
Scoping strategy for the Three Brooks and channel enhancements in the middle Cam River and Tuahiwi Drain

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WAIMAKARIRI
DISTRICT COUNCIL

*Report 17-04
April 2017*

EMA



Citation: Hudson, H.R. 2017. Scoping strategy for the Three Brooks and channel enhancements in the middle Cam River and Tuahiwi Drain. Environmental Management Associates Report 2017-04 for Waimakariri District Council. 110 pages.

Executive Summary

This report examines the North, Middle and South brook headwater streams of the Cam River (the “Three Brooks”; entering the Cam at km 8.4); a major tributary (Tuahiwi Drain entering the Cam at km 4.8); and the Cam River mainstem between Marsh Road (km 9.4) and Bramleys Road (km 6.5).

For the Three Brooks the scoping study reviews issues and options to enhance the waterways and examines works done to date, the effectiveness of these works, and what could or should be undertaken in the future to achieve the vision statement for the waterways.

Tuahiwi Drain in-stream sediment issues are reviewed as background for in-field technical advice that has been provided on design concepts, options and suitable locations for sediment traps and sediment removal.

In the Marsh Road to Bramley Road reach of the Cam River, in-stream sediment related issues are reviewed as background for concepts, options and suitable locations for the in-field technical advice that has been provided on bed raking (for sediment removal), creation of pools and riffles, sediment traps and bank stabilisation.

The vision is to rehabilitate the Three Brooks into a sustainable eco-morphological based exemplar that provides a broad range of ecosystem services and provides cost effective and hydraulically effective erosion and flood control required in a dynamic rural and urban landscape.

ECan streamwalks, undertaken in the Three Brooks and Tuahiwi Drain, are a powerful tool to describe stream corridor condition. Coupled with other information, the streamwalks show instream habitat is degraded because of excessive fine sediments on and in the stream bed, contaminants, and limited instream and riparian habitat diversity. Further, the streamwalks identify critical source area (e.g. bank erosion; surface runoff areas; and livestock crossings); riparian habitat condition; and the extent of streamside fencing excluding livestock. The streamwalks are a significant contribution to identifying what could or should be undertaken in the future to achieve the vision statement for the waterways.

A major threat to stream rehabilitating is paralysis by analysis. It's the author's belief that enough is known about what is wrong with the system, and how to address the causes of these problems, to act now with a range of proven management measures at specific locations. However, it is important to recognise that the effectiveness of these measures will vary with local conditions, and continual refinement to optimize outcomes, are required. Hence, any works should be treated as experiments, with appropriate monitoring and reporting of successes and failures.

A second major threat is ad hoc rehabilitation efforts rather than systematic implementation of a management framework to facilitate an ecosystem approach that cuts across various roles and responsibilities, to provide direction for decisions and expenditures that lead to incremental and systematic improvements in a coherent and cost effective way (e.g. sediment removal and bed raking as part of routine drainage maintenance).

Regarding paralysis by analysis, it is important to state what is known and what information is required before specific actions are undertaken. We know:

- Excessive sediment deposition on and within the bed, and flux of these sediments (and contaminants), continue to be major limitations to ecosystem health throughout these waterways;
- An integrated catchment management approach is required to achieve the Cam vision which includes controlling generation and delivery of sediment and contaminants from upland areas to waterways as well as the waterways themselves;
- Actions should start in the headwaters and move downstream otherwise upstream sediment and contaminants may overwhelm downstream rehabilitation;
- Critical source areas (hot spot or point sources) of sediment and contaminants can be managed at specific locations (e.g. controlling excessive bank erosion; stream crossings; tributary drain and tile drain outfalls);
- Correctly undertaken riparian planting can provide appropriate instream and terrestrial habitat; buffering from upland inputs of sediment and contaminants; and erosion control;
- Sediment and contaminants can be trapped and treated in and along waterways to stop downstream degradation and limit reaches requiring repeated rehabilitation;
- Excessive fine sediment deposits can be removed from waterways to enhance habitat quality;
- Bed reshaping can be used to remove fine sediment and enhance habitat diversity;
- Bank reshaping can be employed to control erosion and facilitate riparian planting;
 - Bank reshaping may be undertaken at the same time as routine channel maintenance for drainage outfall; and
 - Bank reshaping may be modified to provide a “two-stage” or compound channel;
- Two stage and compound channels (deviating from trapezoidal channels) are effective in maintaining a clean bed and trapping and treating sediment and contaminants; and facilitate riparian planting:
 - A narrower low flow channels can flush fine sediment;
 - Frequently flooded benches act as linear wetlands to trap and treat sediment and contaminants; and
 - Infrequently flooded stream margins trap and treat sediment and contaminants and buffer the stream from upland inputs.
- Many of these activities can be combined with routine drainage outfall maintenance, but this requires an integrated, and incremental approach, to waterway management.

In terms of what information is required to evaluate the effectiveness of stream corridor works done to date, and to specify what could or should be undertaken in the future to achieve the vision statement for the waterways, what we don't know includes:

- How to cost effectively clean extensive reaches of legacy sediments:
 - A “sand wand” vacuum system is effective, but expensive, hence is probably limited to small, high sensitivity, high value, areas (e.g. springhead trout spawning areas);
 - Bed raking appears to be able to dislodge interstitial fine sediments and create habitat diversity in waterways (i.e. a pool and riffle structure with a sinuous channel) but costs and effectiveness need to be rigorously quantified; and
 - Hydraulic excavators are effective at removing channel surface and edge fine sediment deposits (and weeds), and costs are well established from routine maintenance; but these operations should be coupled with localized trapping to control the downstream flux of sediment.
- Sediment traps are an essential component of instream rehabilitation but traps have to be designed to be fit for purpose, and the cost and effectiveness of unconventional designs, and ongoing maintenance costs, need to be rigorously quantified. Sediment traps can include:
 - Temporary structures (e.g. sand bag or straw bale dams for the duration of bed raking);
 - Enhancing natural sediment deposition areas to revitalize deposition; and
 - Larger, more permanent features that widen and deepen a watercourse and require periodic maintenance.
- Drainage outfall wetlands are an essential component of instream rehabilitation, but have to be designed to be fit for purpose, and the cost and effectiveness of unconventional designs, and ongoing maintenance costs, need to be rigorously quantified. Wetlands can include:
 - Enhancing existing “ponds”;
 - Mini-wetlands (~80 m²) excavated at the ends of tile drains; and
 - Constructed wetlands for larger streams.
- The effectiveness of previous riparian management is uncertain because the design philosophy is uncertain and there is limited before and after information on stream corridor condition.

While the Cam River Enhancement Fund can contribute in a meaningful way toward applying and verifying these ideas at specific locations – hence ticking the box for actions – there are two major considerations:

- The entire budget, or a large portion, could be spent on any one of these elements for the ~13 km Three Brooks (e.g. compound channel realignment ~\$1,000 per linear metre (LM); bank reshaping ~\$5 LM; riparian planting ~\$8 to \$20 LM), so choice of activities is critical; and
- The Three Brooks and Tuahiwi Drain are a microcosm of issues facing lowland streams regionally, and a coordinated, co-operative approach is required between WDC, ECan and other stakeholders, such as the University, to achieve the vision here and elsewhere, with various sources of funding.

In terms of bang for the buck, the greatest benefit for the vision is to control sediment and contaminants getting into and moving down waterways and removing excessive fine sediment that is already in the waterways. Habitat complexity, and compound channels can be created at the same time for a modest incremental cost. Specific activities at specific locations are recommended with indicative costings.

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1 Introduction

Waimakariri District Council (WDC) commissioned Environmental Management Associates (EMA) to undertake three further investigations in the Cam catchment (Figure 1):

- North, Middle and South Brook headwater streams of the Cam River (the “Three Brooks”; entering the Cam at km 8.4);
- Tuahiwi Stream (Maori Drain), a major tributary which enters the Cam at river km 4.8; and
- The mainstem of the Cam River between Marsh Road (km 9.4) and Bramleys Road (km 6.5).

The Three Brooks scoping strategy includes a vision statement, outlining potential improvements projects and a summary of works completed, underway or programmed by stakeholders on the Three Brooks from spring head to the confluence of each brook with the Cam River. The strategy also outlines benefit and potential budgets for each proposed option. The works to be considered include habitat restoration through measures such as stream enhancement, shading, habitat creation and bank stabilisation/reshaping projects, sediment traps and legacy sediment removal approaches, creation of riffles and pools and options for two stage channel formation. Other factors affecting water quality and in-stream habitat are also considered to provide context. The strategy will scope the potential for a “two stage channel design” for the Three Brooks and provide indicative costings.

Tuahiwi Drain in-stream sediment issues are reviewed as background for in-field technical advice that has been provided on design concepts, options and suitable locations for sediment traps and sediment removal. The sites chosen were based on previous investigations and work undertaken by WDC,

In the Marsh Road to Bramley Road reach of the Cam River in-stream sediment related issues are reviewed as context for concepts, options and suitable locations for the in-field technical advice provided on bed raking (for sediment removal), creation of pools and riffles, sediment traps and bank stabilisation.

Based on the in-field technical advice that has been provided, and this report, WDC staff will prepare the draft plans and designs for the proposed works, which will be reviewed by the consultant prior to being presented to the sub-committee for approval.

Elements of this report are based on previous investigations by EMA, which are referenced throughout. The Executive Summary and Recommendations from the lesser known Tuahiwi report are appended.

2 Vision statement

As discussed by Hudson (2010), prior to European settlement the Cust River and Eyre River fed into flax and raupo swamps that extended over much of the area from present day Rangiora to the Waimakariri River. Drainage of the swamp began in the 1850s, and in 1929 the Eyre was diverted to the Waimakariri and the Cust River into the Cust Main drain which now flows into the Kaiapoi River. The Waimakariri River was channelized in the 1930s, removing a complex of islands and channels, and the remnant North Branch became the Kaiapoi River thus establishing the present drainage pattern (Figure 1).

The Cam River now has a ~35 km² catchment and flows about 13 km from north east of Rangiora to the Kaiapoi River (Figure 1).¹ The Cam River joins the Kaiapoi River 5.6 km from the sea and the Kaiapoi joins the Waimakariri River 2.6 km from the sea. The main tributaries (the North Brook, Middle Brook, South Brook, South-South and upper Cam/Coldstream) are spring-fed and also receive surface water runoff from the rural and urban catchment. Flows in the tributaries and the Cam River are thought to be influenced by groundwater from the Ashley River to the north.

Development of the Cam catchment has had profound effects on land use and biodiversity. Over about 150 years the catchment has been extensively modified and is now largely pasture and arable land that is virtually devoid of native vegetation. Recently land use has evolved from large rural holdings and small service centres to rapidly expanding urban centres with surrounding rural residential properties. The combination of the increased urban and rural population almost invariably has a negative impact on water quality and stream biota (e.g. Suren & Eliot 2004).

The vision is to rehabilitate the Three Brooks into a sustainable eco-geomorphological based exemplar that provides a broad range of ecosystem services and provides environmentally friendly, cost effective and hydraulically effective erosion and flood control required in a dynamic rural and urban landscape.

This vision statement is applicable to the Cam River and many other similar streams and rivers. “Sustainable” refers to intergenerational sustainability, with minimum continuing intervention over the long term. “Eco-geomorphological” refers to linking the physical form and processes of waterways with ecological response by adopting an ecosystem perspective (Hudson 2002). “Ecosystem services” can be categorised as provisioning (e.g. mahinga kai), regulating (e.g. waste treatment, buffer zones), supporting (such as primary production, nutrient cycles and pollination) and cultural (such as spiritual and recreational benefits).² These services and actions are fleshed out in Appendix 1.

Underlying concepts include (Hudson 2002):

- Physical habitats have been lost or degraded;
- Sufficient water quality, physical habitat structures and abiotic processes are pre-requisite for re-establishing ecosystem services;
- Realistic goals and objectives are required;
- River corridor improvements are usually based on physical templates and processes; and
- Structural habitat improvements and restoration of flow regimes are necessary, but not necessarily sufficient, to restore particular species, because other factors may be equally, or even more, important.

Regarding goals and objectives, Hudson (2002) noted the goal of ecosystem management must be intergenerational sustainability, but objectives are conditioned by political, scientific, and economic realities, which often differ

¹ Gerard (2002) reports there are about 80 km of banks (40 km of waterways) in the Cam catchment. The actual area is difficult to accurately define because of the relatively level landscape, drains, culverts and road embankments modifying flow paths.

² https://en.wikipedia.org/wiki/Ecosystem_services Accessed February 2017.

significantly from natural or reference conditions. This frequently precludes restoration, but there are a number of options:

Enhancement: “any improvement of a structural or functional attribute” (NRC, 1992), but the endpoint of that improvement is not to resemble the original state.

Rehabilitation: “... improvements of a visual nature to a natural resource; putting back into good condition or working order.” (NRC, 1992). The direction of change is toward the original state.

Restoration: “return of an ecosystem to a close approximation of its condition prior to disturbance ... ensuring that ecosystem structure and function are recreated or repaired, and that natural dynamic ecosystem processes are operating effectively again.” (NRC, 1992).

There are several guiding principles for stream habitat rehabilitation and enhancement that are discussed at length in Hudson (2002, 2005). These may be summarised as follows:

1. Prevent further degradation of existing relatively intact ecosystems;
2. Re-establish the structure, composition and natural processes to make rehabilitated ecosystems resilient and self-sustaining;
3. Use references sites as models to guide rehabilitation and enhancement and as a comparison for assessing the success of the project;
4. Use native species from the local area where possible;
5. Take a broad view of factors that influence the rehabilitation reach and receiving waters, and address ongoing causes of degradation;
6. Take a broad view of how the rehabilitation may impact local, upstream and downstream ecosystems;
7. Take a long term view of how the catchment may change to influence stream conditions;
8. Take a long term view of rehabilitation (e.g. riparian margin tree growth and vegetation succession);
9. Determine if passive rehabilitation (e.g. controlling causes of degradation; rewatering a wetland) will allow recovery in a reasonable timeframe;
10. Management approaches must be sensitive to local conditions and be adapted as necessary;
11. Systematic learning is required with activities treated as experiments using appropriate experimental designs, monitoring, and assessment and reporting;
12. Experiences, both successes and failures, should be shared;
13. A co-operative approach, between multiple stakeholders, is required;
14. Minimise risk by careful planning with a multi-disciplinary team; and
15. The project must be ecologically and practically feasible.

Feasibility is determined by physical, political, and economic realities (Hudson 2002, 2005). In the case of the Three Brooks and the Cam system the objective is not restoration – as this would involve reverting the landscape back to an extensive raupō swamp. Also, the drainage network is required to control

flooding and erosion, within a limited stream corridor (i.e. the stream channel, the stream margins/floodplain and the infrequently flooded upland fringe).

At best we can rehabilitate the highly modified waterways by naturalizing aspects of the stream corridor i.e. the direction of change is toward free flowing streams that would be found in the original state. At worst, there are highly modified segments of the Three Brooks and Cam drainage network that are steep sided ditches with no marginal strips. In these instances, limited enhancements might be possible. The tools chosen to address these issues depends on correctly defining the problems and the causes of these problems. This is undertaken in the next section.

3 Situation analysis

3.1 Introduction

For the Three Brooks the scoping study reviews issues and options to enhance the waterways and examines works done to date, the effectiveness of these works, and what could or should be undertaken in the future to achieve the vision statement for the waterways. There are clear overlaps with issues and actions on the Cam mainstem and Tuahiwi Drain.

To understand the effectiveness of completed works, as a platform to recommend further works, the ideal scenario is to treat each activity as an experiment and undertake before and after measures of stream corridor condition. This is the approach advocated for all habitat restorations (Hudson 2002) and in previous investigations in the Cam system (Hudson 2010); and is the approach taken in the CAREX experiments by the University of Canterbury.

Works recommended in the past were specifically undertaken to address issues in the system which are outlined below. The only way to evaluate the effectiveness of these works is to examine stream corridor condition before and after the works were undertaken using the existing surveys, long term ECan monitoring at a limited number of sites, and ECan streamwalks over the catchment.

To facilitate discussion, stream corridor issues are reviewed, the options that were acted upon are described, and the effectiveness of these actions are assessed in terms of changes in stream corridor condition. In addition, some preliminary results from the CAREX experiments are discussed.

3.2 Issues

Previous investigations, reported in Hudson (2010), showed that a combination of bacterial contamination, nutrient enrichment, loss of clarity and sedimentation lead to a degradation of the amenity value, and benthic invertebrate and fish habitat of the Cam River and tributaries. Numerous sites were sampled in detail (e.g. Figure 2 and Figure 3); but these investigations are dated (EOS 2005 and Golder and Associates 2008); but have not been updated as recommended.

Regarding sediment, Golder Associates (2008) quantified composition of stream bed sediments at 16 sites in the Three Brooks (Figure 2). Many of the sites had gravel- sized sediments that could provide good quality habitat for invertebrates and trout spawning. Most of the South and Middle brook sites were dominantly gravel size whereas 4 of 8 North Brook sites had more than 50% fine sediment (<2 mm) (Figure 3). EOS Ecology (2005) also reported an abundance of relatively coarse, silt-free riverbed in the Three Brooks.

The lowest habitat quality occurs in Rangiora Township, with higher quality habitat both upstream and downstream on South Brook. North and Middle brook habitat improves from the Township site downstream. Habitat quality is lower than other rural sites in the North Brook tributaries (N5 & N7) and near the confluence of the Three Brooks (N8 & N9) (Figure 2). With the exception of N8, which has ~10% fine sediment, the lower habitat quality rural sites assessed by Golder Associates (2008) are dominantly fine sediment. This is fundamentally important because many species have a low tolerance for fine sediment substrates.

Golder Associates (2008) followed the approach of EOS Ecology (2005) and ranked the Three Brooks based on benthic invertebrate indices, as well as fish taxa richness. The low ecological value sites were located in the uppermost reaches of the North and Middle brooks (N1, N2, M1 M2), and lower reaches of North Brook at the Cam confluence (N8 & N9; Figure 2).

A large decline in trout numbers was reported based on similar surveys in 1982 and 2005 in the Cam and tributaries. Taylor (2005) observed 38 trout during the 2005 survey compared with 323 trout in the 1982 survey; and 124 fully excavated trout redds in 2005 compared with more than 260 observations in 1982. Taylor (2005) reports some of the gravel reaches utilized by spawning trout in 1982 had silt deposits in the 2005 survey (e.g. North Brook upper reaches, North Brook tributary upstream of Boys Road, and Middle Brook). However, Taylor (2005) considered that "... silt depth is still considered sufficiently thin in most reaches for spawning to be re-established. Preventing, or at least reducing, further silt inputs may allow freshes to flush sediment from affected reaches." Taylor (2005) does not discuss other limitations, but ECan long term monitoring would strongly suggest that stream water temperature is not limiting.

Hudson (2010) looked at patterns of ecological values with habitat suitability criteria (substrate, depth and velocity) and found some obvious relations such as N1 site at North Brook has unsuitable depth and velocity and 80% fine sediment cover which is unsuitable for high quality macroinvertebrates. In contrast, the 7 top ranked sites had depths ranging from 0.25 to 0.35 m and velocities of 0.80 to 1.00 m/s and ~5 to 15% fine sediment. The concluded these relations strongly suggest the most productive sites have riffle like characteristics with shallow fast flows over a clean gravel bed, a known characteristic of good benthic invertebrate habitat (e.g. Jowett & Richardson 1991).

More recent surveys of water quality and macroinvertebrates have been undertaken by ECan (Greer and Meredith 2016) at four sites in the Three Brooks and Cam River (Figure 4). Details of the state and trends over the past five years are summarised in Appendix 2. Key points for the period 2011 to 2015 include:

- Invertebrate communities are in a degraded state in the Cam at Bramleys Road and South Brook at Marsh Road, consistently failing to meet Land and Water Regional Plan (LWRP) outcomes.
- Invertebrate community composition (QMCI scores are indicative of poor (South Brook) or fair water quality (Cam at Bramleys Road)³ and degraded habitat.
- Spot measurements show some sites periodically meet the LWRP $\leq 20\%$ fine sediment threshold, but others have not:
 - The Cam at Marsh Road had consistently high sediment cover (90 to 100%);

³ Invertebrate communities were not monitored at the other sites of interest to this investigation

- The Cam at Bramleys Road and North Brook at Marsh Road vary from 10 to 80% fine sediment cover; and
- The South Brook at Marsh Road varies from 15 to 25% fine sediment cover.
- Recorded total suspended solid (TSS) concentrations are relatively low at the study sites (i.e. less than the 25 mg/L TSS threshold for onset of detrimental effects); but measurements were not taken during the rising stages of a flood when concentrations are expected to be greatest.
- Temperatures from all the spring-fed stream sites in the study area are low as expected (ranging from 13.3 to 15.8 °C; and the minimum recorded dissolved oxygen saturation exceeds LWRP outcomes.⁴
- Cam River at Marsh Road median dissolved reactive phosphorus (DRP) concentrations exceed the 70% probability of nuisance macrophyte growth; and the other study area sites median values were below the 30% probability of nuisance macrophyte growths. However, other factors are important because nuisance macrophyte growths have been regularly observed in most spring-fed streams.
- Plant available nutrient concentrations (DIN: dissolved inorganic nitrogen is composed of nitrate-nitrite nitrogen (NNN) and ammoniacal nitrogen (NH₄N)) were sufficiently high in all spring-fed streams in the Kaiapoi River catchment to allow macrophytes to proliferate. South Brook at Marsh Road was in the high range with median values exceeding the 90% probability of nuisance macrophyte growths. North Brook and the Cam River sites were usually below the 70% probability of nuisance macrophyte growths.
- Under the NPS for freshwater management (MFE 2014) national bottom lines for nitrate toxicity are not being met in the upper Kaiapoi River which requires better management of nutrient inputs to meet the C band requirement at Harpers Road. The Cam system sites are often around the A band; with a high degree of protection of biodiversity, the exception being South Brook at Marsh Road with is generally between the A and B bands (Figure A2: 1).
- Plant available nutrients (DIN) and dissolved reactive phosphorus (DRP) NNN concentrations are stable or downward trending at the study sites.
- All of the sites in the Kaiapoi catchment are above the alert level for *E.coli*. Most of the measurements for the Cam at Marsh Road and Bramleys Road exceed the threshold at which a site is considered unsuitable for contact recreation. Some exceedances also occur on the South Brook and North Brook, but the majority of measurements are between the alert level and unsuitable for contact recreation level. The Cam sites are trending up for unadjusted flows whereas the South and North brooks are trending down for the period of record (1999-2016).

ECan are developing and testing an advanced streamwalk protocol. While many of the attributes previously reported from the stream walks of Gerard (2002), are

⁴ This is consistent with previous investigations. Concentrations of dissolved oxygen were high enough and water temperatures low enough to be of no concern for aquatic life (ECan 2003). Dissolved oxygen at N2 (in Rangiora) was the only site below guideline values (74% against >80% saturation) in baseflow conditions. In high flows DO approached 100% saturation (Golder Associates 2008). Water temperatures were lower than guideline values in late November sampling at 17 sites (Golder Associates 2008). Water temperatures are expected to be relatively low in baseflow conditions in largely spring-fed streams.

repeated, the scientific framework, and extensiveness of the protocols have been enhanced (Golder Associates 2015). ECan kindly undertook a “test run” in the Cam River system; and agreed to enhance the sediment cover protocol to include an assessment of dominant substrate (akin to that used in instream flow modelling). The streamwalks provide a fundamental basis for identifying hot spots to target remedial actions and provide context for evaluating the success or otherwise of different initiatives.

