. Rain garden 500: Application guide. Available from: www.epa.sa.gov.au/files/10793_raingarden_guide.pdf.

Queensland

Moreton Bay Waterways (2006) Water sensitive urban design: Technical design guidelines for south east queensland. Moreton Bay Waterways and Catchment Partnership. Available from: http:www.melbournewater.com.au/Planning-and-building/Applications/Documents/South-Eastern-councils-WSUD-guidelines.pdf

Victoria

Melbourne Water (2013) Water sensitive urban design guidelines: South eastern councils. Melbourne Water. Docklands, Melbourne.

Western Australia

Department of Water (2004) Stormwater management manual for western australia. Available from: http://www.water.wa.gov.au/urban-water/urban-development/stormwater/stormwater-management-manual.

Commission, P.D. (2006) Peel-harvey coastal catchment water sensitive urban design technical guidelines. Available from: http://www.epa.wa.gov.au/sites/default/files/Policies_and_Guidance/AppendixE_2.pdf.

Biofiltration guidelines

Australia Wide

Deletic, A., et al. Adoption guidelines for stormwater biofiltration systems. 2015; Available from: https://watersensitivecities.org.au/content/stormwater-biofilter-design/

New South Wales

Water By Design(2017) Draft wetland technical design guidelines (version 1). Healthy Land and Water Ltd. Brisbane. Available from: http://hlw.org.au/u/lib/mob/20170530131525_2632c5a65b696f6b1/wetlands-guidelines-final-v1.pdf.

Queensland

Water sensitive urban design engineering guidelines (superseded) and factsheets. 2000; Available from: https://www.brisbane.qld.gov.au/planning-building/planning-guidelines-and-tools/superseded-brisbane-city-plan-2000/water-sensitive-urban-design/engineering

Victoria

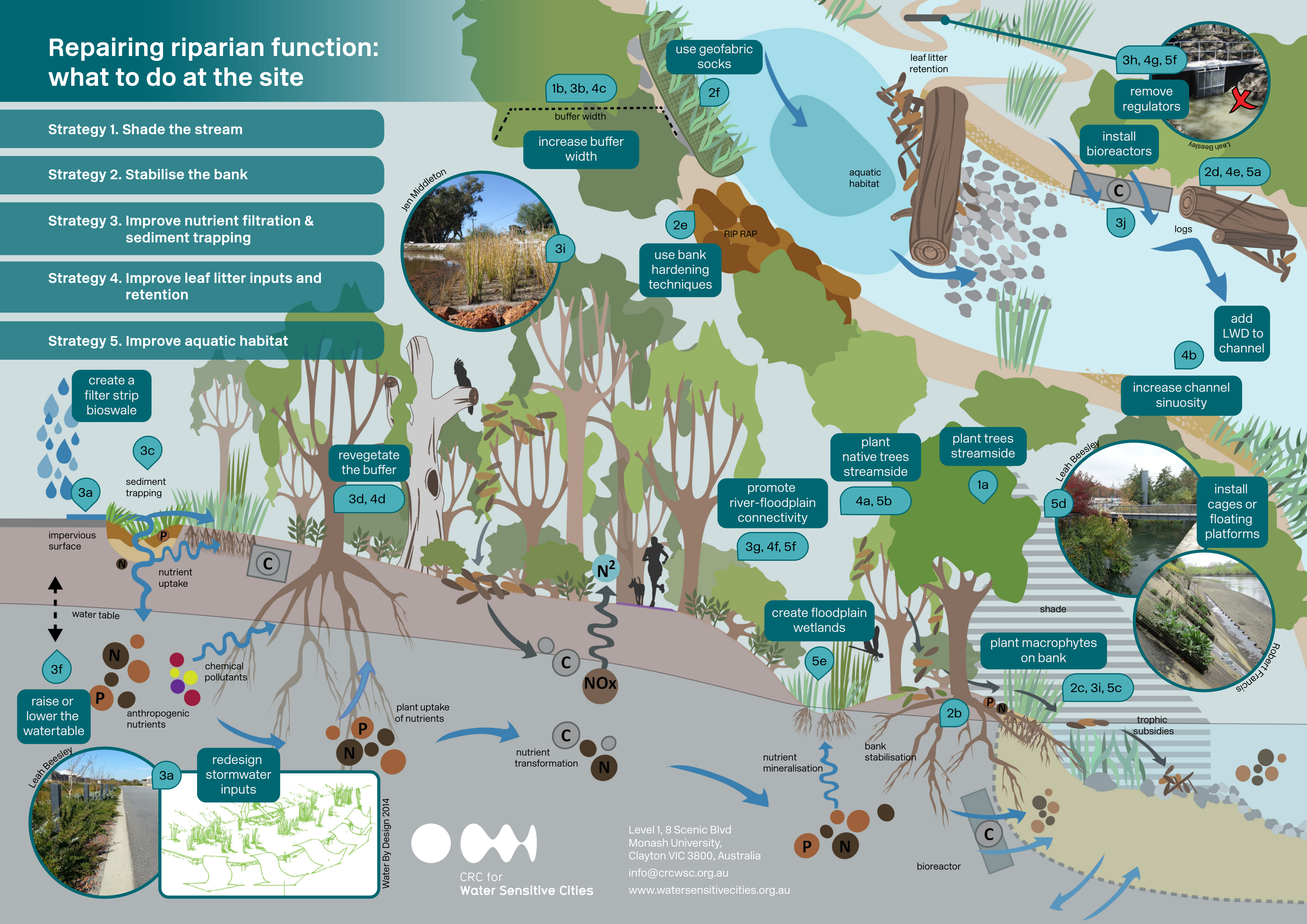
Melbourne Water (2017) Design, construction and establishment of constructed wetlands: design manual. Melbourne Water. Available from: https://www.melbournewater.com.au/planning-and-building/standards-and-specifications/design-wsud/pages/constructed-wetlands-design-manual.aspx.

Western Australia

Hatt, B.E. and E. Payne (2014) Vegetation guidelines for stormwater biofilters in the south-west of Western Australia. Cooperative Research Centre for Water Sensitive Cities. Melbourne, Australia. Available from: https://watersensitivecities.org.au/content/vegetation-guidelines-stormwater-biofilters-south-west-western-australia/

Other useful tools

Beesley, L., et al. (2017) Riparian design guidelines to inform the repair urban waterways. Cooperative Research Centre for Water Sensitive Cities. Melbourne Australia.


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
1b, 3b, 4c
buffer width
increase buffer width
use geofabric socks
2f
leaf litter retention
3h, 4g, 5f
remove regulators
install bioreactors
Leah Beesley
2d, 4e, 5a
aquatic habitat
C
3j
logs
add LWD to channel
4b
increase channel sinuosity
Jen Middleton
3i
2e
RIP RAP
use bank hardening techniques
create a filter strip bioswale
3c
sediment trapping
3a
impervious surface
P
N
nutrient uptake
C
water table
3f
raise or lower the watertable
N
P
anthropogenic nutrients
chemical pollutants
revegetate the buffer
3d, 4d
N2
NOx
plant uptake of nutrients
P
N
C
nutrient transformation
C
N
promote river-floodplain connectivity
3g, 4f, 5f
plant native trees streamside
4a, 5b
plant trees streamside
1a
Leah Beesley
5d
install cages or floating platforms
shade
create floodplain wetlands
5e
plant macrophytes on bank
2c, 3i, 5c
2b
P N
trophic subsidies
Robert Francis
nutrient mineralisation
bank stabilisation
P
N
C
bioreactor
Leah Beesley
3a
redesign stormwater inputs
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