Key points from Gerard (2002) include:

- The quantity of material derived from bank erosion appears to be relatively small, and largely associated with stock access;
- About a third of the ~80 km length of stream bank in the Cam and major tributaries was accessible by livestock. As well, there was stock access to drains feeding into the Cam River;
- Cam River: “Heavy sedimentation” occurred upstream of the confluence of the Cam and South Brook which was attributed to low stream gradient with natural deposition (there is limited stock access to the waterway upstream);
- North Brook: High levels of bank damage occurred in the unfenced sections which comprised 40% of the stream bank length, and there was also natural bank erosion which was rare elsewhere in the Cam system. Several dairy crossings were identified which were thought to be likely to be the source of episodic plumes of sediment;
- Middle Brook: Significant bank damage in the unfenced reaches of Middle Brook (27% of the bank length of the 3.1 km stream) was observed, and several culverts in poor condition, contributed sediment to the stream, and there was a “considerable amount” of sediment deposited at the rail bridge “indicating that the urban area has been a significant contributor”;
- South Brook: Stock access occurred over 34% of the stream bank length, and to springs and tributaries, causing bank instability and contributions to the sediment load. Stock crossings were also identified as a source of sediments and contaminants;⁵
- South-South Brook: A “dirty little stream” with poor aquatic habitat and water quality resulting largely from stock access by deer causing significant damage in the springs and stream itself. Stormwater from the industrial area was identified as a potential issue;
- Tuahiwi (Maori) Drain: The drain was heavily sedimented for much of its length, with very poor aquatic habitat, which was attributed to poor riparian management with stock access to 30% of the stream bank length and to springs and drains; and
- There were limited reaches with high native biodiversity (e.g. the Holcroft reach of the Cam River); with most of the banks of the Cam waterways featuring grass and willow trees.

⁵ Gerard (2002) identified the Waste Water Treatment Plant (WWTP) as “... the prime issue... responsible for considerable discoloration, particularly by algae, and a number of contaminants. It is impossible to achieve high water quality in the Cam until this discharge ceases.” The discharge ceased in 2006.

There has been no reporting at this stage of the latest ECan streamwalk, but ECan have very kindly provided the maps (Appendix 3) and photographs from the streamwalk. In summary these maps illustrate several key points:

- Fencing along both banks is more extensive than in 2002 (Appendix 3):
 - Cam River: There is no stock access on the Cam from Marsh to Bramleys Road (with ~750 m of stock access from Marsh to Boys Road);
 - North and Middle Brook: There is no stock access;
 - South Brook: <500 m of stock access;
 - South-South Brook: about half the reach has stock access from both banks; and
 - Tuahiwi Drain: ~1000 m has stock access from both banks.
- Fencing on one bank is similarly limited (Appendix 3):
 - Cam River Marsh Road to Bramleys Road: ~300 m;
 - North Brook ~500 m;
 - Middle Brook ~600 m;
 - South Brook: ~1100 m; and
 - Tuahiwi: ~800 m;
- Stock damage to stream banks ranges from no damage to severe (Appendix 3):
 - Cam River: no damage upstream of the Three Brooks, and on the right bank downstream to Bramleys Road; with minor damage on the left bank from the Three Brooks downstream to Bramleys Road;
 - North Brook: no damage;
 - Middle Brook: no damage;
 - South Brook: no damage (or not assessed for one tributary) for most of the Brook, with minor erosion over ~2000 m of one bank (including the oxidation pond reach that is described by Gerard as having ineffective fencing);
 - South-South Brook moderate bank damage over ~500 m (coinciding with a segment of unfenced reach); with no damage for ~2300 m; and
 - Tuahiwi Drain: ~200 m severe bank damage.
- Fine sediment cover exceeds the LWRP⁶ outcome of <20% for extensive reaches of the waterways (Appendix 3):
 - Most of the Cam between Marsh and Bramleys Road exceeds the LWRP outcome (~600 m at the South-South Brook confluence meets the outcome);
 - About half of North Branch;
 - All but ~185 m of Middle Brook;
 - About 60% of South Brook (with <8% not assessed);

⁶ http://files.ecan.govt.nz/public/lwrp/LWRP-Plan-Volume_1.pdf

- All of South-South Brook (a small reach was not assessed); and
- All of Tuahiwi Drain.
- There are subtleties within the fine sediment patterns in a figure titled Fine Sediment Cover that was provided earlier by ECan. Cover is reported in 5 classes in Figure 5: 0-20%; 21-40%; 41-60%; 61-80% and 81-100%. This detail is useful in identifying reaches for remedial works or to prevent further downstream degradation with sediment traps (Figure 5). In this regard:
 - Cam River: Most of the Cam above the Three Brooks confluence has 80-100% fine sediment cover; The segment from the Three Brooks to Bramleys Road has a sub-equal mix of the 0-20 to 61-80% fine sediment cover. To protect the higher quality reaches from upstream resuspension and transport of fine sediment, sediment traps are recommended on the Cam near Boys Road, Marsh Road, near the Three Brooks confluence, and at the South-South Brook confluence (the latter combined with a wetland);
 - North Brook: Two tributaries above Boys Road have 61-80% fine sediment cover as does the reach between Boys and Marsh Road. The remainder of the Brook is high quality. A sediment trap is recommended at Marsh Road, and also in the main tributary above Boys Road;
 - Middle Brook: The ~200 m segment with <20% fine cover is immediately below the main CAREX sediment trap (CX-01 in Figure 5). Further downstream ~ 500 m of channel has 21-40% fine sediment cover. The upper portion of this section has three shallow CAREX traps. Upstream of the main trap, the bed has 61-80% fine sediment cover over a ~320 m reach, and mainly 41-60% cover over the upper ~680 m. This strongly suggests the main CAREX trap is effective and the shallow traps are ineffective;
 - South Brook: The upper ~300 m below the springhead, the drain along Lehmans Road and tributary entering above Townsend Road have 81-100% fine sediment cover. These reaches can be isolated with sediment traps to control downstream impacts. The middle reach has <20% fine sediment cover; and the lower reaches dominantly 41-60% fine sediment cover. A sediment trap at the confluence with the Cam would control downstream impacts in the Cam.
 - South-South Brook: The upper ~460 m and lower ~725 m have >80% fine sediment cover; with short segments of mixed cover, with 41-80% fine sediment cover dominating (~950 m ~35% of the total length surveyed); a sediment trap at the confluence with the Cam is recommended; and
 - Tuahiwi Drain: The drain is heavily sedimented for almost the entire length. Traps are recommended at a few locations.
- Considerably more information is now available on vegetation, specifically riparian groundcover, understory and canopy vegetation and shading:
 - The waterways are dominated by exotic vegetation, with some mixed vegetation; with limited shading;

- None of the Cam from Marsh to Bramleys Road is classed as native vegetation (The Holcroft reach (which is 50 m long) was identified as having a mixed, not native, riparian ground cover and canopy); and
- The most extensive native vegetation reach is on the South Branch through town (~225 m); with smaller sections on upper North Branch and Tuahiwi Drain.

In the Cam above Revells Road, Hudson (1999) found that in low flow conditions the main source of suspended solids is resuspension of sediment from the riverbed. In high flow conditions sediment concentrations and loads increased downstream, with erosion from farm land and sub-divisions identified as major sources. Extensive drapes of easily re-suspended sediment in Tuahiwi Drain contained high levels of caesium-137 and beryllium-7 radionuclides which are indicative of surface erosion. Further downstream in the tidal reach, backwash and bank erosion were important additional sources of sediment. Sediment fingerprinting suggested that over half the material at the Cam mouth is probably derived from the upper catchment (i.e. above Revells Road). There was little evidence of significant contemporary bank and bed erosion.⁷

With respect to upland and stream bank erosion, the ECan streamwalk mapped and photographed critical source areas (Appendix 3):

- Overland flow paths (OLFP) were identified at several locations in the Three Brooks, one site in the Cam and seven sites on Tuahiwi Drain
 - The worst case scenario would be gullying or rilling, but no such sources of sediment were observed;
 - Some OFLPs were vegetated, acting as grassed waterways which would trap and treat sediment and contaminants (e.g. Figure 6);
 - Of concern are exposed surface drains directly contributing sediment and contaminants to the waterways (e.g. Figure 7).
- Bank erosion was identified in three sites in the upper Cam, three sites on North Brook, one site on Middle Brook, six sites on South Brook and two sites in Tuahiwi Drain. Various type of bank erosion were observed, which require different management measures (Hudson 2005):
 - Bank trampling by stock (Figure 8);
 - Toe scour undermining banks and cause slumping (Figure 9);
 - Unvegetated over steepened banks contributing sediment by dry ravel and surface wash (e.g. Figure 10).

Sediment and contaminants from surface runoff and drains were identified as significant sources in the Cam (Hudson 1999); but subsurface drains may also be an important source (Figure 13).

⁷ Golder Associates (2008) examined bank erosion in the North, Middle and South brooks. They noted the stream channels at their sampling sites were typically incised, with steep banks. However, active bank erosion was relatively uncommon. Notable exceptions were site N7 in a tributary of North Brook which had active bank erosion along the entire reach, and M2 in the upper Middle Brook where bank slumping and erosion were prevalent. These sites no longer have active bank erosion (ECan maps A:2S).

3.3 Conclusions: situation analysis

While there are improvements since earlier investigations reported by Hudson (2010) specific issues remain:

- Excessive sediment and contaminants are still generated and delivered to waterways.
- Water quality guidelines are exceeded for faecal coliforms.
- Plant available nutrient concentrations allow macrophytes to proliferate. South Brook at Marsh Road was in the high range with median values exceeding the 90% probability of nuisance macrophyte growths. North Brook and the Cam River sites were usually below the 70% probability of nuisance macrophyte growths.
- In contrast to the wider Kaiapoi Catchment where national bottom lines for nitrate toxicity are exceeded, Cam system sites are often around the A band; with a high degree of protection of biodiversity, the exception being South Brook at Marsh Road with is generally between the A and B bands.
- Concentrations of dissolved oxygen continue to be high enough, and water temperatures low enough, to be of no concern for aquatic life.
- There are excessive sediments throughout the Three Brooks, Tuahiwi Drain and the upper Cam River, which has adverse effects on aquatic life, particularly trout spawning and benthic invertebrates.
- Flushing of excessive fine sediments from the upper river put further stress on the lower river where tidal fluxes compound the issues.

4 Review of management measures

4.1 Introduction

The vision is to sustainably manage the waterways which requires moving from reactive management treating symptoms (e.g. removing fine sediment drapes) to proactive management addressing causes of problems (e.g. controlling sediment and contaminants before they become a problem in the waterways). The analogy is to move the ambulance from the bottom of the cliff to preventing problems at the top of the cliff.

Sometimes underlying causes of problems are not readily apparent or there are a combination of causes. For example, a decline in the trout fishery could be related to several limitations in the trout fishery, such as excessive stream temperatures, lack of dissolved oxygen, lack of physical habitat structures (e.g. spawning riffles), and degraded habitat (e.g. excessive fine sediment causing egg mortality).

Once limitation(s) have been identified (e.g. excessive fine sediment limiting spawning opportunity and success), then the cause can be addressed. For example, excessive fine sediment could be generated from farmland erosion, livestock trampling stream banks, or erosion of the channel. Each of these sources require different approaches (management measures) and methods (best management practices) to fix the problems (Table 1). Before rushing into action, some key decisions are required (Table 2).

This approach was employed to recommend management measures, and where possible specific actions (and costs), by Hudson (2010) for the Cam and tributaries. In addition, works were recommended for the residential/lifestyle

development of the Tuahiwi catchment (Hudson 2013). The rationale was as follows:

- The first priority must be to avoid generating excessive runoff, soil erosion and contaminants through appropriate land management practices;

It is futile, and not cost effective, to attempt to rehabilitate the river itself by treating the symptoms (e.g. removing excessive fine sediment on the riverbed) without fixing the causes;

- The second priority is to control the transfer of sediment and contaminants between sources and waterways and treat sediment and contaminant problems (e.g. slow runoff through buffer strips and filter sediments and contaminants);

While the emphasis is on avoidance, it is recognised that it is not feasible to completely control generation of sediment and contaminants at a catchment scale; and

- The third line of defence is to trap and treat sediment and contaminants in waterways with instream traps and wetlands.

Waterways themselves are sources of sediment (e.g. bank erosion) and sometimes contaminants; and even with good catchment management, upland and inchannel legacy issues must be dealt with. The traps and wetlands will enhance water quality.

The position taken was that enough is known to recommend management measures to address the issues identified in the Cam catchment with confidence. However, some data gaps and uncertainties were also apparent. This is not perceived as an excuse for inaction, but an opportunity to be adaptive and fill the gaps and learn by treating the recommended management measure as experiments. It was thought that such an approach, and interim developments in knowledge and circumstances, may lead to an evolution in thinking and reassessment of priorities and actions with time. This has been the case as described in the next section.

4.2 Recommended actions

Key ideas, with updates, from the recommendations of Hudson (2010) are summarised.

1. Avoid excessive contributions of soil erosion & contaminants from urban stormwater & new subdivisions

In essence, the recommendation was to utilise low impact urban design principles in future development as part of normal operating procedures. It was thought that such activities would be governed by rules in the Waimakariri River Regional Plan (WRRP operative 11 June 2011), and would be designed and implemented without cost to the Cam River and Tributaries Enhancement Fund (the Enhancement Fund). However, the main focus of the WRRP appears to be information and advocacy of appropriate land management practices. The WRRP does not impose rules on key items such as discharges of sewage tank effluent, water containing animal effluent and stormwater.

2. Avoid excessive contributions of runoff, soil erosion & contaminants from farmland.

A major focus of ECans Living Streams initiative (and actions by the Cam River Working Party), is to identify sources and causes of contaminants and to

implement control measures. This complements the WRRP, but is information and advocacy not rules based. There are a broad range of management measures that can be effectively implemented as part of modern farming practices which are vital to the success of the Cam River rehabilitation, that are not directly funded by the Enhancement Fund.

3. Avoid erosion & contamination from livestock access to waterways.

Control of livestock access to lowland spring fed streams is now required in the Environment Canterbury Natural Resources Regional Plan (NRRP) (cattle, farmed deer and farmed pigs).⁸ The concern remains that exclusion should be extended to important spring fed waterways that are not identified in NRRP Planning Maps Series A. Livestock exclusion may be accomplished using the ECan (2013) drainage bylaw.⁹ Provision should be made to allow selected riparian grazing by sheep for weed control.

4. Avoid erosion & contamination from uncontrolled stream crossings

Plumes of sediment and faecal contamination of waterways and bed disturbance occurs where livestock cross streams. Preventing livestock access to waterways, including stream crossings, is incompletely required in the NRRP, but is proposed in the Next Steps for Freshwater consultation document dated March 2016.¹⁰ However, the Clean Water Package (2017) proposes exclusion of dairy cattle and pigs from most lakes, rivers and streams from 1 July 2017, and will continue to 2030 when cattle, pigs and deer will be excluded from waterways.¹¹

The original recommendations remain - there may be some requirement for financial incentives to enhance stream crossings in particular non-delineated waterways and to rehabilitate degraded waterways by the Enhancement Fund.

5. Control & treat runoff, soil erosion & contaminant movement into waterways with buffers, streamside planting & channel naturalisation

Updated stream surveys were recommended to identify priority reaches for stream stabilisation, buffers and riparian planting. An updated and enhanced ECan survey is reported here.

Use of the Enhancement Fund, in combination with the Biodiversity Fund, was recommended for riparian planting to provide multi-faceted benefits including control of runoff, sediment and contaminants entering waterways, bank erosion protection, provision of habitat and food supplies, improved amenity and cultural values, and improved aquatic habitat. Ad hoc planting, largely based on aesthetics, was a recurring risk when a range of planting options was required to address particular outcomes (Table 4 & Table 5).

Bank reshaping may be required to provide the required stability and conditions for riparian planting (Figure 11 & Figure 12). A logical extension is naturalisation of waterways to improve habitat quality and to trap and treat sediment and contaminants. These actions would be facilitated with a global consent, with the requirement to employ best management practices.

⁸ <http://previous.ecan.govt.nz/advice/your-business/farming/Pages/what-farmers-need-to-know-and-do.aspx> Effective June 2012

⁹ <https://www.ecan.govt.nz/document/download/?uri=1758285> ECan Flood protection and drainage Bylaw 2013.

¹⁰ <http://www.mfe.govt.nz/publications/fresh-water/next-steps-fresh-water-consultation-document> (accessed March 2017)

¹¹ <http://www.mfe.govt.nz/fresh-water/freshwater-management-reforms/clean-water-package-2017> (accessed March 2017).

6. Control bank erosion

An assessment of bank erosion has been repeated by ECan and reported here. This confirms the quantity of material derived from bank erosion is probably relatively small, and often associated with livestock access. However, the recommended detailed site assessments, to plan control measures that are tailored to address the type of erosion, have not been undertaken. Bank reshaping, channel naturalization and riparian planting should be considered as a package with support from routine drainage works (Table 4 & Table 5; Figure 11 & Figure 12), the Enhancement Fund and Biodiversity Fund,

7. Control downstream spread of sediment with instream sediment traps

Construction of sediment traps in the riverbed will limit movement of sediment and contaminants from the upper catchment to the lower river. Further sites have been added and costs refined based on recent sediment trap construction and quantities trapped.

The recommendation for a global consent for small scale sediment traps on tributary streams using existing design guides has not been acted on. This consent would reduce cost and facilitate construction resulting in improved downstream bed conditions and limiting bed disturbance.

8. Control upstream tidal flux & sedimentation with the flood gates

Controlling upstream and downstream tidal fluxes of sediment with the Cam River floodgates has not been acted upon. It is not considered further in this investigation, because the floodgate is in the lower river.

9. Treat excessive sediment deposition by removal of fine sediment from within the gravel bed

Trials were recommended in the upper reaches because all such works should progress from upstream to downstream. The idea was to target a control reach and test reach that include a riffle, pool, riffle, pool, riffle sequence. Effectiveness would be quantified based on the before and after sediment sampling and before and after biological sampling.

Some investigations have been undertaken which have established costs and effectiveness of sand wand fine sediment removal. However, there is limited information on large scale bed raking to remove fine sediment from on and in the bed and to create habitat diversity. These trial are reviewed.

10. Quantification of sediment deposits

Benchmark surveys of fine sediment deposits on and in the bed were recommended to quantify the extent of rehabilitation activities to improve habitat and limit sediment resuspension, and to quantify the amount of sediment that may have to be removed. Also, a follow up survey was suggested to quantify the success of management measures. The recent ECan streamwalks provide useful information on bed material character, and fine sediment cover, but information on the depth of fine sediment is limited. Site inspections are recommended prior to sediment removal works being undertaken.

11. Quantification of stream health

To benchmark and evaluate rehabilitation it was recommended that periphyton, benthic invertebrates and fish are quantified at key locations in the Cam and major tributaries. The recent ECan streamwalk provides extensive comparative information on algae, macrophytes and benthic invertebrates and is reported

here. Information on fish is also required to evaluate the success or otherwise of management measures.

12. Management framework

Development of an ecosystem approach to catchment management was recommended to allocate appropriate resources, formalize priorities across jurisdictions, and ensure actions are consistent with an overriding strategy, policy and plans, leading to incremental and systematic improvements in a coherent and cost effective way. The objective was to move from somewhat ad hoc and reactive initiatives by WDC and ECan.

The WDC 2015 report “Cam River: Towards a whole of Catchment Strategy” reiterates some of the issues and opportunities discussed previously, but does not outline a locally relevant eco-systemic management framework to go forward.

13. Reshape the channel & floodway

Limited attention was given to creation of two-stage or compound waterways, because of the perception of the lack of opportunity in the confined waterways of the Cam and tributaries. Instream structures (large wood debris, spurs) were proposed as options. However, different approaches to two stage waterways have since been found, there is more information on costs and benefits, and some trials in the Cam tributaries have been undertaken and are reviewed.

Regarding the latter, Allibone & Hudson (2015) recommended a compound channel design requiring negligible to major bank reprofiling, and instream structural elements (e.g. pools-riffles, woody debris, boulder clusters and spurs) in Waituna Creek, Southland. Additionally, linear wetlands along the stream channel, and point source wetlands, were recommended to control sediment and contaminants from surface drains and tile drains (Figure 14).

5 Completed and proposed works

In terms of the recommendations of Hudson (2010 and 2013), and discussion above, the following works were started, have been undertaken or are planned in the Three Brooks, Cam and Tuahiwi Drain (Appendix 4):¹²

- In channel sediment traps;
- Wetland traps at surface and tile drains;
- Sediment removal from the stream channel;
- Bank stabilisation and reshaping;
- Two stage/compound channels;
- In channel habitat structures; and
- Riparian planting.

¹² Maps were kindly provided by Greg Bennet, Drainage Engineer, WDC.

6 Recommendations, costs and effectiveness

6.1 Trapping and treating sediment and contaminants

6.1.1 In channel sediment traps

In-channel sediment traps have been recommended for the Three Brooks, Tuahiwi Drain and Cam River. Key questions for this scoping study are:

- What are sediment traps;
- Why would you construct them;
- What would be constructed;
- Where should traps be located;
- How should traps be maintained; and
- What are the expected costs and benefits?

In-channel sediment traps are depressions in the stream bed designed to stop the downstream movement of coarse particles (sand and gravel) as well as varying proportions of fine sediments (fine sand, silt and clay that move in the flow rather than along the bed). Their widespread use is testament to their cost effectiveness and/or environmental benefit (Hudson 2002). This type of trap is often used in conjunction with wetlands.

Sediment traps have been recommended as a tool to trap and control spread of fine sediment deposits that limit stream life throughout the Three Brooks, Tuahiwi Drain and the Cam River. Linear wetlands in compound channels are also recommended to trap and treat very fine sediment and contaminants. The objective is to remove excessive sediment by trapping and excavation to achieve less than 20% cover of fine sediment (i.e. sediment less than 2 mm) on the stream bed (Clapott et al. 2011). This will benefit fish and macroinvertebrates that prefer relatively clean gravel beds (Figure 15).

Sediment trap guidelines were developed for Ministry of Agriculture and Fisheries (MAF) based on extensive, comprehensive, international experiences and well understood hydraulics (Hudson 2002). A “rule of thumb” best management practice was developed to facilitate sediment trap construction based on existing channel dimensions (Figure 16). In addition, two other types of sediment traps are recommended:

- Enhancing natural sediment deposition areas to revitalize deposition (e.g. inner bend and lee deposits, and deep pools); and
- Temporary structures (e.g. sand bags or straw bale dams) for the duration of channel works such as bed raking.

Several sediment trapping sites are proposed (green) or already exist in various forms (red) (Figure 5). The sites identified consist of conventional sediment traps and enhancements to natural deposition areas along the edge of the channel and across the channel (Figure 17). Also ponds that already trap sediment effectively (e.g. Northbrook), or could be enhanced to be more effective (e.g. Tuahiwi Drain and South Brook drain), are identified. Temporary structures would be constructed as required for bed raking and other channel works to control sediment plumes and to facilitate removal of fines that were flushed downstream.

Some of the existing traps are opportunistic, coinciding with drainage outfall works (e.g. Tuahiwi Drain willow removal). Others are to address a specific

problem (e.g. Fernside Road) (Figure 5) or control reach sedimentation (the latter are referred to as primary sediment traps). Once primary traps are constructed, it is proposed that the opportunistic element of sediment trap construction will become part of routine operations as an integrated approach to waterway management becomes embedded.

In terms of what to expect from conventional traps, a series of equations are provided in Hudson (2002) to calculate trap efficiency. For these equations we need to know:

- Trap dimensions;
- Design or effective streamflow; and
- Size distribution of inflow sediment.

Trap dimensions are proportional to the effective streamflow. The effective streamflow is the combination of magnitude and frequency of flow events that over the long term transport the most sediment. It may take a few years of record, or spot gauging's and flow regionalization, to adequately describe this flow range, hence traps are often sized based on a design flow or scaled from existing channel dimensions (i.e. the guideline trap).

The size distribution of incoming sediment is normally based on measurements of the total sediment load in a variety of flow events. The major consideration in the Three Brooks, Tuahiwi and Cam, is the transport of sand and finer material. Much of the former will move on or near the bed, and the latter in suspension. Sill plates should be employed if suspended sediment samplers are used to develop sediment rating curves. Turbidity metres (and conventional suspended sediment sampling) are unlikely to measure suspended sediment on or near the bed, which might be a significant portion of the total load.

Some idea of sediment load is required to determine the frequency of clean-out. In high load streams the trap may infill rapidly and become ineffective in preventing resuspension. Hence, the guideline trap is relatively deep (Figure 16). To refine the depth a design streamflow is required.

Often sediment traps are maintained with an hydraulic excavator using a conventional bucket to scoop sediment out. Alternatives include simple suction dredges (essentially a pipe connected to a centrifugal pump that sucks loose sediment off the bed and disposes through a pipe); and suction combined with mechanical loosening or the use of water jets (e.g. the "sand wand") to remove firmer surface material and interstitial fine sediment. This is discussed further in the section on sediment removal from stream channels.

Traps have to be designed to be fit for purpose, and the cost and effectiveness of unconventional designs, and ongoing maintenance costs, need to be rigorously quantified.

An indicative cost of excavation for within exiting channel small traps, from routine drainage maintenance, is \$1.60 /m³ plus disposal (if required).¹³ Transport of equipment to site is an additional cost for one off operations. This illustrates the need to integrate enhancement works into routine operations while a machine is in the vicinity of the trap or is undertaking other work at the trap site.

¹³ Greg Bennet, WDC Land Drainage Engineer, written com. 16 Feb 2017 "Cleaning of sediment traps: Based on standard drain cleaning rates \$1.60 per lineal m + disposal of spoil. This is how the two traps along Tuahiwi Stream (Maori Drain) were charged & we have only done this once per site so far."

Costs of conventional traps are proportional to channel size. For refining design to be context sensitive, the recommendation is to produce relatively shallow (~750 mm) traps that are 1.5 times the stream width and 10 times the channel width in length. To provide indicative costing, the channel base is assumed to be 2.0 m, with a 1.5 m bank height. Increasing the depth by ~750 mm, increases the cross sectional area by ~6.6 m². A 20 m long trap requires removal of ~130 m³ of sediment and edge planting of both banks (~80 m²).

Fletcher & Hudson (2016) provide indicative costs for one off operations for large areas in the Kaiapoi River, with costs for the hypothetical trap as follows:

- Excavation: \$4.00 /m³, ~130 m³, ~\$520;
- Removal from stock pile and levelling on a nearby site \$2.00 /m², 130 m³, ~\$260;
- Grassing of the infill ~\$1.00 m², assume ~250 mm depth, ~525 m², ~\$525; and
- Planting of banks ~\$5.50 to \$8.50 /m², 80 m², ~\$440-\$680.

For the hypothetical test traps (to establish rates of sediment infill), the estimated costs would probably range from ~\$1,000 for excavation, no cost disposal, and least cost bank planting to ~\$2,000 for excavation, off-site disposal, levelling and seeding, and high cost bank planting. If traps infill rapidly, then more frequent cleaning is required or deeper, more costly, traps are required.

To verify the efficiency of traps (particularly unconventional traps such as the edge trap or enhanced natural pool trap), the following information is required:

- The streamflow for the period of accumulation;
- The input sediment load;
- The amount of sediment that has accumulated;
- The output sediment load; and
- The size distribution of the outflow sediment

CAREX constructed a sediment trap on the Middle Brook (CX-01 in Figure 5). The dimensions are given as 2.5 m wide (the same as the stream channel upstream), 12 m long and up to 0.70 m deep. The claim is made that the theoretical trap efficiency for this trap is about 95% for 125 µm sediment based on Hudson (2002) whereas the reported trap efficiency was 60-70% over an 8-month period. It is unclear how the theoretical and reported trap efficiencies were calculated.

For the CAREX trap, no information is available on streamflow, the input and output sediment load or size distribution characteristics of the input and outputs (Figure 18b).¹⁴ This is unfortunate because it is not possible to calculate the theoretical trap efficiency unless the flow regime and input sediment size distribution is adequately described.

Also, it is unclear how the reported efficiency of 60-70% was derived – it appears to be based on how much sediment accumulated (4 m³ in 8 months) and the size fractions of the accumulated sediment (Figure 18 a). Mention was also made of silt plates, but it is unclear how these can be used to calculate sediment loads.

¹⁴ Summaries of the information were requested, but ultimately the requests were denied.

In order to assess the reported trapping efficiency of 60-70%, information is required on the particle size distribution of material entering the trap and leaving the trap; as well as the accumulation history and associated hydrographs. Unfortunately, CAREX could not provide this information or a summary of this information.¹⁵

It would be helpful to more fully evaluate the CAREX design, because it might be employed elsewhere, but is unconventional. As shown in Figure 16, for a rule of thumb trap:

- The traps should be in a straight section of channel, not a bend;
- The trap should be 1.5 times wider than the upstream channel;
- The trap should gradually widen downstream;
- The depth (to provide freeboard to stop resuspension after a reasonable volume of trapping) should be 1.5 m deeper than the existing channel; and
- The trap is effectively shorter than reported because of the bend – the straight section should be 4 to 10 times longer than the stream width (i.e. 10 to 25 m long).

Nevertheless, the CAREX-01 trap is useful from a practical perspective because it trapped 4 m³ of the target sediment; and because we can learn from its performance as an enhancement to a natural pool (i.e. a trap that is relatively shallow and contained within the existing banks).

Regarding learning from the trap, the absence of streamflow information is problematic because, based on the available information (Figure 18), there are uncertainties about the stream inflow which is critical in determining trapping efficiency.¹⁶

- There is an apparent discontinuity in flow which should not occur; and
- It is unclear if the reported velocities and depths refer to a random measurement, design discharge or flood discharge.

The CAREX main trap is an unconventional design – perhaps driven by the aim “... to develop an “ideal” sediment trap design.” (Figure 19). Nonetheless, based on the reported dimensions, and some assumptions, trapping efficiencies can be assessed.

In terms of streamflow (see footnote 16):

- To trap 95% of 125 µm sediment, the effective input flow would have to be about 100 L/s;
- If the effective input flow was 300 L/s, the trap efficiency would be about 60% for 125 µm sediment; and
- If the effective input flow was closer to 600 l/s, the trap efficiency would be about 40% for 125 µm sediment.

¹⁵ Dr Febria Oabel, written com., 16 February 2017.

¹⁶ The input and trap discharges should be the same because there is no loss of water between the two points. However the schematic suggests the input discharge is ~560 L/s (a scaled depth of 0.45 m, reported width of 2.5 m and reported velocity of 0.5 m/s) and the mid trap discharge is 75 L/s (a scaled depth of 0.60 m, reported width of 2.5 m and reported velocity of 0.05 m/s). In response Professor Harding (written com. 13 Feb 2017) noted “I think the upstream depth is probably less than 0.45 m and the middle of the trap is certainly deeper than 0.60 m. It was at least 0.75 m when initially dug and cleaned.” This doesn’t make a material difference – for the reported flow velocity the input flow depth would have to be less than 0.10 m in order for the input and throughput flows to be equal.

The theoretical trapping efficiency (based on the effective sediment trap being $\leq 30 \text{ m}^2$ and flows less than $\sim 300 \text{ L/s}$) can be compared with the observation that about one third of the material in the trap was coarser than 1.00 mm and two thirds was finer than 1.0 mm :

- Sediment larger than 0.5 mm is expected to be trapped;
- Perhaps 90% of 0.25 mm sediment is expected to be trapped;
- Perhaps 70% of 0.125 mm sediment is expected to be trapped; and
- Perhaps 25-30% of 0.0625 mm sediment is expected to be trapped.

With the above assumptions and assuming an equal proportion of these sizes in the incoming sediment load, the theoretical trapping efficiency for this mixed load is $\sim 70\%$.

Additionally, when the bed level in the trap decreases to $\sim 300 \text{ mm}$ (the depth shown), at flows over $\sim 350 \text{ L/s}$ material finer than 1.0 mm is likely to be resuspended and flushed from the trap (Figure 19). This indicates the critical nature of a design flow to refine trap depth and trap storage capacity. Also, it shows the importance of trap depth – if it's too shallow there will be relatively little storage before resuspension occurs. In the event that the ability to excavate the bed is limited to $\sim 700 \text{ mm}$, then relatively frequent cleaning is probably required. Given the importance of flood flows on sediment loads reported by Hudson (1999) in the Cam River, traps should be inspected, and cleaned if required, after each flood.

Very shallow sediment traps (CX-02, 03 & 04 in Figure 5) were also excavated downstream of CX-01 the main trap on Middle Brook. There is no formal description of these traps. I had the occasion to visit the very shallow traps near Marsh Road. There was no apparent widening of the channel for the trap, and the bed level resembled a shallow pool. At the time of inspection sediment was trapped along the edges of the shallow pools (which is typical of the upstream and downstream reach), but much of the bed was scoured clean of fine sediment (Figure 20). This is likely to be a general problem with very shallow sediment traps – resuspension will occur with freshes when most of the sediment transport occurs.

The expectation from extensive international research is that sediment traps will be a key tool to help remove excessive fine sediment deposits from the waterways. In Middle Brook, the main sediment trap CX-01 accumulated 4 m^3 of fine sediment (Figure 18). This sediment was probably derived from upstream erosion and from the upstream channel itself (the bed $\sim 150 \text{ m}$ upstream of the trap contains 41-60% fine sediment cover). The bed immediately downstream of the trap has a clean gravel bed (Figure 5 & Figure 21).

It is important to place the 4 m^3 from 8 months of trapping in CX-01 in Middle Brook in context. The dry weight of a cubic metre of fine alluvial sediment is roughly a tonne. Suspended sediment loads were estimated by Hudson (1999) who reported that a single large storm dominated the sediment flux over a three month survey period. Suspended sediment loads (excluding organics) were estimated at 73 tonnes at Youngs Road, more than 160 tonnes at Revells Road and 470 tonnes at the mouth of the Cam River. Thus, it is likely that the trapped amount is a meaningful proportion of the expected sediment load in Middle Brook. The CAREX estimates of sediment loads would be useful in this regard, but were not available.¹⁵

Once the overall integrated catchment management plan has been implemented, and measures are in place to avoid and control the generation and

delivery of sediments and contaminants to waterways, the importance of sediment traps will decline with time. This will be some years from now as the legacy sediment are cleaned up.

6.1.2 Drain wetlands

The role of open drains and tile drains in agricultural catchments as point sources of sediments and contaminants is recognised in Europe and the United States; and in New Zealand (e.g. Tanner et al. 2011). Various configurations of natural, restored and constructed wetlands have been shown to be effective in reducing agricultural runoff impacts on receiving waters. However, diffuse runoff and associated contaminant loads are inherently variable, and it is difficult to directly transfer results because of differing climates, wetland vegetation, flow regimes and land use practices. Also, various parts of wetlands vary in effectiveness and with age. In this regard, to provide a guide to sizing wetlands, Rutherford & Wheeler (2011) report entire wetland maximum removal rates of ~250 mg N/m²/day from various New Zealand studies.

In a simple, cost effective approach for tile drains, Petersen et al. (1992) excavated mini-wetland to expose tile drains and allow water to pass through vegetation before entering a waterway (Figure 14). They found small wetlands (8 m by 10 m wide) were effective with high trapping efficiencies reflecting local conditions. The expectation, for New Zealand plants and conditions, is that an 80 m² wetland would remove ~0.02 kg/day (7.3 kg/year) (based on Rutherford & Wheeler 2011); which would be beneficial, and cost effective, in the local and regional context:

- In the Canterbury Plains, CAREX quantified export of nitrate-nitrogen in small agricultural streams <2 m wide and tile drains (Goeller et al. 2016). They reported flux of nitrate-N from <1 to >50 kg/day from streams; with <0.01 to >5 kg/day for tile drain “hotspots;”
- The low end “hot spot” load of <0.01 kg/day equates to <3.7 kg/year which is about half the rate of removal from an 80 m² mini-wetland; and
- Therefore, it is likely to mini-wetlands would be effective in trapping and treating nutrients from many low end “hot spots” and other tile drains.

The generality of this finding can be further evaluated using ECan summary statistics of NNN concentrations from hundreds of measurements in lowland stream and rivers across the region:

- Lower quartile NNN concentrations are ~0.42 mg/L, median concentrations are ~1.3 mg/L, with upper quartile concentrations are ~3.4 mg/L (Meredith and Hayward 2002);
- For the Kaiapoi catchment, Greer and Meredith (2016) report median values over several years of 4 to ~8 mg/l for Kaiapoi River sites; 0.45 mg/L for North Brook at Marsh Road; 0.64 mg/L for Cam at Bramleys Road; 0.67 mg/L for Cam at Marsh Road and 1.47 for South Brook at Marsh Road (Figure A3: 1); and
- Kaiapoi River sites exceed the upper quartile of all of ECan’s Canterbury lowland sites; South Brook is above the median; and North and Middle Brook are between the lower quartile and median.

This further supports the contention that, apart from South Branch, the Cam catchment is at the lower end of the spectrum of nutrient concentrations and mini-wetlands would probably be effective trapping and treating nutrients from tile drains and small waterways.

Indicative costs for hypothetical mini outfall wetlands (8 m wide and 10 m long with 1.5 m bank height) are based on section 6.1.1 In channel sediment traps. Additional excavation of ~90 m³ is required, with 80 m² of wetland base planting and 40 m² of bank planting. Costs would probably range from ~\$1,000 for excavation, no cost disposal, and low cost planting to ~\$1,900 for excavation, off-site disposal, levelling and seeding, and high cost planting. Cost could possibly be lower for wetlands created as part of routine drainage operations.

Locations of mini wetlands cannot be specified at this stage because the location of tile drains was not mapped by ECan, and is not reported in WDC drainage management plans. It is recommended that tile drain locations are mapped, and a rating of possible sediment and contaminant discharge is assigned, to identify several suitable drains for trialing drainage outfall wetlands.

The next question is whether larger wetlands or bioreactors would be cost effective in trapping and treating nutrients from larger streams and more nutrient rich sites. This requires information on nutrient loadings.

Based on reported median NNN concentrations, and estimates of catchment area and median flow,¹⁷ ball park estimates of NNN loads were calculated:¹⁸

- Cam River at Marsh Road: 0.67 mg/L, ~360 ha, ~190 L/s, ~11 kg/day, ~3,900 kg/year;
- Cam River at Bramleys Road: 0.64 mg/L, ~2,700 ha, ~1,400 L/s, ~76 kg/day, ~28,000 kg/year;
- North Brook at Marsh Road: 0.45 mg/L, ~600 ha, ~310 L/s, ~12 kg/day, ~4,400 kg/year; and
- South Brook at Marsh Road (excluding Middle Brook; but extending to the Cam mouth): 1.47 mg/L, ~990 ha, ~510 L/s, ~65 kg/day, ~24,000 kg/year.

Tanner et al. (2010) provide guidelines of design and expected efficiencies for constructed wetlands (Figure 22 & Figure 23) based on New Zealand experience over several years. Titoki wetland, Northland, is particularly relevant, with the ~900 m² area being 1.6% of the 5.65 ha catchment; with a depth of ~1.0-1.5 m; and tall growing native sedges (40-50% cover), interspersed with sprawling emergent herbs and grasses (20-30% cover) and floating leaved and submergent plants and free floating plants. The embankments were planted in flax (Tanner & Sukias 2011).

For Titoki wetland the ground was excavated 1 to 1.5 m into low permeability clay subsoils. Original topsoil (50-200 mm depth) was returned to the base of the wetland as a growth medium and source of organic matter for denitrifying bacteria. The upper sediment trap water depth is 0.4 and 0.8 m; with an average wetland depth of 0.3 m (Tanner & Sukias 2011).

Nitrate-N loads (54-82 kg/ha) were reduced seasonally by a median of 68% for spring-summer and 49% for autumn and winter (Figure 24) which places the

¹⁷ Tony Gray, ECan, kindly provided provisional flow data for 66409 Cam River at Youngs Road. For the period 16-06-2010 to 06-02-2017 the median flow was 1,322 L/s; the maximum 33.58 m³/s, and minimum 641 L/s.

¹⁸ Reported NNN concentrations were combined with estimates of streamflow. The only site with several years of streamflow record is the Cam River at Youngs Road. Median flow values were estimated for the ECan water quality sites by prorating by catchment areas and the median flow for the period of record at Youngs Road. As noted in footnote 1 catchment area delineations are problematic in this type of environment.

Titoki constructed wetland at 1.6% of the catchment area at or above the upper performance band in Figure 23.

Annual nitrate-N loads at Titoki (54 to 82 kg/ha) are far in excess of the estimated yields from the Brooks and Cam River (Cam at Marsh Road ~11 kg/ha/year; Cam at Bramleys Road ~10.5 kg/ha/year; North Brook ~7.4 kg/ha/year and South Brook ~24 kg/ha/year).

Streamflow was highly variable in the irrigated Titoki catchment with dairying, but flow information is not available. As noted by Tanner & Sukias (2011) more attenuated and sustained flow rates will enhance treatment performance. Therefore the expectation is that with spring-fed streams, such as the Three Brooks and upper Cam, coupled with smaller input loads and relatively constant water temperatures, trapping and treating in constructed wetlands would reduce significantly nitrate-N loads.

For constructed wetlands the major issue is the drainage area size, hence wetland construction cost and lost opportunity cost for productive land. For example, South Brook is a critical source of nutrients of the Three Brooks and upper Cam River. To treat the whole of South Brook based on the Tanner et al. (2010) guidelines requires a ~260,000 m² wetland (~160 m wide and 1,200 m long). This is larger than the Rangiora water treatment plant, so is clearly impractical.

In order to target treatment areas, macrophytes were used as an indicator of excessive nutrients. Emergent macrophytes exceeded LWRP outcomes (with greater than 30% cover) in the upper South Brook and two tributaries (Appendix 3). The smaller tributary (at Townsend Road) has a catchment area of approximately 13.5 ha. A constructed wetland of 1% of the catchment area, has a footprint of 1,350 m². Lehmans Road tributary drain is significantly larger: ~70 ha (and ~1,350 m in length) for a 1% wetland footprint of ~7,000 m².

An elongated shape with inflow and outflow at opposite ends promotes even flow and avoids short circuiting or dead zones to maximize efficiency. Tanner et al. (2010) recommend a length to width ratio of 3:1 to 10:1 for small wetlands (<1,000 m²) and 3:1 to 5:1 for large wetlands (>1,000 m²). At a 5 times length to width ratio, the Townsend wetland would be ~16 m wide and ~85 m long; and Lehmans wetland ~37 m wide and 190 m long.

Construction would involve considerable excavation as the existing drains are relatively narrow (0.6 m to 2.5 m water surface) with moderate banks angles (31-60°) in the lower reaches. The estimated volume of removal is ~1,100 to ~1,600 m³ for Townsend and ~6,500 to ~9,500 m³ for Lehmans (depending on bank height). Based on estimates discussed in section 6.1.1 In channel sediment traps, an indicative cost for the excavation and disposal is ~\$8,000 to ~\$11,000 for Townsend and ~\$45,000 to ~\$66,000 for Lehmans. Planting costs would add an estimated ~\$7,500 to ~\$11,500 for Townsend and ~\$38,500 to ~\$60,000 for Lehmans.

While these constructed tributary wetlands could probably significantly improve water quality in South Brook, spending this amount is not recommended for the following reasons:

- It would be more cost effective to address the cause of the problem; and
- Where the cause is not apparent, a more targeted approach is warranted.

In the case of Townsend Road tributary there is stock access from the right bank for ~300 m, and from both banks for ~200 m of the ~500 m long stream. Around 700 m of fencing is required to exclude stock. The recommended approach is as follows:

- Enforce the NRRP requirement for stock exclusion from designated waterways - Lehmans drain is identified in Planning Map A.¹⁹
- Fine sediment resuspension and dispersion downstream would be addressed with the recommended sediment trap at the mouth of Townsend tributary.

It is not clear what causes excessive macrophyte growth and excessive fine sediment cover in Lehmans Road drain. There is no stock access to the drain, but ECan mapped three tributary drains that flow into Lehmans Road drain. Further investigation is warranted to determine cause, and examine if small wetlands would be viable for the small tributary drains. Three potential locations are suggested based on the ECan minor tributary locations in the Lehmans Road drain (Figure 5).

The efficiency of the proposed Lehmans Road tributary drain constructed wetlands should be evaluated. A staged approach is suggested. As a first stage, the recommendation is to construct small wetlands based on Titoki, but scaled to the channel dimensions rather than the percent catchment area guide (Figure 23). Reasons include:

- The catchment areas are difficult to accurately determine;
- Drain sizes are proportional to design flows;
- Nutrient loads are probably much smaller than Titoki; and
- Efficiencies may be greater than Titoki because of the spring fed source.

As for Titoki (Figure 22), it is recommended to construct a sediment trap at the inflow to the wetland. Assuming a 1 m wide drain, for the sediment trap widen the channel to 1.5 m over a length of 10 m, and lower the bed ~750 mm. For the wetland, widen the channel to 5 m over a 25 m length, partially infill with topsoil as a growing medium, and constrict the downstream end to provide a low flow water depth of ~300 mm. Plant an assemblage on the edge of the sediment trap and wetland, and plant the wetland with sedges and other plants as for the Titoki wetland.

The cost would be relatively modest and will provide a learning experience for further small wetlands. The major costs are for planting the wetland (~\$700-\$1,000 for 125 m² of planting at \$5.50 to \$8.00 /m²) and bank edge planting (~\$200-\$300 for 35 m of channel). Excavation of ~100 m³ is possibly required at \$4.00 /m³ for excavation, \$2.0 m² nearby spreading (~250 mm depth) and grassing (400 m² at \$1.00). The total indicative cost is ~\$1,300 for excavation and least cost planting, to ~\$2,400 for excavation, off-site soil levelling and seeding and higher cost planting.

Seasonal monitoring of nutrient inputs and outputs would be required if this is to be learning experience. After a few years, once local performance is better understood, the applicability of small constructed wetlands should be reviewed for possible further installation.

6.1.3 Bioreactors

Bioreactors have been shown to be effective in stripping nutrients. For example, Robertson & Merkley (2009) placed wood chips under a gravel veneer in excavated stream channels in the Avon River, southern Ontario, Canada; and

¹⁹ <http://canterburymaps.govt.nz/maps-apps?q=%5bcategory%3aPlanning%5d&page=3&orderby=MostRecent> Accessed March 2017.

Christianson et al. (2012) undertook long term tests of large off channel bioreactors in the US Midwest.

In the excavated Avon Stream channel the 40 m³ reactor reduced mean nutrient loading (Nitrate-N) from 4.8 mg/L to 1.04 mg/L over a period of 1.5 years. Almost complete removal occurred when effluent temperature was >10°C with lower efficiencies at effluent temperatures as low as 2 to 4°C (with ice cover). Robertson & Merkley (2009) noted a decrease in dissolved oxygen downstream and fine sediment deposition limiting efficiency. They proposed staging reactors downstream if DO was an issue and incorporating a sediment trap. Costs are not cited, it was merely noted the costs were for excavation of the 40 m³ reactor, the woodchips, and placement of gravel.

Nitrate N loading is similar in the Avon Stream to the upper quartile range of Canterbury lowland streams (Meredith and Hayward 2002); but the Avon flows are very small, with resulting reactor attenuation of only 66 kg N/year. This would suggest bioreactors would have to be much larger than 40 m³ to significantly attenuate nutrient concentrations in the Three Brooks (e.g. North Brook 4,400 kg/year).

Experiments are being undertaken in lowland stream in Canterbury using untreated pine woodchips to provide long term denitrification in conventional bioreactors (CAREX Newsletters May and September 2015) and with bags of woodchips placed in four streams (December 2016). Costs and effectiveness have not been reported for the CAREX experiments.

6.1.4 Conclusions: trapping and treating

In channel sediment traps have proven performance and their wide spread use is recommended (Figure 5), at least until catchment management significantly improves and legacy sediment are removed from waterways. Several locations were recommended and more details on trap locations are provided in the next sections.

Costs of traps are proportional to channel size, with a hypothetical conventional but shallow trap (750 mm) design for a 2 m channel base and 1.5 m bank height. Indicative costs range from ~\$1,000 for excavation, no cost disposal, and bank planting to ~\$2,000 for excavation, off-site disposal, levelling and seeding, and bank planting. Shallow traps are recommended to limit construction costs while rates of infill are established. The traps may suffice, or require more frequent cleaning, or possibly enlarging. Time will tell.

It is probably cost effective to target tile drain outfalls for mini wetland treatment. Some of these mini wetlands could be created by minor excavation, bank reshaping and planting in the drain itself. Sites are suggested in Figure 5), but their use is considered experimental, with monitoring required to determine efficiencies. Costs would probably range from ~\$1,000 for excavation, no cost disposal, and low cost planting to ~\$1,300 for excavation, off-site disposal, levelling and seeding, and high cost planting. Cost could possibly be lower for wetlands created as part of routine drainage operations.

Large scale conventional constructed wetlands are expensive and are not recommended at this stage. It is far more effective to control excessive generation and delivery of contaminants than to construct treatment wetlands (1-2-5% of the catchment area) for larger streams. However, given the relatively low levels of nutrients and steady flows in the Three Brooks, smaller trial constructed wetlands are recommended in three Lehman's Road drains at an indicative cost of \$1,300 to ~\$2,400 each. After a few years, once local performance is better understood, the applicability of small constructed wetlands should be reviewed.

Simple bioreactors – channel excavations with woodchips and gravel overlays – can significantly reduce nutrient levels at low flow rates, but scale may be an issue. Local cost and performance information is required before they can be recommended. For the purpose of experiments with bioreactors, they could be placed at the downstream end of the sediment traps (Figure 5).

The use of bags of woodchips, as flow deflectors, would be a simple, relatively inexpensive, approach to remove nutrients and increase habitat diversity. These could be placed opportunistically in the upper South Brook where abundant macrophyte cover is indicative of high nutrient availability (Figure A3: 2G); but their performance with relatively large streamflow's is uncertain.

6.2 Sediment removal from the stream channel

Excessive fine sediment on and within the bed is recognised as a significant impediment to aquatic health (Clapcott *et al.* 2011). Therefore previous reports recommended cleaning legacy and contemporary fine sediment (<2 mm particle size) from the surface of the bed and from within the bed itself (interstitial fines).

Three instream sediment removal techniques have been used in the Three Brooks, Cam and Tuahiwi Drain:

- Excavation;
- Sand wand™; and
- Bed raking.

6.2.1 Excavation

For decades the conventional means of cleaning weeds and sediment from New Zealand drains is with an hydraulic excavator (Hudson & Harding 2004). A digging bucket (with teeth to penetrate hard soil and rock) is often the default, although a cleanup bucket (a digging bucket without teeth) may be used for soft or well loosened material (e.g. Figure 25 top). Excavation is often undertaken from the bank (sometimes with a long reach excavator), but for wider, or less accessible streams, excavation may be undertaken from within the channel (Figure 25-bottom). Sediment is often scooped out of the drain and spread adjacent to the bank; or temporarily stockpiled for dewatering prior to offsite use; or in some instances loaded into to dump trucks with liners (to contain the slurry of material) for offsite disposal.

As noted by Greg Bennet, WDC Land Drainage Engineer (footnote ¹³), standard drain cleaning rates are \$1.60 per linear metre, plus disposal if material can't be placed adjacent to the channel (e.g. Figure 25 top). This rate, or similar, would be applicable to a large portion of the Three Brooks, upper Cam and Tuahiwi Drain. The relatively low cost is related to long term, not one off, contracts.

Larger watercourse require long reach excavators, draglines, or work from within the channel to excavate bed material (e.g. Figure 25). Large scale excavation costs were estimated at \$4.00 /m³, plus \$2.00 /m³ to move and level on an adjacent site, and \$1.00 m² for hydroseeding in the Kaiapoi River (Fletcher & Hudson 2016).

6.2.2 Sand wand

Gray (2013) undertook a comprehensive review of a new tool - the Sand Wand.™ He notes the wand uses a combination of water jet and suction to mobilise and suck up a slurry of fine sediments beneath an enclosed hood. Practitioners manually move the equipment across the stream bed using a rocking motion moving parallel to flow. The arrangement of pumps relative to the

hood depends on the topography of the stream. Slurry can be discharged to land or into sediment separating equipment. The setup is illustrated in Figure 28. It was noted that in two trials negative environmental effects can be mitigated and are not long lasting. Protocols are recommended for habitat restoration as a discretionary activity requiring resource consent.

In Middle Brook, the CAREX team used a sand wand to clean out the sediment traps and a 10 m section of 2.5 m wide stream. They reported the sand wand was effective at reducing fine sediment cover from ~40% to 10-20% cover from depositional environments (pools and the sediment trap), but not from shallow water (<20 cm deep i.e. riffles). They note the wand is labour intensive and the removed sediment needs to be disposed elsewhere. Time and cost is not reported.

Taylor & Marshall (2013) addressed the issue of shallow water by construction of a temporary sandbag weir. They report it took 2 operators 3 hours of instream time to clean thick liquefaction fine sediments over a 15 m length of the ~4 m wide Wairarapa Stream, Christchurch. 1,350 kg of wet silt (22 kg/m²) was removed. They believe they could achieve cleaning of 60 m of 4 m wide stream in a day for a labour cost of ~\$450 for three workers. Machine costs are not reported (e.g. hire, fuel, maintenance). This equates to ~\$2.00 /m². Current labour costs are likely to be higher, so a ball park cost of \$3.00 /m² is used.

Gray et al. (2013) report the sand wand is highly effective in removing fine sediment from the upper 10 cm of the stream bed in Otukaikina Creek (old South Branch, Waimakariri River) (Figure 29). Sediment cover decreased from ~70% to ~5% with the trial, but this was short lived as sediment was delivered into the trial reach and deposited. After 6 weeks the trail reach increased to ~45% fine sediment cover, but further downstream cover decreased.

The Otukaikina Creek trial emphasises several very important points:

- Bed restoration is futile if upstream sediment sources are not controlled;
- Sand wands can clean fine sediment from the bed;
- Removing fine sediment deposits can result in downstream fine sediment cover reductions;
- The sand wand is not very effective at deep cleaning (>100 mm); and
- The work is labour intensive, and slow, with the expectation of cleaning perhaps a couple of hundred square metres per day.

Gray et al (2013) noting the importance of clean substrate at depths greater than 100 mm note: "Potential improvements to stream restoration techniques which involve the removal of fine sediment from deeper substrates would be a suitable topic of further investigation." In this regard, bed raking was proposed by Hudson (2010).

6.2.3 Bed raking

Bed raking was proposed by Hudson (2010) based on observations of hydraulic excavators cleaning drains and extracting sand and gravel from river beds (Figure 25). The proposition was that standard hydraulic excavator digging buckets with teeth could be used to push around gravel to create habitat diversity (pools and riffles) and in doing so promote the downstream flushing of fine material from within and on the stream bed.

This idea was encouraged by the availability of a modified land clearing rake for cleaning aquatic weeds in the District. The rake was constructed by a local contractor in collaboration with WDC (Figure 26). The rake is routinely used to clean weeds while allowing stream fauna to pass through with minimal bed

disturbance (Bennett 2012). It was thought that the rake could be used as a ripper to deeply penetrate the bed to release fine sediment and to push around gravel to create habitat diversity (pools and riffles).

Protocols need to be developed (as for the sand wand – Gray 2013), including:

- Effective operational procedures, for example:
 - remove surficial fine material from the channel edges and mid channel using a digging bucket or suction dredge;
 - disturb the bed to remove interstitial fines by bed raking or water blasting with the sand wand; and
 - if using a digger bucket or bed rake, push bed material around to create shallow pools and riffles (this could be undertaken as part of the bed disturbance above);
- Effective environmental controls (e.g. trapping disturbed fines further downstream behind a temporary silt barrier, straw bale or sand bag weir); and
- Appropriate disposal of fine sediment (e.g. spread on adjacent land as nutrient rich soil or stockpiled and disposed offsite).

Initial removal of fine sediment drapes, could be undertaken with a digging bucket or suction dredge (essentially a pipe connected to a centrifugal pump that sucks loose sediment off the bed and disposes through a pipe). A sand wand (discussed above) could also be used, but there is no real need to utilise a water jet to mechanically loosen the fine sediment. Removal of material from the sediment trap may be undertaken with the digger, suction dredge or sand wand. This cleaning would probably occur immediately for temporary traps, but as part of routine drainage maintenance for permanent sediment traps.

Bed raking was undertaken in the Middle Brook CAREX reach for ~180 m upstream of the CX-01 trap (Figure 5; Appendix 4). In this reach ECan report a fine sediment cover of 41-60%. Some months later I found confined sections of the reach had exposed gravel, and the margins and weed beds had fine sediment drapes (Figure 27), whereas further upstream the bed has bank to bank fine sediment cover. This suggests bed raking was successful, but long term success requires control of upstream sediment inputs.

WDC undertook bed raking in upper South Brook ~300 to ~700 m downstream of Lehman's Road (Appendix 4). Results have not been reported, other than to state that the South Brook bed was hard and the raking was not very effective. The bed in this reach is described by ECan as "very fine" substrate with 80-100% fine sediment cover. More information is required to understand what was used, how it was used and what occurred with bed raking.

At this stage it is unclear where bed raking can be successfully undertaken and how to undertake bed raking (i.e. operating procedures for different conditions). There is also a lack of rigorous quantification of the effectiveness of bed raking (i.e. before-after-control-impact-paired differences (BACIP) and habitat creation:

- Experiments are required to develop protocols, and quantify the extent and depth of fine sediment surface cover and interstitial fine sediment content at various depths in the bed before and after treatment.
- Further, the optimum channel profile for pools and riffles has to be determined so that flushing of sediment occurs in freshes. Low flow pool depths of ~300 mm, with riffle depths of ~100 mm would provide habitat diversity for many aquatic species.

What is known is that extensive reaches can be raked in a relatively short period, with apparent reductions in fine sediment cover, and possibly interstitial fine sediment. Costs are not reported, but would probably be in the range for routine drain cleaning (~\$1.60 per linear metre for small waterways) to remove fine sediment drapes; with a similar additional cost to disturb the bed to release interstitial fines and create pools and riffles.

Given the potential to clean large reaches at relatively low cost in a short period, a rigorous appraisal of bed raking is warranted in conjunction with using bed raking to create habitat diversity (i.e. pools and riffles ~7-10 channel widths apart). Test reaches are suggested below.

6.2.4 Bed clearing locations and costs

Removal of fine sediment deposits from on and within the streambed would probably be beneficial at most locations in the Three Brooks, Cam and Tuahiwi Stream. However, it is considered futile, and not cost effective, to clean a reach only for the reach to be inundated by fine sediment from upstream. The preferred strategy to deal with this is relatively simple:

- First, stop the excessive contribution of fine sediment into waterways by controlling critical source areas such as bank erosion;
- Second, progressively clean the bed from spring head downstream; and
- In the event upstream bed cleaning is not possible, and/or if sediment delivery into the upstream waterway cannot be controlled, then the flux of material into the rehabilitation reach must be controlled with sediment traps at the head of the reach.

Indicative costs are based on excavation costs for drainage maintenance (\$1.60 per linear metre for small drains)¹³ and sand wand costs reported by Taylor & Marshall (2013) from Wairarapa Stream which are revised to \$3.00 per square meter of stream bed to allow for increased labour costs and some equipment cost.

Sand wand removal of fine sediment on and in the bed is a one pass process. Removal of fine sediment drapes with a cleanup bucket or digging bucket is also a one pass process and is a prerequisite for bed raking. A second pass is required to rip the bed and create pools and riffles. A change in equipment for the hydraulic excavator is required – from a cleanup bucket to a digging bucket or rake. The second pass is expected to be a similar cost to the first pass for the hydraulic excavator. For larger streams, and for offsite disposal of fine sediment, costs are greater as noted earlier.

Fine sediment removal costs have to be verified as protocols are developed. It is assumed that a global consent is in effect that permits these activities following specific protocols. Options, and ball park costs, include:

- Sand wand removal of surface and shallow subsurface fines (~100 mm) ~\$3.00 /m²;
- Hydraulic excavator removal of surface fine sediment ~\$1.60 /Lm; and
- Hydraulic excavator disturbance of deep subsurface fine material (~300 mm) by ripping the bed and creating pools and riffles ~\$1.60 /Lm in addition to the removal of surface fines of ~\$1.60.

In terms of locations, the ideal place to start remediation of excessive fine sediment deposits is in the headwater streams of the Three Brooks, specifically North Brook and South Brook. For the time being, activities in Middle Brook should be avoided so as to not interfere with the CAREX research. South-South

Brook is probably in the too hard basket – with limited opportunity for rehabilitation – hence for at least the medium term – emphasis should be on stopping downstream impacts with a mouth sediment trap - linear wetland.

The upper part of North Brook from the water races west of Rangiora and spring heads within the upper portion of the town, were not surveyed by ECan. Periodic drain maintenance occurs in this reach and future works are proposed for stormwater management at Dudley Park (Appendix 4). Bed clearing should be undertaken opportunistically with routine maintenance and with the proposed stormwater management at Dudley Park. Temporary sediment traps should be employed to control downstream flux of fine sediment into Northbrook ponds.

Downstream of Northbrook ponds (ST-ponds in Figure 5) to Boys Road, the bed has less than 20% fine sediment cover, but is potentially under threat from downstream flushing of fine sediment from Crayfish Creek which has 80-100% fine sediment cover. While it is tempting to remove extensive fine sediment from this headwater stream, it may be prudent to avoid interference (Table 2).

Crayfish Creek is managed by WDC as a high value site because of the presence of koura (freshwater crayfish). Removing excessive fine sediment deposits may not be helpful for koura – of overriding importance is cover, such as tree roots, undercut banks, leaf litter and wood, relatively shallow depth and low velocity pools (<0.4 m/s) (Jowett et al. 2008). Substrate is important between streams but not within streams, with young being associated with fine substrate and adults with cobbles.

The recommended action is to control downstream sediment flux from Crayfish Creek with a sediment trap (Figure 5). Taylor & McCaughan (2012) noted fine sediment discharging into Crayfish Creek from North Brook road drain. A sediment trap is also recommended to control this influx.

A tributary entering North Brook ~100 m upstream of Boys Road is largely 80-100% fine sediment covered, with the potential to flush into a clean segment of North Brook. The recommended action is to control downstream sediment flux from this tributary with a sediment trap (Figure 5) and to undertake sediment removal over the ~830 m spring head reach of the tributary. Also, to control surface erosion, the overland flow path shown in Figure 7 should be grassed (e.g. as in Figure 6).

This tributary varies in width. Above Northbrook Road the tributary is in the 0.6-1.5 m wetted width category; and downstream the wetted width of the lower ~400 m is generally in the 1.6-2.5 m wide category (Appendix 3). The surface area to be cleaned is approximately 1,250 m². Indicative costs for the three sediment removal options are as follows:

- Sand wand removal of surface and shallow subsurface fines (~100 mm) ~\$3,750;
- Hydraulic excavator removal of surface fine sediment ~\$1,350; and
- Hydraulic excavator disturbance of deep subsurface fine material (~300 mm) by ripping the bed and creating pools and riffles an additional \$1,350.

Fine sediment removal is recommended over the ~1,000 m North Brook reach from Boys Road to Marsh Road where the bed cover is 61-80% fine sediment. Trout spawning is limited in this reach, because of fine sediment cover (Taylor 2005). The channel is in the ~2.6 to ~4 m category (Appendix 3), with wetted width measurements frequently at the top end of this range (Google Earth); hence the surface area is probably ~4,000 m². Ball park costs are:

- Sand wand ~4,000 m², ~\$12,000;

- Excavator surface removal ~1,000 m, ~\$1,600; and
- Excavator rip and contour an additional \$1,600.

A sediment trap has been proposed for North Brook at Marsh Road which would control flux into the clean reach that extends to the confluence with South Brook. This trap would be cleaned as part of routine drainage maintenance.

Upper South Brook has patches of heavily sediment (80-100% fine sediment cover) to relatively clean bed (<20% fine sediment cover). The narrow, heavily sedimented, ~375 m spring head reach, is a priority: Ball park cost are:

- Sand wand ~600 m², ~\$1,800;
- Excavator surface removal ~375 m. ~\$600; and
- Excavator rip and contour an additional ~\$600.

The remaining ~1,500 m of upper South Brook consists of 21-40% to 80-100% fine sediment cover, in a narrow channel (~1.5 m wetted width). Brown trout spawning was observed in this reach (Taylor 2005). It is recommended that tributary inputs are controlled with sediment traps and drainage wetlands as discussed earlier. Ball park cost are:

- Sand wand ~2,250 m², ~\$6,750;
- Excavator surface removal ~1,500 m, \$2,400 (but access may be limited in sections with trees); and
- Excavator rip and contour an additional \$2,400.

WDC described bed raking as not very effective in the most heavily sedimented section of this reach where the bed was described as hard. The effectiveness of the sand wand and bed raking could be compared in upper South Brook with an objective being to develop operating procedures for difficult conditions. If half the reach were cleaned with the sand wand; and half with an excavator undertaking cleaning, ripping and contouring, the estimated cost is ~\$6,000; plus supervision and reporting.

For the inchannel cleanup, temporary sediment traps are recommended. These temporary sediment traps could be constructed with overlapping silt fences or straw bales at a cost of ~\$250 installed. The traps would be cleaned out at the completion of the channel clean up to stop downstream flux of fine sediment. Cleaning of the trapped sediment could be undertaken with the sand wand as part of the overall estimated cost of the channel works.

Lower South Brook, from below the water treatment plant, past Middle Brook and South Brook confluences to the junction with the Cam, is a distance of ~1,800 m. This reach is moderately sedimented (21-60% fine sediment cover). Taylor (2005) did not observe brown trout spawning in most of this reach, which may in part be attributed to lack of habitat diversity and fine sediment on and in the bed.

With channel width ranging from ~1.5 to ~5 m (median 3.0) (Google Earth), the bed area to be cleaned in lower South Brook is ~5,400 m². The cost for sediment removal probably increases from normal drainage cleaning rates because of the channel size. Cleaning rates are assumed to double. Ball park cost are:

- Sand wand ~5,400 m², ~\$16,000;
- Excavator surface removal ~1,800 m, ~\$5,800; and
- Excavator rip and contour an additional ~\$5,800.

A sediment trap at the mouth of Middle Brook would control sediment coming into South Brook while CAREX operations are underway. Sediment from the bed disturbance in lower South Brook would be trapped at the confluence of the Three Brooks and Cam River (Figure 5).

For the Cam River mainstem, the focus of this review is the reach between Marsh Road (km 9.4) and Bramleys Road (km 6.5). However, context is important. In this regard, while the spring head reach is relatively clean, much of the Cam above the Three Brooks and Marsh Road has 81-100% fine sediment cover. Downstream of the Three Brooks to Bramleys Road there is a sub-equal mix of the 0-20% to 61-80% fine sediment cover (Figure 5).

To protect the higher quality reaches from upstream resuspension and transport of fine sediment, sediment traps are recommended on the Cam near Boys Road, Marsh Road, near the Three Brooks confluence, and at the South-South Brook confluence (the latter combined with a wetland). In addition, drainage wetlands are proposed at several sites (Figure 5).

In terms of fine sediment removal in the Cam mainstem, the preference would be to start in the spring fed headwaters. Failing that, fine sediment removal is recommended in the reach below the Marsh Road sediment trap to Bramleys Road.

From Marsh Road to the Three Brooks confluence, the Cam is narrow (1.6-2.5 m category Appendix 3). For an average wetted width of ~2 m, the ~950 m of channel has 80-100% fine sediment cover. For this reach, ball park estimates to remove fine sediment are:

- Sand wand ~2,000 m², ~\$6,000;
- Excavator surface removal ~950 m, ~\$1,500; and
- Excavator rip and contour an additional ~\$1,500.

Below the Three Brooks to ~300 m above Youngs Road, the Cam is sub equally 21-40% and 41-60% fine sediment cover. This reach was utilised for trout spawning (Taylor 2005) therefore may be a lower priority for removal of fine sediment. The wetted width is classed as 4.1-7.0 m (Appendix 3); with aerial photographs often showing a wetted width of ~7.0 m (Google Earth).

Over the ~670 m reach, with an average width of ~7.0 m, an area of ~4,700 m² could be cleaned. A sediment trap is proposed at the lower end to control sediment flux into the clean bed reach (<20 fine sediment) that extends ~300 m upstream and ~300 m downstream of Youngs Road (Figure 5). A ball park cost to clean this reach is based on triple the routine drain clearing rate because of channel size:

- Sand wand ~4,700 m², ~\$14,000;
- Excavator surface removal ~670 m, ~\$3,200; and
- Excavator rip and contour an additional ~\$3,200.

The ~700 m reach from above Youngs Road to above Power Road has <20% fine sediment cover. Fine sediment removal is not required. The reach would be protected with the recommended sediment trap on the Cam River above Youngs Road, the South-South Brook sediment trap and the drain wetland on Youngs Road (Figure 5). The bed in this reach is relatively narrow (classed as 1.6-2.5 m in Appendix 3).

Immediately downstream of the clean bed reach around river km 7.13, the wetted width widens to 4.1-7.0 m (Appendix 3); averaging around 6.5 m (Google

Earth). Here the bed has 61-80% fine sediment cover for the ~660 m reach to Bramleys Road, with 80-100% fine sediment cover beyond the study reach to Revells Road (Figure 5) (and further downstream through the tidal reach – Hudson 1999). A ball park cost to clean this reach is based on triple the routine drain clearing rate because of channel size:

- Sand wand ~4,600 m², ~\$14,000;
- Excavator surface removal ~660 m, ~\$3,200; and
- Excavator rip and contour an additional ~\$3,200.

Enhancement of a natural inner bend sediment trap is proposed ~300 m downstream of Bramleys Road (km 6.54). This will trap some fine sediment entering the lower tidal reach. Upstream tidal flux appears to stop around Revells Road (river km 4.85).

A number of actions were proposed for Tuahiwi Drain, including fine sediment removal (Hudson 2013; Appendix 5). The bed is almost exclusively 100% covered in thick sediment drapes. Sediment traps are recommended to control flux into the Cam River. However, the minutes of the Cam River Enhancement Fund Subcommittee, dated 30 July 2015, note:

- The use of the fund for mahinga kai restoration in the Tuahiwi (Maori) Drain is not supported by Ngai Tuahuriri. This is because the establishment of new mahinga kai areas in this drain is unlikely to be effective given the extent of legacy sediment and degradation.
- The Runanga view is that enhancement of existing remnant mahinga kai populations (particularly koura) should be a priority. This includes: a) an area just upstream from the Revells Road bridge; b) the area along Cox Road; c) the area between Boys Road and Marsh Road; d) the side tributaries of the Middle Brook; and e) the Crayfish Creek tributary to the North Brook

Regarding the latter, the first two reaches are out of the study area; and Middle Brook is the CAREX test bed and was not considered further in this report. It was recommended that Crayfish Creek be protected from sediment inputs from a tributary drain, but that drapes of fine sediment are not removed from the bed because of potential adverse effects on koura.

6.2.5 Conclusions: sediment removal

Extensive drapes of fine sediment occur through the Three Brooks and Cam River. Surface deposits can be effectively removed with hydraulic excavators at low cost (~\$1.60 per linear metre for drain and small streams). Surface fines and shallow (~100 mm) subsurface fines can be effectively removed with a sand wand at an estimated cost of ~\$3.00 per square metre. Bed raking (ripping the bed) has the potential to loosen and flush fine sediment from deeper in the bed (~300 mm) and to create habitat diversity (e.g. pools and riffles) for a similar cost to routine drain cleaning (an additional \$1.60 /Lm for small streams). It is envisioned that bed raking-habitat creation can be undertaken once surface sediment was removed.

Extensive removal of surface and subsurface fine sediments has been recommended, with indicative costs for selected reaches, for the three approaches:

- The least cost approach is to remove the surface deposits of fine sediments with an hydraulic excavator. This may be sufficient to improve habitat quality significantly, but this is not rigorously quantified. If this were the only approach used, the reach length of recommended cleaning

is ~7,800 m; for a cost of ~\$20,000. This is greater than the \$1.60 /LM because some reaches are relatively wide and costs may increase by a factor of two or three;

- Sand wand fine sediment removal is effective in removing surface material and shallow subsurface fines (~100 mm). Improvements in habitat quality have been documented. If all the channels were cleaned by the sand wand (~7,800 m; ~25,000 m²), the ball park cost is ~\$75,000; and
- Bed raking is proposed as a two stage process. The first pass is to remove fine sediment surface deposits at a cost of \$1.60 /Lm for much of the study area. The second pass would double the cost and would rip the bed to a depth of ~300 mm and push around bed material to release interstitial fines and create pools and riffles. If all the channels were treated, and an allowance is made for increased costs for wider channels, the ball park costs for cleaning and diversifying a ~7,800 m length of channel with an areas of ~25,000 m², a ball park estimate of the total cost is ~\$40,000.

There are three significant issues:

- There is a lack of rigorous quantification of the effectiveness of bed raking (ripping the bed) and no reporting of using hydraulic excavators to push around bed material to release interstitial fines and create pools and riffles;
- Recommended protocols need to be tested and refined as required; and
- A global resource consent, with appropriate resource consent conditions, is required to facilitate habitat rehabilitation.

As a way forward, and in the spirit of adaptive management and continual learning, the recommendation is to work with all conventional excavator clearing, sand wand and bed raking. The first two are well understood. Bed raking is definitely experimental, and comprehensive trials of a two-step approach for fine sediment removal with an hydraulic excavator are recommended based on potential. This is considered a worthy investment because if bed raking proves to be effective environmentally and cost wise, it may be widely utilised in the Three Brook, Cam River and elsewhere.

6.3 Bank stabilisation, bed and bank reshaping

6.3.1 Bank stabilisation

Previous investigations noted there was little evidence of significant contemporary mainstem riverbank erosion in the Cam River catchment.²⁰ Hudson (1999) reported the major sediment sources were upland soil erosion (from farmland and subdivisions) and streambed erosion (re-suspension). Although the quantity of material derived from bank erosion may be of lesser importance than other sources, bank stabilisation is a prerequisite for successful control of bank erosion and riparian planting (Figure 11), and control of bank erosion will improve habitat by reducing local deposition of sediment in the channel.

²⁰ Golder Associates (2008) examined bank erosion in the North, Middle and South brooks. They noted the stream channels at their sampling sites were typically incised, with steep banks. However, active bank erosion was relatively uncommon. Notable exceptions were site N7 in a tributary of North Brook which had active bank erosion along the entire reach, and M2 in the upper Middle Brook where bank slumping and erosion were prevalent.

ECan's mapping has identified places with conspicuous bank erosion (e.g. Figure 8, Figure 9 and Figure 10). These sites are discussed previously with respect to stock damage and stream bank erosion and overland flow paths (Appendix 3). Three sites were identified in the upper Cam, three sites on North Brook, one site on Middle Brook, six sites on South Brook and two sites in Tuahiwi Drain.

ECan kindly provided photographs of several of these sites which were useful in determining the magnitude of the erosion problem. These photographs documented a few additional and/or miscoded sites such bank collapse identified as an overland flow path for North Brook R5-R6 (Appendix 3).

The photographs and context (Google Earth) suggest localized scour is occurring, generally in bends, as expected. To determine the nature of the bank erosion, site inspections are required. But in terms of magnitude, at individual sites, bank collapse or scour is occurring over several metres, perhaps up to 20 or 30 metres; and the banks are generally quite low (1-2 m).

In terms of recent bank reshaping works, Greg Bennett, WDC, noted costs of \$5.00 per linear metre for 1 m high banks with a 1:1 to 1:2 batter, plus disposal of material if adjacent uses could not be found.¹³ Riparian planting costs were cited as \$20 per linear metre or \$8-\$10 per linear metre for a single row of carex.

Assuming an average length of 20 linear metres, bank reshaping is estimated to cost ~\$100 (plus transport to site and any disposal cost); and riparian planting ~\$400. Therefore, the 15 identified sites could be reshaped and planted for ~\$10,000 to \$15,000.

Other bank reshaping and planting is discussed in section 6.5 Riparian planting - buffers.

6.3.2 Two stage/compound channels

A hierarchy of actions can be undertaken to enhance highly modified and artificial waterways (Hudson (2000) reviewed the rationale for these channel modifications):

- Reshaping the channel by removing fine sediment drapes and shifting bed material to create shallow pools and riffles (as discussed above);
- Reshaping the channel from a flat-bed trapezoid to concentrate flow (to maintain a weed free corridor and flush fine sediments), and encourage trapping and treating of sediment and contaminants along the vegetated channel margins (Figure 30);
- Reshaping banks to create benches for wet edge and bank planting (Figure 31 & Figure 32); and
- Reshaping the bed and banks to create a "two-stage" channel to concentrate flow in a narrow low flow channel and trap and treat sediment and contaminants and provide more floodway capacity in the high flow channel (Figure 33).

The first option was discussed and costed in the previous section on removing sediment from waterways. The second option is a modification to this approach where the fine sediment is removed with a digging bucket, and gravel is pushed out of the channel onto the margins as part of creating shallow pools and riffles. This will deepen the channel (requiring resource consent unless a global consent is granted for this purpose) to concentrate flow and flush fine sediment from within the bed with the disturbance. To be conservative, and incremental cost of

\$1.60 per linear metre could be added to the stream cleaning cost discussed earlier.

Performance Standards

Hudson (2005) describes three drainage maintenance performance standards. In summary these are:

Hydraulic efficiency:

To maintain drainage outfall as cost effectively as possible, with a focus on how maintenance improves outfall to provide the required level of service, not how much drain was cleaned.

Agricultural productivity:

The value of various levels of hydraulic efficiency should be related to agricultural productivity, and maintenance geared to provide a cost effective level of drainage.

Environmental performance:

The focus is to meet sediment and water quality standards, conserve and protect flora and fauna, and manage for multiple purposes where appropriate.

On the channel margins fine sediment will over time accumulate as vegetation grows and trapping is enhanced. If sediment deposition reaches a point where channel capacity impacts the hydraulic **performance standards** (see text box), the sediment can be removed.

Reshaping banks to create a planting bench for (Figure 31) is discussed in section 6.5 Riparian planting - buffers. The ball park cost for excavation is ~\$1.00 to \$5.00 per linear metre (when undertaken with recommended sediment removal works), with a single row of carex secta costing ~\$8-\$10 per linear metre over short lengths.

Banks could be further reshaped by pushing material and vegetation into the existing channel ("bank sliding" in Figure 32). This would provide an edge buffer and constrict the stream. Marginal plants would be planted along the wet edge. Shrubs and trees would be planted upslope for erosion protection.

Bank sliding may be a viable option as part of the channel reshaping discussed earlier. The incremental cost of bank sliding is probably in the same ball park as drain cleaning (\$1.60 per linear metre). Planting costs would have to be factored in. Wet edge planting is estimated to cost \$5.50 to \$8.50/m² for large areas (Fletcher & Hudson 2016).

As discussed in Hudson (2005), significant increases in channel capacity can be achieved by multi-stage (compound) channel designs in unconfined streams (Brookes 1989; Brookes & Shields 1996; RRC 2002) and in restricted corridors in urban areas (Ellis & House 1994). Increasing the high flow channel width increases channel capacity, while retaining a relatively narrow low flow channel is essential for aquatic fauna. Works can be undertaken on the floodplain with minimal disturbance to the existing low flow channel (Brookes 1989). Similarly, bank reshaping can be used to increase channel capacity and to increase channel stability and suitability for vegetation control.

In the two stage channel illustrated in Figure 33, the overall channel corridor is somewhat widened (by about the bank height), upper bank slopes are steepened (if corridor width is limiting) and a bench is cut. As a result, the floodway capacity increases, which decreases the bank erosion potential of the waterway. The low flow channel supports aquatic life, and the shallow marginal bench accommodates flood flows and supports emergent and wetland plants in addition to providing locations for small linear ponds for habitat diversity and contaminant filtering.

Costs for significant works of this nature have not been estimated for a rural environment in New Zealand. However, in town, the Northbrook enhancement at Ward Park stream realignment, secondary channel benching and slope battering cost ~\$250 per linear metre (WDC, written com.).

A multi-stage channel design was employed in Ritobäcken Brook, Finland, which is a similar size to the Cam River Bramleys Road reach. The Brook required

frequent dredging, had very unstable banks causing erosion and sedimentation, had limited floodway capacity causing flooding and poor habitat (Restore 2013). The benefits were reduced flooding risk, bank stabilisation with vegetation, lower maintenance cost as dredging and vegetation management is no longer required, improved water quality and habitat. The cost for Ritobäcken Brook in 2010 was €15,000 with €2,500 planning cost for an 800 m length of channel. The extent of significant excavation is not specified. It is noted that the excavated bank material (2,500 m³) was transported to nearby arable land to fill in the lowest areas. This equates to ~\$30 per linear metre. Planting costs were not included.

6.3.3 Conclusions: bank stabilisation and reshaping

Bank stabilisation is recommended for the 15 eroding banks identified by ECan, with potentially a few other sites. Eroding banks are localized in extent. Assuming works are undertaken over an average 20 m length of bank, excavation and replanting could be undertaken for \$10,000 to \$15,000.

Extensive removal of surface and subsurface fine sediments has been recommended. If this were coupled with reshaping the channel from a flat-bed trapezoid to concentrate flow and create a frequently wetted edge, the incremental cost is estimated as \$1.60 /Lm. For the 7,800 m of bed recommended for cleaning this would cost ~\$12,500.

Bank sliding is an alternative approach to achieve a partial two-stage channel, with linear wetlands, but this has yet to be investigated in New Zealand. Uncertainties relate to bank stability following bank sliding and whether banks will revegetate naturally with desirable species or if planting is required. Testing is recommended. Excavator costs are estimated to be in the same ball park as drain cleaning (\$1.60 per linear metre); with wet edge planting costs of \$5.50 to \$8.50/m². Several test reaches, each of 100 m length, would have a ball park cost of ~\$1,000 per reach. If this proves cost effective and environmentally beneficial, the cost to undertake the remaining ~7,000 m of channel would be ~\$70,000.

Costs for a fully developed two stage channel are uncertain and should be investigated. A showcase trial is recommended, such as continuing stream rehabilitation from Railway Road to below Marsh Road on South Brook (~175 m); and/or North Brook at Marsh Road (~75 m upstream and ~75 m downstream). At tentative budget of \$50 per linear metre is suggested.

6.4 In channel habitat structures

The starting position is that the Three Brooks, upper Cam River and drains are highly modified, or artificial, and were designed to convey stormflow efficiently and to dewater extensive poorly drained soils usually in a flat bottom trapezoidal channel. Instream woody debris, logjams and snags are removed for hydraulic efficiency. As a result the waterways have poor very poor instream and riparian habitat.

As noted by Allibone & Hudson (2015), the objective is to create instream conditions that provide habitat for both the desired fish community, and also habitat for prey items for these species. This includes resting and feeding habitat, spawning habitat for some native species and migrations requirements. Taylor & McCaughan (2012) identify species of ecological importance, such as lamprey (clean gravels; marginal soft herbs in silt banks), longfin eel (bank refugia, overhead cover, clean gravel, pools and riffles), common smelt (no cover requirements), inanga (spawning occurs much further downstream), giant kokopu (logs, tree roots, overhanging vegetation), koura (soft sediment

waterways with stable banks for burrows), and brown trout and Chinook salmon (spawning gravels).

In addition to the pools and riffles discussed previously, that will address many of these needs, there are a variety of instream and bank aquatic habitat structures that would add diversity to the waterways. Two of particular relevance are large wood debris (LWD) and flow deflection structures (Allibone & Hudson 2015).

The restoration of LWD has become common in North American and also in Australia. These actions also recognise that if restoration is left to natural process the colonisation and growth of trees to a size that will provide LWD to rivers and stream is a process that will take decades or longer. Therefore, typically riparian plantings are undertaken to re-establish the bank side vegetation and tree trunks and stumps with roots wads are placed in the waterway.

To prevent flood events removing the LWD, the logs are partially buried in the stream banks and anchored by partial burial or rope tie downs. ECan has considerable expertise in this area.

Flow deflection structures include boulder clusters placed in the waterway, and wood or rock groynes extending from the bank downstream to form an open ended V shape, and channel constrictions (Figure 34). These structure act as partial dams while still allowing fish passage, raise water levels and creates fast sections of flow and provide habitat and detritus. CAREX is investigating these structures in lowland streams and may provide estimates of cost and effectiveness.

It is recommended that these options are discussed by the Cam River Enhancement Subcommittee.

A significant element of the proposed rehabilitation is with habitat improvements in the riparian zone and the infall of plant material – leaves to whole trees to provide food and fish cover. This is discussed in the next section.

6.5 Riparian planting - buffers

Extensive riparian planting has been undertaken in lowland streams across Canterbury, and throughout New Zealand, with a broad range of purported benefits.²¹ Often however, benefits are incidental, because planting is often more aesthetically driven than focused on addressing particular issues or habitat requirements (Table 5).

As described in detail in Hudson (2005), plants should be selected based on the purpose of the planting (e.g. biodiversity, erosion control; contaminant trapping; shading), the bank shape (profiles) and how frequently the zones are flooded. This ranges from the "margins" that are continuously wet (they intercept the groundwater table and are flooded by streamflow), to frequently wet lower bank zones; to stopbanks and upland fringe zones that are flooded infrequently.

For the Kaiapoi River rehabilitation Hudson & Fletcher (2015) based recommendations on Landcare Research guides²² and in consideration of the Mahaanui Iwi Management Plan (2013) that includes provision for the ongoing protection and restoration/enhancement of mahinga kai, source to sea fish passage, catchment management, and establishment and maintenance of

²¹ <http://www.doc.govt.nz/Documents/conservation/native-plants/Streamside-planting.pdf>

²² Dr Colin Meurk developed comprehensive guides which are widely used.
<http://natureservices.landcareresearch.co.nz/app/> (accessed April 2017)

indigenous planted riparian zones. The Christchurch City Council (2005) guide “Christchurch City and Lowland Canterbury Streamside Planting” (which is based on the advice of Dr Meurk), to specify plants for different parts of the river profile (Table 6). This approach is recommended for the Three Brooks and upper Cam.

Locally sourced, assemblages of plants are recommended. Streamside planting would be established along the edge of the channel and up the bank following the pattern illustrated in Figure 12 and Figure 35. The first priority is to establish ground cover on disturbed areas (e.g. hydro-seeding grass). In a short time the grass will provide a high degree of protection against streamflow and surface wash (rainsplash and runoff). The additional step is to establish marginal plants such as rushes, flax and toitoi; and shrubs and trees progressively further up the bank. Upland planting is also recommended to provide a bio-diverse stream corridor. Deep rooted plants may be required on benches and side slopes to control mass failure and provide additional erosion resistance in the event of channel migration.

Streamside planting has to be carefully planned to allow excavators to gain access to the creek and to be able to reach over or around planting to maintain the channel if required. However, the expectation is that the channel will be self-sustaining with minimal or no intervention required over the long term.

Environmental benefits of the selected plants were summarised from the Landcare factsheets and database by Hudson & Fletcher (2015). For example, *Schoenoplectus tabernaemontani* (Kāpūngāwhā, bulrush, club-rush) is a tall, spiky, sedge found in shallow, freshwater and estuarine habitats and on the margins of rivers and wetlands. Growth is seasonal with stems dying back over winter. The traditional use of the dried stems is for plaiting mats and baskets. Kāpūngāwhā is tolerant of pollutants, growing vigorously in nutrient-enriched water, and taking up and storing large quantities of nutrients, particularly nitrogen and phosphorus. These characteristics, and its ease of propagation, have made this plant popular for use in artificially constructed wetlands for treatment of sewerage and agricultural wastewater in New Zealand and overseas. Similarly, *Eleocharis acuta* (spike sedge) is a perennial spreading sedge with slender creeping rhizomes, and is an excellent nutrient stripper and soil stabiliser.

Streamside buffers have been proven effective in trapping sediment. Specifically, a steep decline in surface erosion and delivery is expected with increasing ground cover. This is illustrated in an application of the Universal Soil Loss Equation (USLE) where a river bank situation is simulated for default rainfall and soil characteristics, with a no till bank with a 1:4 slope (25%), 3 m long with 0 to 95% grass cover. Erosion decreases exponentially with grass cover increasing from 0 to 95%, with a 97% explanation (Figure 36).

CAREX has presented results of soil loss against percent ground cover for some lowland streams. There is a low degree of explanation (22%), a much flatter decline in sediment inputs to a stream, with a considerable amount of variance (several orders of magnitude) for 10% cover for 5 cases. The results are presented without detailed explanation.

In my opinion, two factors play a critical role in determining effectiveness of buffers:

- Considerably wider buffers are required as the rate of erosion from the contributing area increase (Table 4); and
- Different types of cover provide different degrees of buffering for different situations (Table 5).

Design of riparian buffers should take these factors into account.

To this point, as noted earlier, much of the riparian planting has been aesthetically driven, and attempting to do the right thing. Future planting should be more context driven and purpose driven. For example, experiments on shading by CAREX are useful regarding macrophytes, but results suggest shading may provide shelter that encourages growth. Further, shading for stream temperature moderation does not appear to be required in the spring fed Three Brooks and upper Cam based on reported stream temperatures which are relatively low and relatively steady.

A major issue facing the Cam Enhancement Subcommittee is related to the degree of support, and type of support, that can or should be offered to landowners or other stakeholders who could or should undertake riparian planting. The conundrum is that there is a paucity of native riparian planting but that riparian planting could consume the entire Cam Enhancement budget.

Planting of wet edge and bank vegetation often requires bank shaping. Greg Bennett¹³ indicated costs of ~\$5.00 per linear metre of bank for Middle Brook (bank height of ~1.5 m). As discussed previously, planting costs range from ~\$5.50 to \$8.50 per square metre. For an hypothetical 1.5 m bank, for a 1:1 slope ~2.0 m² /Lm of planting is required and for a 1:2 slope ~3.4 m² /Lm of planting is required. The low end cost would be ~\$16.50 and high end ~\$34 /Lm. For each \$10,000 about 300 m to 600 m of 1.5 m high bank could be reshaped and planted with an assemblage of appropriate species.

Recommendation areas follow:

- Provide non – financial support to landowners or other stakeholders who wish to plant (e.g. support applications to the Intermediate Steps and Biodiversity funds);
- Target financial support to otherwise unfundable sites and/or high profile sites (e.g. where public walkways or cycleways are intended);
- Fund, or co-fund, riparian planting for bank stabilisation works that have been identified earlier; and
- Fund, or co-fund, riparian planting for the two stage channel trial, which was discussed earlier.

7 Conclusions and recommendations

A review of issues and options provides the Cam River Enhancement Subcommittee with an opportunity to cherry pick through a range of management measures and specific actions to enhance the Three Brooks and upper Cam River. The actions, potential benefits, and indicative costs, have been outlined.

Priorities remain:

- Avoid generating excessive runoff, soil erosion and contaminants through appropriate land management practices as a prerequisite;
- Control the transfer of sediment and contaminants between sources and waterways;
- Trap and treat sediment and contaminants in waterways to stop downstream transfer; and
- A regional or district global resource consent, with appropriate conditions, is required to facilitate habitat rehabilitation in stream corridors.

Some of the recommend actions are well established. Notably, a major issue is excessive fine sediments in and on the stream beds. This issue can be addressed by enforcement of livestock exclusion rules in problem areas, better land management, and more specific to the Cam Enhancement fund, trapping and treating sediments and contaminants and removing sediments from waterways. Specific actions and indicative costs are as follow:

Trapping and treating sediment and contaminants:

- Sediment traps: 14 additional traps and enhancement of an existing pond, at an indicative cost of ~\$1,000 to ~\$2,000 each;
- Mini wetlands at tile drain outfalls: sites are to be identified, at an indicative cost of ~\$1,000 to ~\$1,900 each;
- Constructed wetlands: conventional constructed wetlands are prohibitive in terms of cost and land area – a trial of 3 smaller drainage wetlands is recommended at an indicative cost of ~\$1,300 to ~\$2,400 each; and
- Bioreactor trials are underway, with unknown cost and effectiveness in lowland streams with relatively high flows.

Sediment removal from the stream channel is recommended, using a combination of three approaches, starting in headwater streams where possible, and moving downstream:

- Removal of surface fine sediment from 7,800 m of waterway with excessive fine sediment cover with conventional drain cleaning by hydraulic excavator ~ \$20,000;
- Removal of surface and shallow subsurface (~100 mm) fine sediment from 7,800 m of waterway (~25,000 m²) with excessive fine sediment cover by sand wand ~\$75,000; and
- Experiment with bed raking to remove surface and deep subsurface (~300 mm) fine sediment from 7,800 m of waterway with excessive fine sediment cover and create more habitat diversity (shallow pools and riffles) ~\$40,000.

Bank stabilisation, bed and bank reshaping:

- Bank remediation, with reshaping and riparian planting, of 15 sites ~\$10,000 to \$15,000;
- Creation of pools and riffles with bed raking (above) coupled with reshaping the channel from a flat bottom trapezoid to concentrate flow in a V shaped channel over the 7,800 m reach ~\$12,500;
- Bank reshaping opportunistically at ~\$1.00 to \$5.00 /Lm when undertaken with recommended sediment removal, with a single row of carex planting at \$8-10 /Lm (over small lengths);
- Bank sliding trial to create a constricted low flow channel with linear wetlands, over several 100 m test reaches at an indicative cost of \$1,000 per reach. If this is successful extend the trial to the remaining 7,000 m of channel where sediment removal is planned at an indicative cost of ~\$70,000; and
- Two stage/compound channels, undertake two trials over ~ 175 m on South Brook and ~150 m on North Brook, at a tentative budget of \$50 per linear metre (~\$16,000).

In channel habitat structures:

- Trials are underway, with large woody debris and boulder clusters, with unknown cost and effectiveness in lowland streams.

Riparian planting is often more aesthetically driven than focused on addressing particular issues or habitat requirements. Specific recommendations are made regarding planting. There is a huge opportunity to improve riparian condition, but at a very large cost. For each \$10,000 about 300 m to 600 m of 1.5 m high bank could be reshaped and planted with an assemblage of appropriate species. Direct funding might be directed to otherwise unfundable sites and/or high profile sites (e.g. where public walkways or cycleways are intended as discussed in the Vision Statement (appended).

Once the overall integrated catchment management plan has been implemented, and measures are in place to avoid and control the generation and delivery of sediments and contaminants to waterways, the importance of sediment traps will decline with time. This will be some years from now as the legacy sediment are cleaned up. Removal of fine sediment legacy deposits should be one-off operations, unless something catastrophic occurs in the catchment.

8 Acknowledgements

The support and feedback from the Cam River Enhancement Subcommittee, and Waimakariri District Council (in particular Janet Fraser and Greg Bennett) is greatly appreciated. A major contribution to the understanding of river corridor condition in the Three Brooks and Tuahiwi Drain is the updated, and more sophisticated, "Stream walk" trial by ECan. I greatly appreciate discussions, and the collection and provision of this information, by Andrew Arps, Jarred Arthur, Duncan Gray, Anna Veltman, and other members of the team.

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10 Report limitations

The information in this report and any accompanying documentation is accurate to the best of the knowledge and belief of the Consultant acting on behalf of Waimakariri District Council (WDC). While the Consultant has exercised all reasonable skill and care in the preparation of information in this report, neither the Consultant nor WDC accept any liability in contract, tort or otherwise for any loss, damage, injury or expense, whether direct, indirect or consequential, arising out of the provision of information and advice in this report.

DRAFT

Tables

Table 1 Sediment related management measures and best management practices (Hudson 2005)

Problem	Management measure	Best management practice
Sediment build up in the channel	remove sediment deposit	<ul style="list-style-type: none"> channel excavation work windows coarse sediment trap
Sediment movement downstream	control sediment transport	<ul style="list-style-type: none"> grassed waterways sediment traps instream filters
Upland erosion	on-farm soil loss control	<p>a large range of practices are available including:</p> <ul style="list-style-type: none"> - cropping management practices: <ul style="list-style-type: none"> conservation tillage contour strip-cropping conservation cropping sequence cover control - stock management practices: <ul style="list-style-type: none"> stock & waterways rotational grazing - water and sediment control practices: <ul style="list-style-type: none"> grassed waterways interceptor drains critical area planting control basins terraces
	off-farm loss control	<ul style="list-style-type: none"> filter strips field borders wetlands
Bed erosion	grade stabilization	<ul style="list-style-type: none"> drop structures – weirs vanes deflectors placement of large organic debris
	bed stability	<ul style="list-style-type: none"> stock & waterways restricted access watering points stream crossings
Bank erosion	lateral erosion protection	<ul style="list-style-type: none"> streamside vegetation bank reshaping multi-stage floodways anchored trees rip rap groynes retards flow deflectors
	bank stability protection	<ul style="list-style-type: none"> streamside vegetation bank reshaping stock & waterways vegetation (weed) control
	surface wash protection	<ul style="list-style-type: none"> rehabilitating land grassed waterways stock & waterways farm tracks

Table 2 Key questions in decision making (Hudson 2005)**Key questions in decision making**

1. **What is the problem?**
A clear identification of the particular problem(s) is a prerequisite to any management intervention.
2. **What are the causes?**
There may be multiple causes of a particular problem. The sources, and magnitude and frequency of contribution to the problem must be identified to prioritise actions. Management should always try to address the causes of a problem. Treatment of effects without addressing the causes may result in expensive, repetitive actions that are unsustainable and unsuccessful.
3. **What is the objective?**
Have a clear idea of what you have to achieve both locally (e.g. removing sediment) and at a reach (e.g. general channel instability) or perhaps catchment scale (e.g. changing land use). Check if these objectives are realistic and will bring a demonstrable benefit.
4. **Is intervention required?**
In some cases indirect actions may solve the problem. E.g. local bank failures may stabilise and the blockage may be naturally removed by streamflow if livestock grazing on the banks is controlled.
5. **What are the most appropriate methods to relieve effects and to achieve a long term solution?**
The choice of management practices and the location and timing of operations will determine the success of the project and likely impacts.
6. **Is consultation and resource consent required?**
Early and extensive consultation with relevant regulatory authorities, interest groups and individuals is crucial. Obtain the required authorisations.
7. **Are there negative local impacts?**
Think what other activities might be indirectly or inadvertently affected. E.g. riparian planting may prevent access for future drainage management; using heavy equipment to clear a channel may cause land disturbance and loss of farm productivity.
8. **What effects might the works have elsewhere?**
Actions in part of a waterway may have impacts upstream (e.g. erosion with channel excavation), downstream (e.g. sediment plumes) or laterally (e.g. de-watering wetlands).
9. **When is the best time to undertake work?**
Some emergency works have to be undertaken immediately. Routine maintenance should avoid sensitive times and places for fish and animals. Use the most effective period for weed management (which is often not when weeds are causing a problem). Flood or erosion risk should also be considered.
10. **What are the chances of success and risks of failure of the proposed actions?**
11. **What are the risks of no intervention?**
12. **Is help or consultation required?**

Table 3 Habitat characteristics of three Brook sampling site in base flow conditions (Golder Associates 2008b)

Site	Depth (m)	Width (m)	Velocity (m/s)	Shade (%)	Macrophyte cover (%)	Filamentous algae ¹ (%)
North Brook						
N1	0.3	2.0	0.0	25	100	60
N2	0.75	0.1	0.2	70	1	10
N3	0.14	2.1	0.7	50	10	5
N4	0.35	3.3	0.8	70	40	5
N5	0.6	1.2		25	20	25
N6	0.3	3.1	1.0	30	40	0
N7	0.5	2.0	0.5	50	5	0
N8	0.4	4.3	0.6	0	65	0
N9	0.6	4.0	0.6	0	80	25
Middle Brook						
M1	0.08	1.8	0.6	60	0	0
M2	0.12	1.6	0.5	70	0	0
M3	0.1	2.0	0.3	40	20	70
South Brook						
S1	0.35	1.5	0.9	25	40	5
S2	0.3	1.8	0.9	10	10	0
S3	0.4	4.3	0.7	0	60	0
S4	0.28	1.9	0.8	30	10	0
S5	0.25	2.1	0.9	10	10	0

Comments: Velocity could not be measured at N5 due to sluggish flow and debris in the channel. % Filamentous algae is streambed cover with green filamentous algae >20 mm (i.e. nuisance growth). See Figure 2 for locations.

Table 4 Relationship between soil loss, slope and filter strip width for dispersed flow (from Hudson 2005, based on Karssies & Prosser 1999)

Soil loss (t/ha/y)	Filter strip slope (%) - filter width (m)									
	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
1	2	2	2	2	2	2	2	2	2	2
2	2	2	2	2	2	2	2	2	2	2
5	2	2	2	2	3	3	3	4	4	4
10	2	2	4	5	6	6	7	7	7	7
20	3	9	11	12	12	13	13	13	13	14
30	9	15	17	18	19	19	19	20	20	20
40	15	21	23	24	25	25	26	26	26	26
50	22	28	30	>30						
60	28	>30								
70	>30									

Table 5 Relative effectiveness of different buffer vegetation types in an agricultural setting (from Hudson 2005 based on Dosskey et al. (1997) and others)

Benefit	Vegetation type			
	Reeds	Grass	Shrub	Tree
Stabilise bank erosion	Low-High	Medium	High	High
Filter sediment	High	High	Low	Low
Filter nutrients, pesticides, microbes				
- Sediment bound	High	High	Low	Low
- Soluble	High	Medium	Low	Medium
Aquatic habitat (cover, food, shade)	High	Low*	Medium	High
Terrestrial habitat				
- Grassland species	Medium	High	Medium	Low
- Forest species	Low	Low	Medium	High
Visual diversity	High	Low	Medium	High
Flood attenuation	Low	Low	Medium	High
Economic products	Low	Medium	Low	Med-High

Table 6 Plants from Christchurch City and Lowland Canterbury streamside planting guide

Sedges, Rushes, Ferns and Ground Covers		frost	sun	shade	wet	dry	wind	grazing (once established)	Aquatic	Edge of stream	Marsh	lower bank
pondweed	<i>Myriophyllum propinquum/triphyllum</i>	●	●	●	●	○	○	●	A			
pondweed	<i>Potamogeton cheesemanii/ochreatus</i>	●	●	●	●	○	○	●	A			
raupo	<i>Typha orientalis</i> (invades open water)	●	●	○	●	○	●	●	A E			
kapungawha, lake club rush	<i>Schoenoplectus validus/tabernaemontani</i>	●	●	○	●	○	●	●	A E			
spike sedge	<i>Eleocharis acuta</i>	●	●	●	●	○	●	●	A E M			
pukio, tussock sedge	<i>Carex secta/virgata</i>	●	●	●	●	○	●	●	EM	■		
makura	<i>Carex maorica/geminata</i>	●	●	●	●	○	●	●	EM	■		
bog rush	<i>Schoenus pauciflorus</i>	●	●	○	●	○	●	●	EM			
swamp kiokio	<i>Blechnum minus</i>	●	●	●	●	○	●	●	EM	■		
swamp nettle	<i>Urtica linearifolia</i>	●	●	●	●	○	○	●	E	■		
puniu, prickly shield fern	<i>Polystichum vestitum</i>	●	●	●	●	○	●	●	EM	■		
harakeke, NZ flax	<i>Phormium tenax</i>	●	●	○	●	○	●	●	EM	■		
tussock rushes, wiwi	<i>Juncus gregiflorus/pallidus/sarophorus</i>	●	●	○	●	○	●	●	EM	■		
umbrella sedge, upoko-tangata	<i>Cyperus ustulatus</i>	●	●	○	●	○	●	●	E	■		
gully fern, pakauroharoha	<i>Pneumatopteris pennigera</i>	○	○	●	●	○	○	●			■	
nini	<i>Blechnum chambersii</i>	○	○	●	○	○	○	●	E			
kiwakiwa	<i>Blechnum fluviatile</i>	○	○	●	○	○	○	●	E			
hen & chickens fern	<i>Asplenium bulbiferum</i>	○	○	●	○	○	○	○				■
mata, water-fern	<i>Histiopteris incisa</i>	○	○	●	○	○	○	○				■
rough pigfern	<i>Hypolepis ambigua</i>	●	●	●	●	○	○	○				■
toetoe grass, toetoe	<i>Cortaderia richardii</i>	●	●	○	●	○	○	○				■
kakaha, bush lily	<i>Astelia fragrans</i>	●	●	●	●	○	○	○				■

Shrubs and Trees		frost	sun	shade	wet	dry	wind	grazing (once established)	lower bank
mikimiki (shrub)	<i>Coprosma propinqua</i>	●	●	●	●	○	○	●	■
cabbage tree, ti kouka	<i>Cordyline australis</i>	●	●	●	●	○	○	○	■
mikimiki (shrub)	<i>Coprosma pedicellata</i>	●	●	●	●	○	○	○	■
manuka, tea tree	<i>Leptospermum scoparium</i>	●	●	○	●	○	○	○	■
kahikatea, white pine	<i>Dacrydium dacrydioides</i>	●	●	○	○	○	○	○	
pokaka	<i>Elaeocarpus hookerianus</i>	●	●	●	○	○	○	○	
karamu	<i>Coprosma robusta</i>	●	●	○	○	○	○	○	
mikimiki (shrub)	<i>Coprosma aff. parviflora</i> (sp.t)	●	●	○	○	○	○	○	■
kohuhu, black matipo, tawhari	<i>Pittosporum tenuifolium</i>	●	●	○	○	○	○	○	
weeping mapou (shrub)	<i>Myrsine divaricata</i>	●	●	○	○	○	○	○	■

Figures

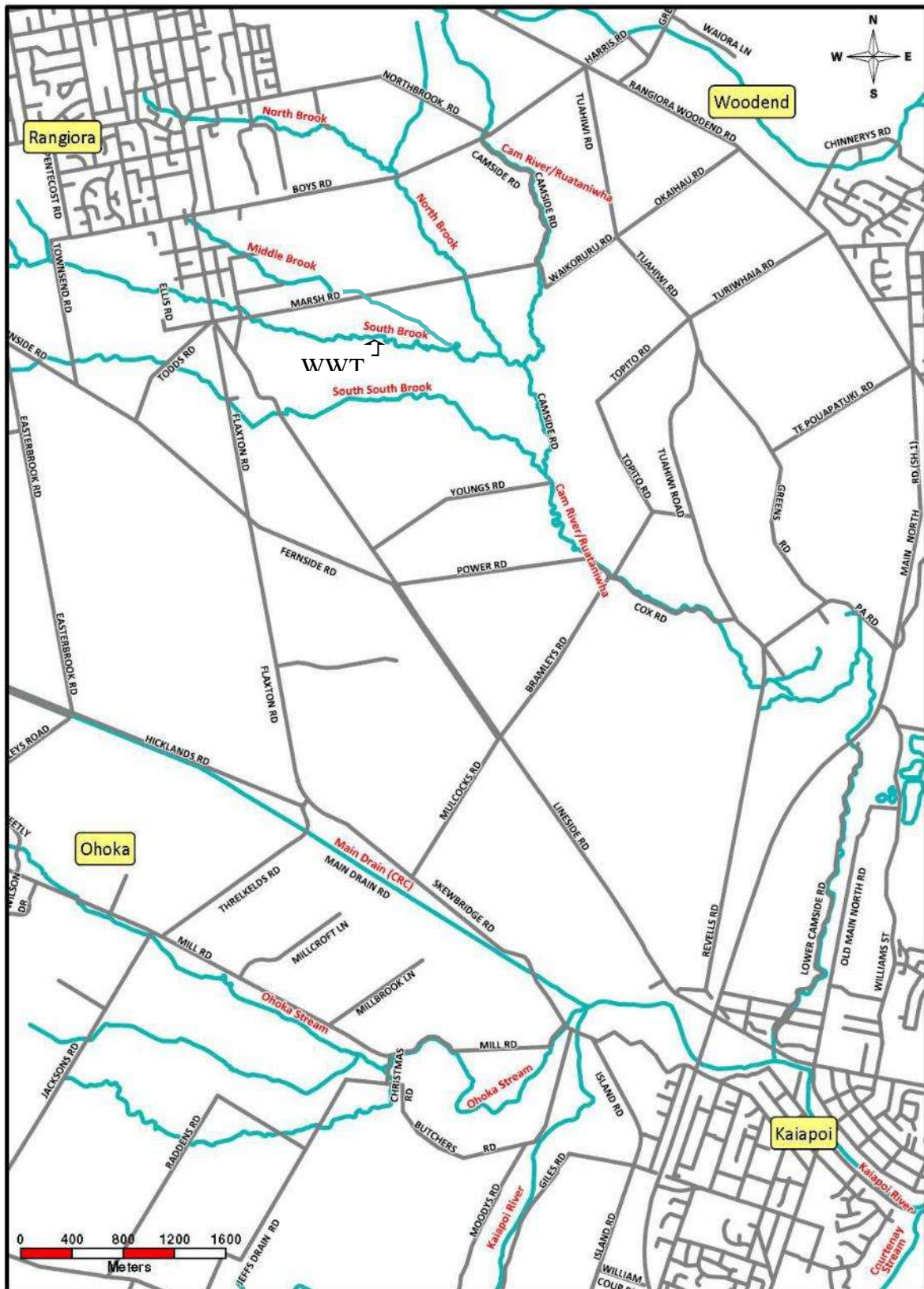


Figure 1 Geography of the Cam River catchment (WDC)



Figure 2 Three Brooks sampling sites (based on Golder Associates 2008)

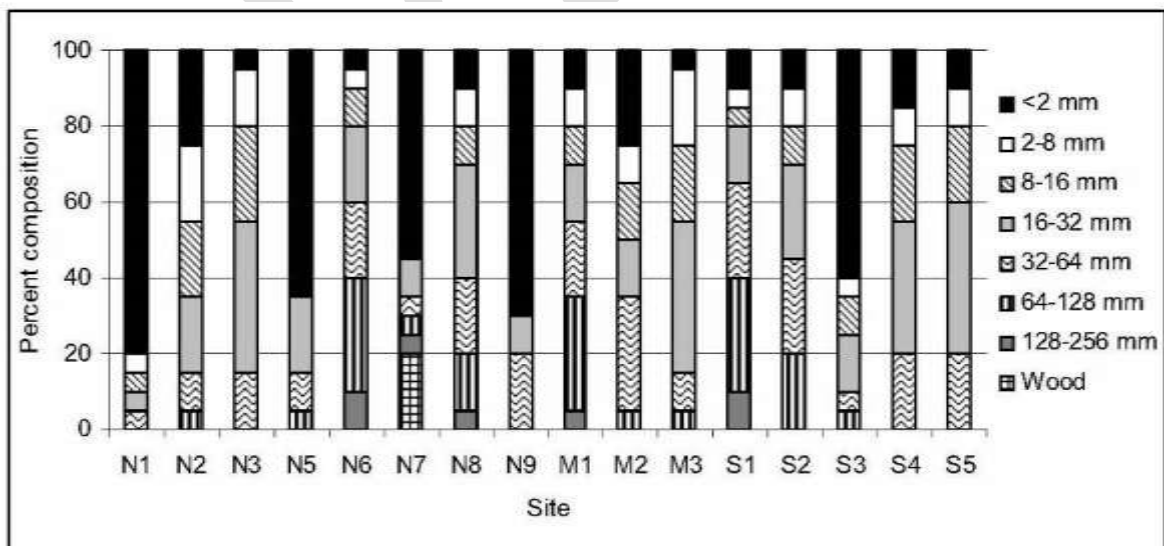


Figure 3 Composition of stream bed sediments in the Three Brooks (see Figure 2 for locations; Golder Associates 2008)



- SQ34905 Cam River at Marsh Rd (CRM)
- SQ30369 Cam River at Bramleys Road (CRB)
- SQ34903 North Brook at Marsh Rd (NBM)
- SQ30390 South Brook at Marsh Rd (SBM)

Figure 4 ECan sampling sites (based on Greer & Meredith 2016)



Figure 5 Fine sediment cover (map kindly provided by ECan) proposed & existing sediment traps & drain wetlands



Figure 6 Overland flow path for land surface drainage, North Brook tributary 1 at R1 in Figure A3: 2A (ECan streamwalk)



Figure 7 Overland flow path for land surface drainage, North Brook tributary 1 at R4 in Figure A3: 2A (ECan streamwalk)



Figure 8 Stock trampling bank collapse, view upstream Middle Brook above Dunlops Road at R15 (ECan streamwalk)



Figure 9 Toe scour and collapse, North Brook above Marsh Road at R4 in Figure A3: 2A (ECan streamwalk)



Figure 10 Over steepened banks can erode by dry ravel, South Brook above Buckleys Road at R22-23 (ECan streamwalk)

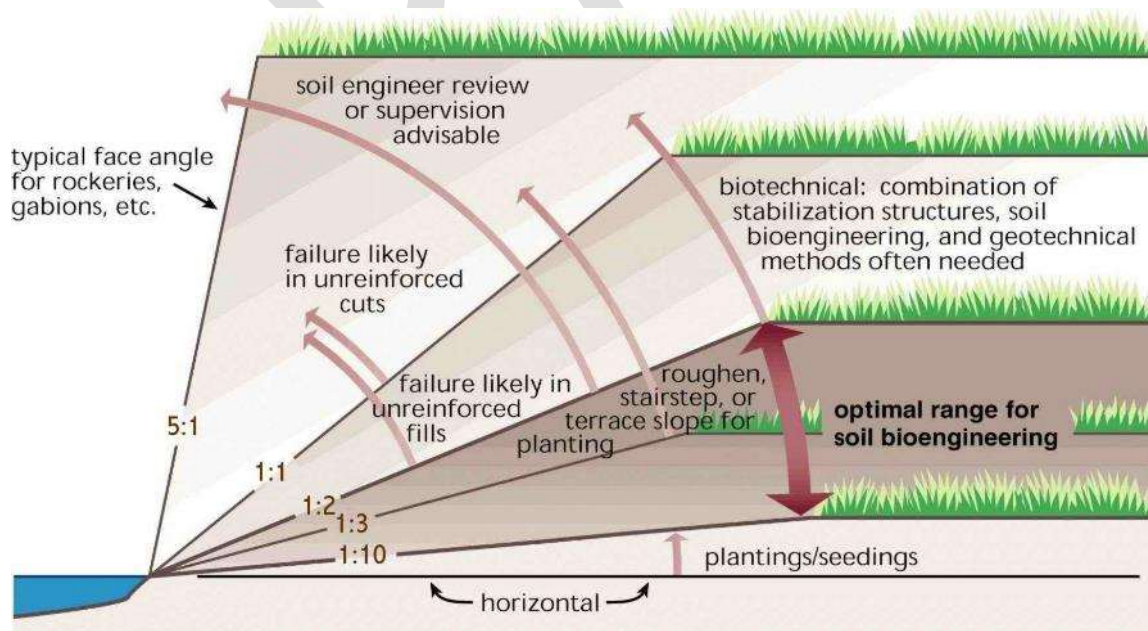


Figure 11 Bank reshaping: guideline (FISRWG 1998)

Comment Slope (rise/run), and bank height relative to rooting depth, are important factors in determining appropriate bank protection measures.

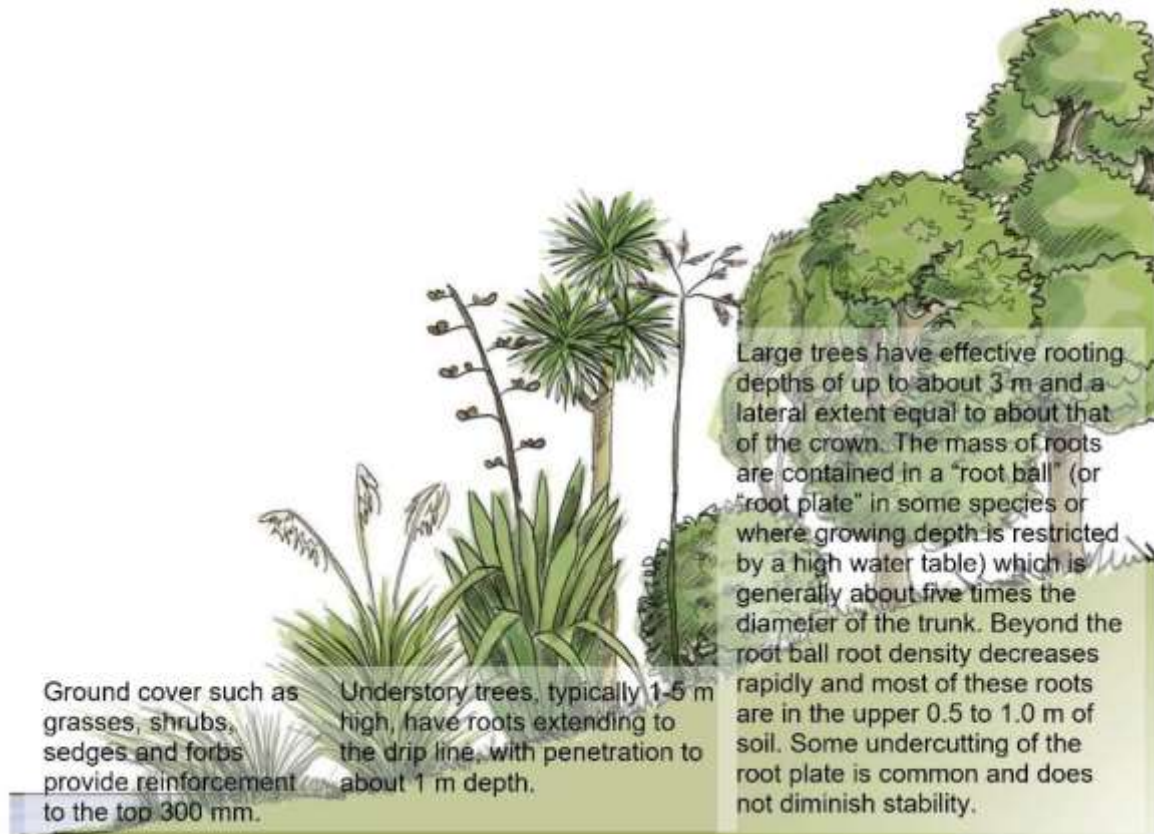


Figure 12 General guidelines for root protection (Hudson 2005 adopted from Greater Wellington Regional Council)

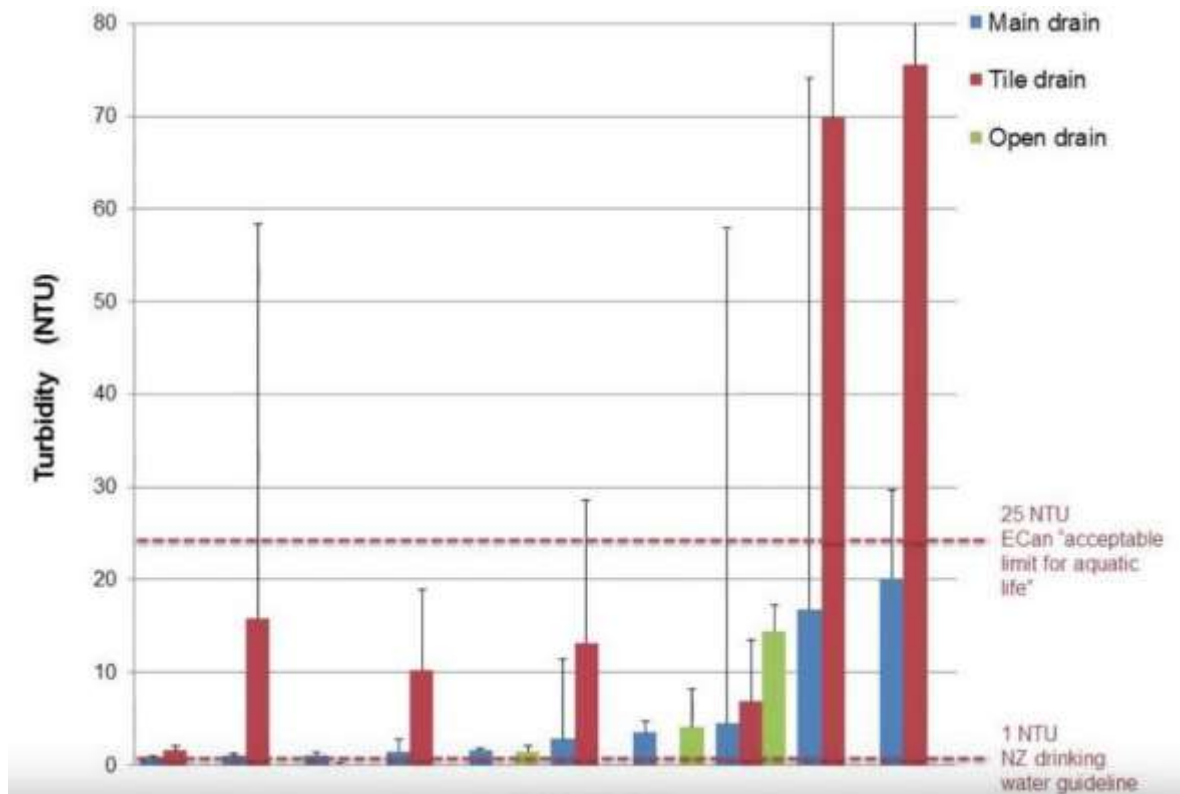


Figure 13 Tile drains may be a source of sediment (and contaminants) (source: McIntosh 2016)

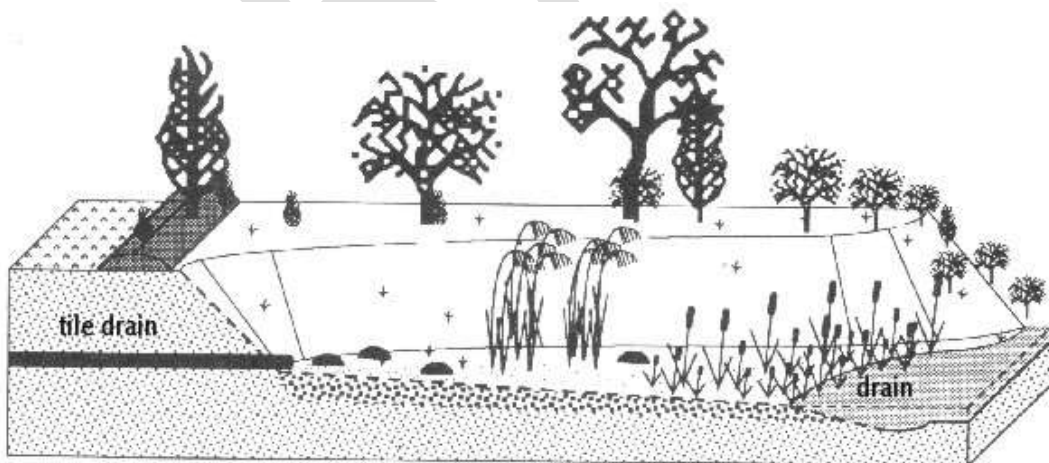
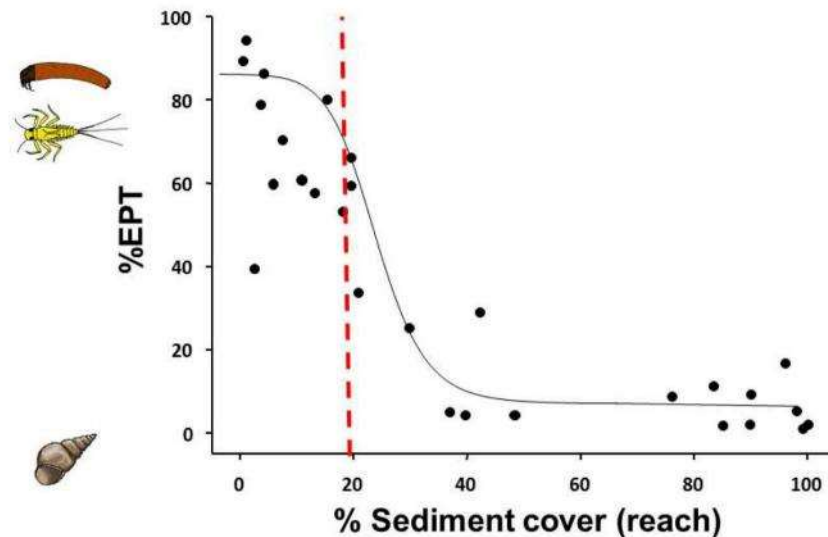


Figure 14 Schematic of a mini-wetland that receives water from tile drains and acts as a sediment and nutrient trap (adapted from Petersen et al. 1992)

Is there a sediment threshold?

Mayflies, stoneflies and caddisflies can be negatively impacted by deposited fine sediment bed cover exceeding approximately 20%, and that legacies of long-term sediment can prevent recovery even when sources are controlled.



Burdon et al. (2013)

Figure 15 Fine sediment cover threshold (CAREX poster-2)

Comment: The recommended guideline for fine sediment (<2 mm) cover for macroinvertebrates and fish is 20% (Clapcott et al. 2011).

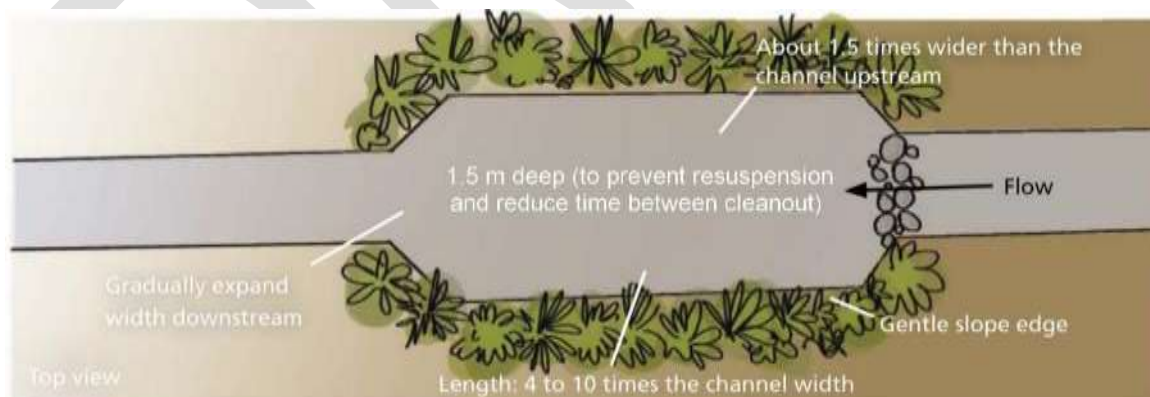


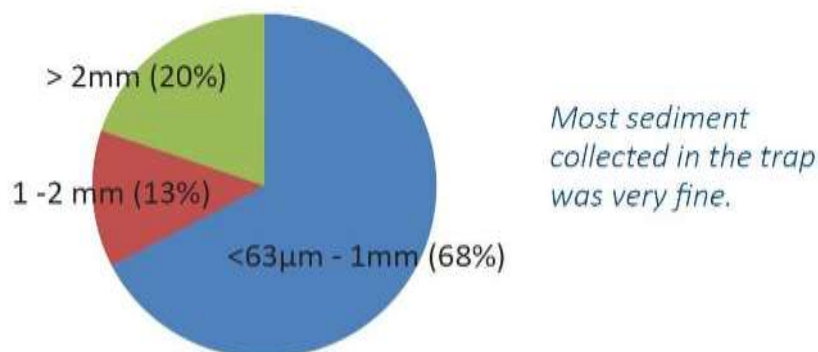
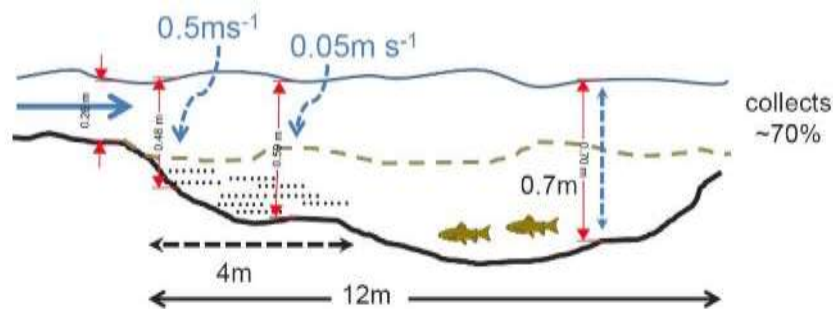
Figure 16 Conventional sediment trap rule of thumb design (after Hudson 2002)



Figure 17 Natural sediment deposition areas can be utilised as sediment traps by removing sediment to revitalise deposition (Cam River ~300 m below Bramleys Road)

More on the sediment traps

Recently, we used a digger to clean out our large (12m long and 0.7 m deep) sediment trap, which has been in place for 8 months. One of our students was monitoring the amount of sediment collected in the trap and we estimate it has captured about 60-70% of the fine sediment entering this length of stream. Over the 8 month period, the trap filled in to an average depth of ~35cm deep. During our cleaning we removed about 4m³ of sediment from the trap! The trap has proven to be very efficient and its success is due to it being long enough and deep enough to reduce the water velocity to less than 0.01m/s¹. This very slow water velocity is enough for very fine silt to drop out of the water column. We will continue to monitor this trap and several others over the next year. Our aim is to develop an "ideal" sediment trap design.



The trap collected 60-70% of the fine sediment entering the reach over a 8-month period. The theoretical trap efficiency for this trap is about 95% for 125 μm sediment based on Hudson (2002).

Figure 18 CX-01 sediment trap (CAREX newsletter Sep 2015 (a - top); CAREX poster 2 (Harding et. al. undated) (b - bottom)

Comment: In the text the trap velocity is reported as less than 0.01 m/s; but the figure below has a trap velocity of 0.05 m/s and input velocity of 0.5 m/s. For the reported cross sectional area of 1.75 m³ (2.5 m width and 0.7 m depth), to achieve a 0.01 m/s mean velocity requires a streamflow of less than 20 L/s which is far less than expected (75 to 560 L/s - see footnote 16). There should be no gain or loss of flow.



Figure 19 Main CAREX sediment trap on the Middle Brook ~400 m upstream of Marsh Road (CX-01 in Figure 5)

Comment: The trap is largely infilled with fine sediment. Some trapping will continue within the vegetation, but this material is easily resuspended with agitation. View upstream.



Figure 20 CAREX shallow sediment trap on the Middle Brook ~240 m upstream of Marsh Road (ST-CX-02 in Figure 5)

Comment: View upstream. Trapping occurs along the edge of the shallow trap (where silt plates are located), but the bed is largely exposed gravel indicating the trap is too shallow to be effective. It is unclear how edge silt plates are used to calculated sediment loads and trap efficiencies.



Figure 21 Middle Brook below the main CAREX sediment trap is a clean gravel bed (ST-CX-01 in Figure 5)



Figure 22 A 900 m² interception wetland with a coarse sediment trap at the top end (right) draining 5.65 ha (revised) (Tanner et al. 2010; 2011)

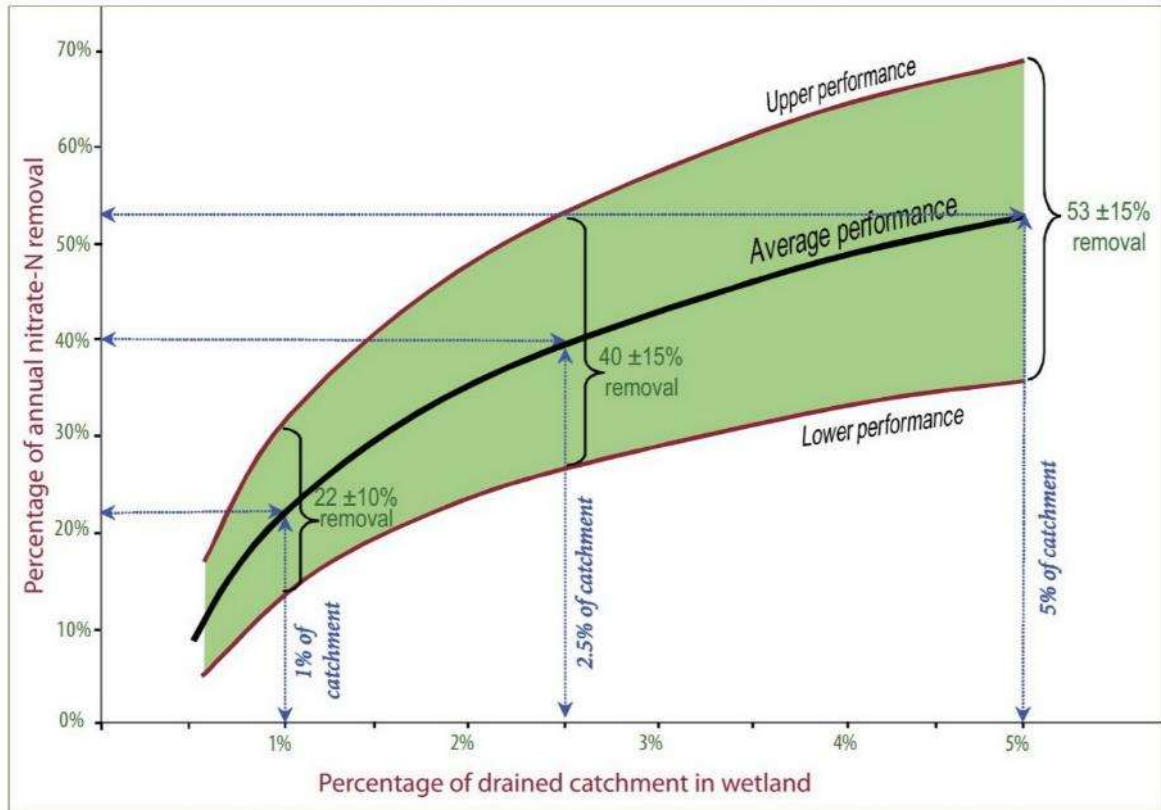


Figure 23 Constructed wetland size and performance (Tanner et al. 2010)

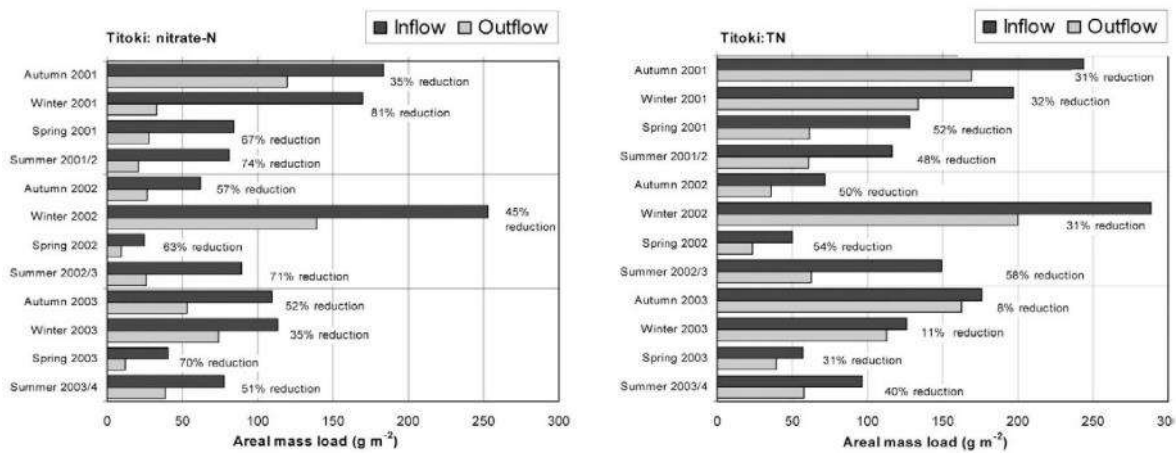


Figure 24 Titoki wetland performance (Tanner & Sukias 2011)



Figure 25 Hydraulic excavators are commonly used to remove sediment (and weeds) from the bank (Duck Creek) and inchannel (Avon River - Sunday Star Times 04 May 2014)



Figure 26 Rake bucket used in the Waimakariri District for aquatic weed removal



Figure 27 Exposed gravel with marginal fine sediment deposits in the bed raking reach Middle Brook

Sand wand trial

A Sand Wand™ (Streamside Environmental) was used to remove sediment from two sediment traps and three 10m reaches of a small waterway (approx. 2.5m wide).



Sand wandling resulted in a reduction of fine sediment cover from approximately 40% cover to 10-20% cover. The sand wand was effective at removing loose sediment from depositional habitats (e.g., a pool or sediment trap) but doesn't work well in shallow water (<20 cm deep). The wand is labour intensive and the removed sediment needs to be deposited elsewhere.

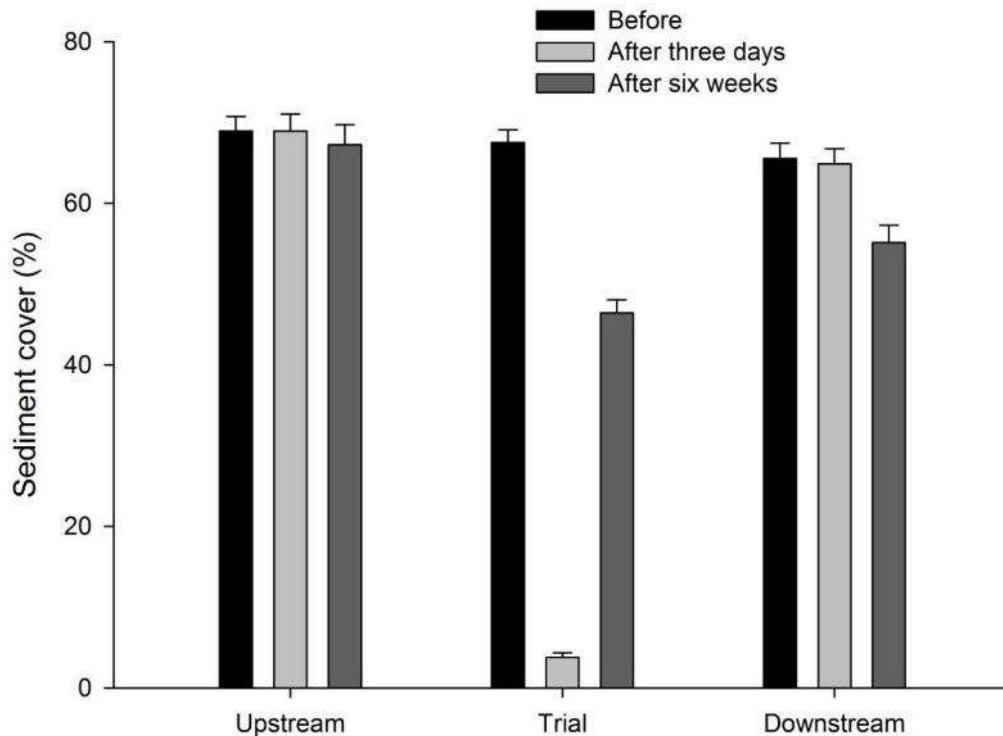


Sediment removed from the waterway using the sand wand was dispersed on an adjacent paddock.



Waterway bed substrate revealed and a lamprey that came to check out potential new habitat after sand wand was used.

Figure 28 Sand wand trials Middle Brook (Harding et al. poster 2 undated)



Mean (\pm 1SE) sediment cover within, upstream and downstream of the trial reach. Sediment cover was estimated using a stream bed viewer, $n = 80$. Differences ($p < 0.05$) between groups and occasions were derived from a two way ANOVA on ranked values

The initial removal of fine sediment, at least on the surface of the stream bed, was very successful with a significant removal of fine sediment. However, over time fine sediment has returned and deposited on the bed, almost reaching pre-trial levels of cover. The source of new sediment to the treatment reach may be deeper deposits within the reach itself or upstream reaches. The latter source appears more likely, particularly given the unusually high flows in the stream between sampling periods. However, despite the migration of fine sediment into the trial reach, sediment cover remained at a lower level than prior to the trial.

Figure 29 Sand wand trials Otukaikina Creek (Gray et al. 2013)

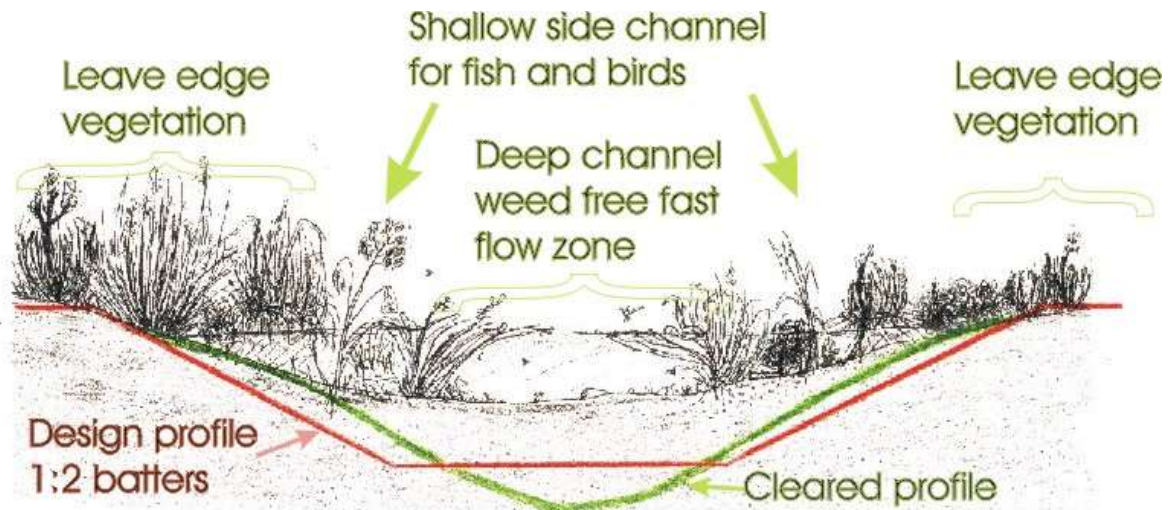


Figure 30 Partial drain clearing, leaving shallow vegetated margins, to concentrate flow to maintain a weed and sediment free narrower channel (Hewson & Hudson 2000)

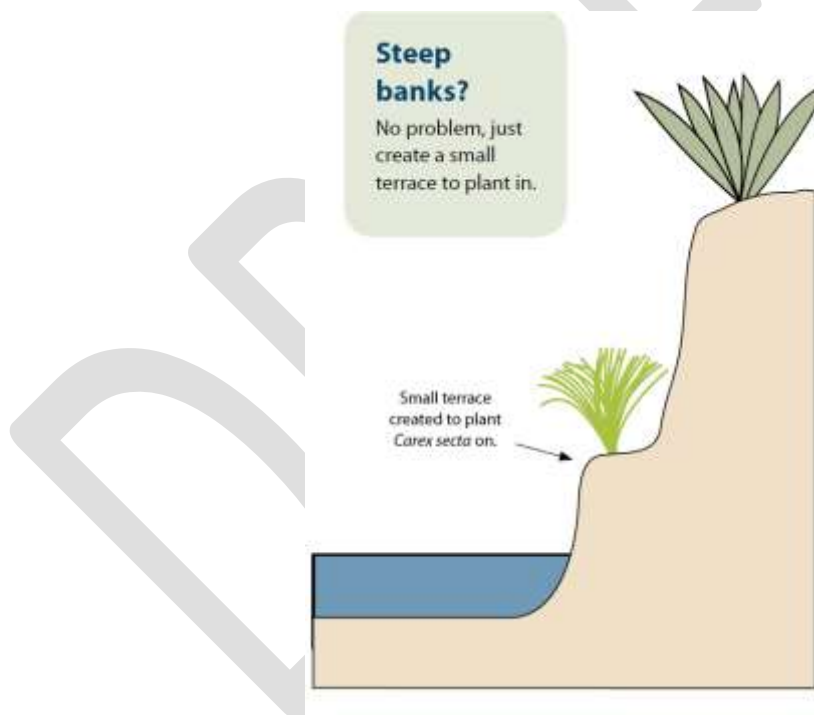


Figure 31 Benching steep banks to provide a planting platform (Environment Canterbury Living Streams Handbook Part 3: Planting and maintenance)

STREAM has used three methods for channel re-shaping, as summarised below:

1. Bank-sliding

An embanked section of river with well established, deep rooted marginal vegetation is selected **1**.

Using an excavator bucket, the vegetation fringe is gradually pushed out 2-3 metres into the channel **2**. The machine operator has to "feel" how far out to push the vegetation without it breaking up and being washed away.

Material from the embankment is then pushed into the space behind the vegetation, creating a gently sloping profile. The overall effect is to slide the whole river bank and part of the old embankment out, reducing the channel width in lower flows **3**, whilst keeping the overall wetted area the same in higher flows.

The upstream end of the new bank takes the brunt of flow and may need to be protected from erosion. In the STREAM project, the bank sliding was therefore done immediately downstream of an overhanging willow tree **4**. A flow deflector can be installed as an alternative.

advice note
RIVER RESTORATION 12 of 20



Figure 32 Bank sliding (Advice note River Restoration)

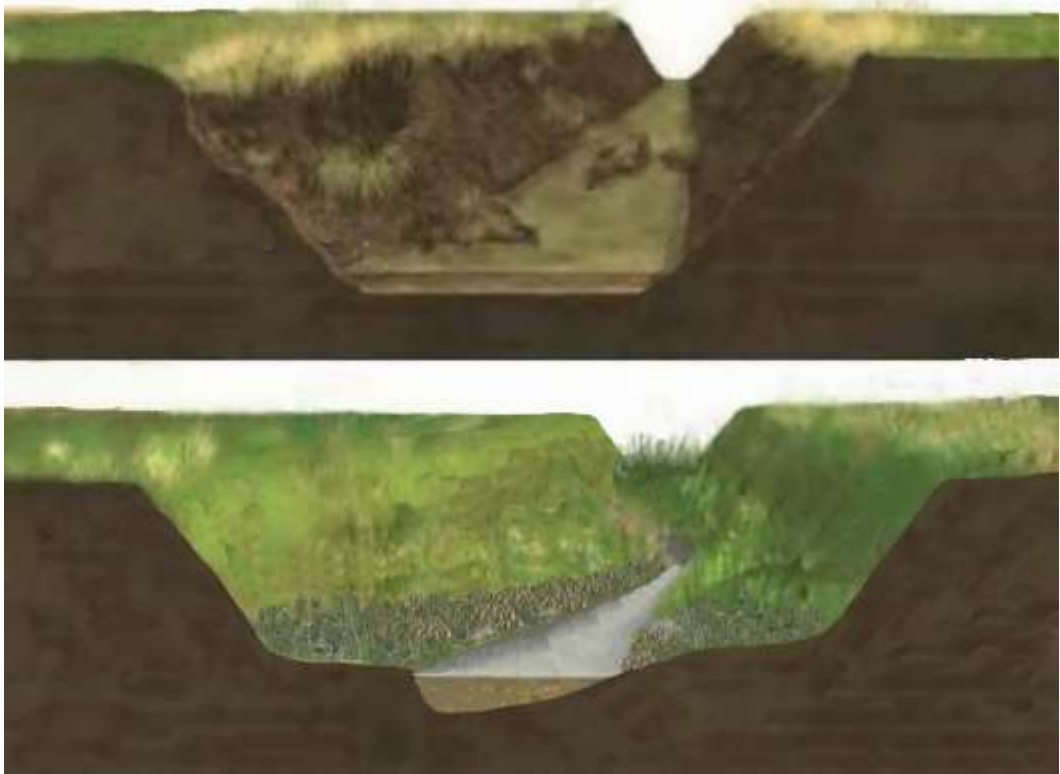


Figure 33 Two stage channel design providing a narrow low flow channel and periodically inundated vegetated high flow channel



Figure 34 Addition of boulder clusters and logs for habitat diversity (CAREX Newsletter May 2015)

Comment: CAREX Newsletter May 2015:

Natural boulders and wood logs have been added to one of our waterways to demonstrate the value of habitat for freshwater insects and fish. Many agricultural waterways lack important habitat for freshwater animals. Monitoring has shown this habitat is being used by insects to lay their eggs and fish are using them for cover. Our plan is to trial a larger-scale demonstration later this year.



Figure 35 Edge planting of raupō , carex secta (pukio/flax) and kiokio fern (*Blechnum novaezelandiae*) with cabbage tree (*Cordyline australis*) in the background

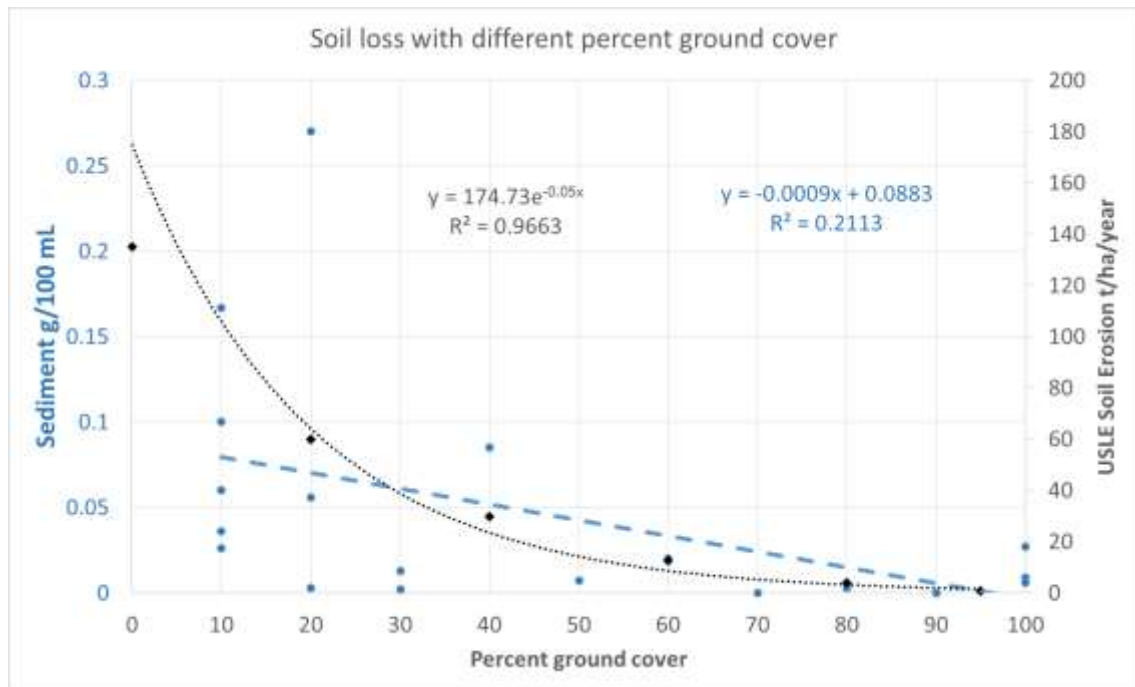


Figure 36 Graph of sediment loss with percent ground cover (CAREX poster 2) superimposed with predicted soil loss for a hypothetical drain bank

Comment: CAREX poster 2 (Harding et al. undated), showing a graph from Porter (2014), under the title “How can we reduce reducing fine sediment in waterways, states “maximising riparian vegetation cover e.g. >50% grass cover.”

The extreme variability at low ground cover is unexpected. Highest yields, and lowest yields, occur with 20% ground cover, with greater yields at 40% cover than 30% cover. The expectation from the Universal Soil Loss Equation, for a hypothetical low steep drain bank, and default soil and rainfall, is that the greatest soil loss would occur with the least ground cover with a rapid decline as cover increases.

Appendix 1: A Vision for the Three Brooks

The vision is to rehabilitate the Three Brooks into a sustainable eco-geomorphological based exemplar that provides a broad range of ecosystem services and provides environmentally friendly, cost effective and hydraulically effective erosion and flood control required in a dynamic rural and urban landscape.

This vision statement is applicable to the Cam River and many other similar streams and rivers. “Sustainable” refers to intergenerational sustainability, with minimum continuing intervention over the long term. “Eco-geomorphological” refers to linking the physical form and processes of waterways with ecological response by adopting an ecosystem perspective (Hudson 2002). “Ecosystem services” can be categorised as provisioning (e.g. mahinga kai), regulating (e.g. waste treatment, buffer zones), supporting (such as primary production, nutrient cycles and pollination) and cultural (such as spiritual and recreational benefits).

Key activities to provide these ecosystem services are summarised, and adapted, based on the issues and options for the Three Brooks, from the Styx River project.²³

Vision 1: To achieve a sustainable spring-fed stream ecosystem

1. Protect, maintain and restore natural drainage patterns by:

- Understanding natural surface and subsurface drainage patterns and processing through research and monitoring
- Ensuring that any development mitigates for stormwater quality and quantity and recognises and works with natural drainage patterns
- Recognising natural variations due to storm events and seasonal changes and allowing sufficient space for these to occur through building setbacks, zoning and land protection
- Avoiding filling and building within floodplains and ponding areas through education, working with landowners, regulation and enforcement
- Maximise ground soakage through minimizing hard surfaces
- Monitor water abstraction and its impacts on waterways and wetlands
- Recognising and planning for the long term effects of climate change and sea level rise

2. Protect springs by:

- Identifying, highlighting and monitoring springflow
- Ensuring that spring flow from the underlying aquifers is maintained
- Preventing livestock access

3. Protect and enhance water quality by:

- Controlling the generation and delivery of sediment and contaminants from the catchment
- Control, and trap and treat sediment and contaminants in the waterways
- Remove excessive fine sediment deposits from waterways

4. Protect and monitor remnant indigenous vegetation and the effect of weed invasion.

5. Identify and protect natural landforms.

6. Undertake instream habitat enhancements such as fine sediment removal and creation of instream habitat structures (such as pool and riffles) and improve riparian habitat.

7. Increase native bird species richness through:

- Protecting and restoring core habitat sites for wetland and bush bird species
- Ensuring that there are adequate buffer zones along waterway and wetland margins

²³ <http://www.thestyx.org.nz/new-zealand/visionone/> Accessed March 2017.

- Developing green corridor linkages
- Reintroduce native species.

8. Undertake predator control as necessary.

9. Monitor effects of land use change and land management practices

- Promote enforcement of applicable rules to avoid or mitigate effects
- Encourage best management practices

Vision 2: To create a lowland stream experience

10. Identify and protect:

- Suitable routes along the Three Brooks, Cam River and other tributary waterways (to be done in the spirit of partnership through negotiation with current landowners)
- Provide improved road crossing facilities so that roads do not become barriers to pedestrians and cyclists

11. Provide a range of experiences through the development of:

- Walkway routes and cycleways; and boating facilities on the Cam and ponds
- A range of landscape experiences based on natural and cultural values
- Innovative interpretative material

12. Develop service nodes that will concentrate human activity and provide facilities for:

- Parking for cars and bicycle
- Relaxation
- Eating facilities
- Learning activities
- Recreation facilities

13. Monitor and remedy the impact of people and recreational activities on ecological values through:

- Preventing or limiting access to core habitat or sensitive areas
- Use of design elements to lessen the impact on wildlife if required (e.g. screening, moats, fences)

14. Promote the lowland stream experience:

- The development of promotional material
- On site interpretation, facilities, and learning experience

Vision 3: Adaptively manage - treat actions as experiments and learn

15. Continue with the Cam River Enhancement Sub Committee to oversee development and implementation of the recommended actions, research and learning programme.

16. Develop partnerships with:

- Operational and Planning units within Waimakariri District Council
- Other organisations (for example Environment Canterbury, Department of Conservation, Ministry of Fisheries, Fish and Games Council)
- Iwi
- Research providers such as consultants, research institutes and educational institutions
- Schools and service organisations
- Community groups and volunteers such as the bio blitz on the Cam

17. Develop joint projects:

- Internally, within Waimakariri District Council
- Externally with Environment Canterbury and with other stakeholders in the Waimakariri Zone

- Externally with others outside the zone (e.g. Styx, Lake Ellesmere-Waihora)

18. Develop a website that:

- Promotes adaptive management
- Provides easy access to data and reports
- Encourages enquiry and discussion.

Vision 4: Make the Three Brooks and upper Cam a destination

19. Recognise, highlight and enhance the unique landscape character by:

- Improving public access, visibility and landscaping
- Promoting the Three Brooks and Cam as green corridors
- Promote stories of the land, its drainage and vegetation patterns, cultural patterns, cultural features and landmarks
- Allow people to express their relationship to the area through consultation and participation

20. Promote the locality through:

- Regular newsletters
- Media articles
- Publications
- Websites of the various organisations involved
- Videos, documentaries

21. Stage a series of events that will enhance this area as a destination

- Cross country run for schools
- Walkathon
- Training circuit.

Vision 5: Foster partnerships

22. Locally

- Work with private landowners in the development of the Vision while at the same time recognising:
 - private property rights
 - the need to use a range of protection methods to accomplish desired outcomes
 - the need to achieve win-win situations
- To work with a wide range of organisations and institutions to adaptively manage
- To work with private enterprise and community organisations in the development of the Three Brooks and Cam River as a destination (e.g. Kaiapoi the River Town)
- To work with private enterprise, landowners and community organisations in the development of the lowland stream experience (e.g. eco homestays)

23. Tangata Whenua

- Develop policies for mahinga kai (food gathering) specific values including habitat and species management
- Recognise and protect sites of significance and where appropriate, mark these by signs or events

24. Regionally

- Continue involvement in regional research initiatives, using the Three Brooks as a case study for adaptive management
- Develop joint projects to compare and contrast with other lowland ecosystems
- Promote information sharing to learn from successes and failures.

Appendix 2: ECan water quality and ecology (Greer Meredith 2016)

Citation: Greer M, Meredith A. 2016. Waimakariri Zone water quality and ecology: State and trend. Environment Canterbury Report R12/68. 86 pages.

From the Executive summary:

What was done

Available water quality and ecology data for the Waimakariri CWMS zone were collated, and the results compared with current regional plan limits and objectives, and established guideline values from the literature. Current state was assessed from data collected over the past five years and trend analyses were undertaken across the entire data set where more than five years of data were available.

What was found and what it means

Many of the rivers in the Waimakariri CWMS Zone, particularly spring-fed streams, exhibit unhealthy ecological communities, poor habitat conditions and degraded water quality. This condition reflects the high intensity land use in many parts of the zone. Without appropriate catchment scale management of nutrient losses and sediment inputs these impacted streams will continue to exhibit unhealthy aquatic communities.

Cam River summary

Environment Canterbury (ECan) undertook an assessment of state and trends of water quality and ecology in the Waimakariri Zone, including sites in the Cam and Kaiapoi river system (Greer and Meredith 2016). The report is intended to inform the zone committee of current state, but also of the key drivers, of ecosystem health. Available water quality and ecology data collected over the past five years were collated, and results compared with current regional plan limits and objectives, and established guideline values from the literature. Current state and trends were assessed for selected sites, including the following, if data were available:

SQ34905 Cam River at Marsh Rd

SQ30369 Cam River at Bramleys Road

SQ34903 North Brook at Marsh Rd

SQ30390 South Brook at Marsh Rd

As discussed by Greer & Meredith (2016) the key drivers and indicators of water quality and ecosystem health include invertebrate community structure, fish, macrophytes, fine sediment cover, water temperature and dissolved oxygen, nutrients, total suspended solids, and E.coli. Fish are only discussed in general terms. Findings are summarised.

Invertebrate communities are in a degraded state in most spring-fed rivers of the Kaiapoi River catchment including the Cam and South Brook (Table A4: 1). Both these sites consistently fail to meet Land and Water Regional Plan (LWRP)

outcomes; and the composition QMCI score) is indicative of poor (South Brook) or fair water quality (Cam at Bramleys Road)²⁴ and degraded habitat.²⁵

Table A2: 1 Minimum QMCI scores recorded from 2011 to 2015 in the Kaiapoi catchment. Highlighted values fail to meet the LWRP outcomes

	LWRP outcome	2011	2012	2013	2014	2015	Mean
Kaiapoi River @ Harpers Rd		5.0	4.3	4.4	4.9	5.6	4.9
Kaiapoi River @ Heywards Rd		6.1	6.6	5.3	5.6	5.0	5.7
Kaiapoi River @ Island Rd		N/A	4.5	2.8	4.5	4.1	4.0
Cust River @ Tippings Rd		5.3	7.1	5.2	3.8	3.8	5.0
Cust River @ Skewbridge Rd	5	4.1	3.3	4.0	3.4	4.8	3.9
Ohoka Stream @ Bradley's Rd		3.6	3.3	2.5	3.8	3.8	3.4
Ohoka River @ Island Rd		N/A	4.8	3.1	5.9	4.7	4.6
Cam River @ Bramleys Rd		4.9	4.2	4.7	3.3	5.0	4.4
South Brook @ Marsh Rd		3.1	2.5	3.1	2.8	4.1	3.1

It is considered by Greer & Meredith (2016) that total macrophyte cover is unlikely to be having significant ecological effects at the Cam River sites, or the South Brook (mean values range from 43 to 48% total macrophyte cover which is below the LWRP outcome of less than 50%). However, the North Brook at Marsh Road usually exceeds the LWRP outcome (mean of 70% cover). Also, emergent macrophytes are considered unlikely to have significant ecological effects in spring-fed rivers in the Kaiapoi River catchment with all sites regularly meeting the LWRP outcome. Benthic cyanobacteria does not appear to be a health risk in spring-fed streams in the Kaiapoi River catchment. All sites met the LWRP outcome for benthic cyanobacteria cover (50%) every year in which monitoring was conducted between 2011 and 2016.

“Fine sediment cover is also high across the Kaiapoi catchment, which is undoubtedly a key driver of poor ecosystem health” (Greer and Meredith 2016).²⁶ The recorded exceptions include the North Brook and South Brook at Marsh Road, where in three of the five years of record maximum fine sediment cover was less than the LWRP outcome of 20% (Table A4: 2).

Greer and Meredith (2016) do not discuss fine sediment trends, but trends are apparent at some of the study sites in the period 2011 to 2015 inclusive. The Cam River at Marsh Road has consistently high fine sediment cover (90 to 100%); the Cam at Bramleys Road has increased fine sediment cover, peaking at 80% in 2012; the South Brook at Marsh Road is below the LWRP outcomes

²⁴ Invertebrate communities were not monitored at the other sites of interest to this investigation

²⁵ Greer and Meredith (2016) note: “Generally, the higher the QMCI score the better the water and habitat quality. Invertebrate communities with a QMCI score below 4 are indicative of poor water quality, communities with a score between 4 and 5 are indicative of fair water quality, communities with a score between 5 and 6 are indicative of good water quality, and communities with a score above 6 are indicative of excellent water quality (Stark and Maxted, 2007). When these grades were established the key concern of the time was point source discharges of agricultural, industrial and urban wastes, and the grades were used as indicators of the level of organic pollution. Nowadays, point source discharges are less common in Canterbury, and the predominant drivers of stream health are diffuse nutrient discharges, habitat degradation and abstraction for irrigation. Consequently, when considering the drivers behind low QMCI scores consideration must be given to a range of habitat and water quality parameters, not just traditional metrics of pollution such as nutrient and toxicant concentrations.”

²⁶ It is noted that the one year of fine sediment data for the Kaiapoi River at Heywards Road has up to 90% cover (median around 20% cover), but has high QMCI scores indicating good to excellent water quality. The reported sediment cover may not reflect normal conditions.

for 3 of 5 years; and the North Brook at Marsh Road has increased fine sediment cover (from 10% to 80%) in the period of record.

Table A2: 2 Maximum fine sediment cover (%) recorded from 2011 to 2015 in the Kaiapoi catchment. Highlighted values fail to meet the LWRP outcomes

	LWRP outcome	2011	2012	2013	2014	2015	Mean
Kaiapoi River @ Harpers Road		N/A	90	N/A	65	80	78
Kaiapoi River @ Heywards Rd		N/A	90	N/A	N/A	N/A	90
Kaiapoi River @ Island Rd		15	100	80	95	95	77
Cust River @ Skewbridge Rd		15	10	60	20	30	27
Ohoka River @ Island Rd	20	30	5	60	20	30	29
Cam River @ Marsh Rd		90	100	100	95	100	97
Cam River @ Bramleys Road		10	15	40	80	40	37
South Brook @ Marsh Rd		20	25	25	15	20	21
North Brook @ Marsh Rd		10	10	15	40	80	31

Single monthly water temperature and dissolved oxygen measurements are recognised as not being representative samples; but might identify LWRP outcome exceedences. Temperatures from all the spring-fed stream sites in the study area are low as expected (ranging from 13.3 to 15.8 °C). For the study sites minimum recorded dissolved oxygen saturation exceeds LWRP outcomes. The limited data suggests that water temperature and low dissolved oxygen may not be a critical issue.

Plant available nutrient concentrations (DIN: dissolved inorganic nitrogen is composed of nitrate-nitrite nitrogen (NNN) and ammoniacal nitrogen (NH₄N)) were sufficiently high in all spring-fed streams in the Kaiapoi River catchment to allow macrophytes to proliferate. South Brook at Marsh Road was in the high range with median values exceeding the 90% probability of nuisance macrophyte growths. North Brook and the Cam River sites were usually below the 70% probability of nuisance macrophyte growths.

Dissolved reactive phosphorus (DRP) is the readily available component of phosphorus for plant uptake, and, as with DIN, the higher the DRP concentration the greater the risk of nuisance periphyton and macrophyte growths. Cam River at Marsh Road median DRP concentrations exceed the 70% probability of nuisance macrophyte growth; and the other study area sites median values were below the 30% probability of nuisance macrophyte growths.

It is noted by Greer & Meredith (2016) that “Nutrient availability is just one of a number of factors that influence macrophyte growth in spring-fed streams, and elevated DIN and DRP concentrations will not always result in nuisance macrophyte growths. However, as nuisance macrophyte growths **have been regularly observed** in most spring-fed streams in the Kaiapoi River catchment, it is apparent that factors such as light availability, flow conditions and rooting substrate are not limiting macrophyte growth, and current DIN and DRP concentrations are sufficient for nuisance growths in these streams.”

There is a downward trend in plant available nutrients (DIN) and dissolved reactive phosphorus (DRP) for the Cam at Bramleys Road and South Brook at Marsh Road. Trends at North Brook are flow dependent (DIN -4% flow adjusted; 0% unadjusted; DRP +4% flow adjusted; -5% unadjusted). There is a negative trend for DIN (-1%) unadjusted flow for the Cam at Marsh Road, with no trend for DRP.

Nutrients may also be habitat limiting toxicants. Nitrate-nitrite nitrogen (NNN) concentrations were much lower in the Cam River catchment, than in the

Kaiapoi, Cust and Ohoka Rivers, and Greer & Meredith (2016) concluded it is unlikely that nitrate toxicity is having detrimental effects on ecosystem health in this system. Ammonia toxicity (NH_4N total ammoniacal nitrogen) concentrations are below the 99% threshold for biodiversity protection at all study sites apart from South Brook at Marsh Road, where most of the measurements are less than the 95% threshold for biodiversity protection. Therefore, there is a low risk of ammonia toxicity negatively affecting invertebrate communities.

NNN concentrations are stable or downward trending at the study sites. Under the NPS for freshwater management (MFE 2014) national bottom lines for nitrate toxicity are not being met in the upper Kaiapoi River which requires better management of nutrient inputs to meet the C band requirement at Harpers Road. Median values for Cam system sites are below the A band; with a high degree of protection of biodiversity (99%), the exception being South Brook at Marsh Road with is generally between the A and B bands (Figure A2: 1). The 95th percentile values (1.87 mg/L, 2.22 mg/L, 1.78 mg/L and 3.5 mg/L for the Cam at Marsh Road, Cam at Bramleys Road, North Brook at Marsh Road and South Brook at Marsh Road, respectively, exceed the threshold for 99% protection of biodiversity, but not the 95% protection level.

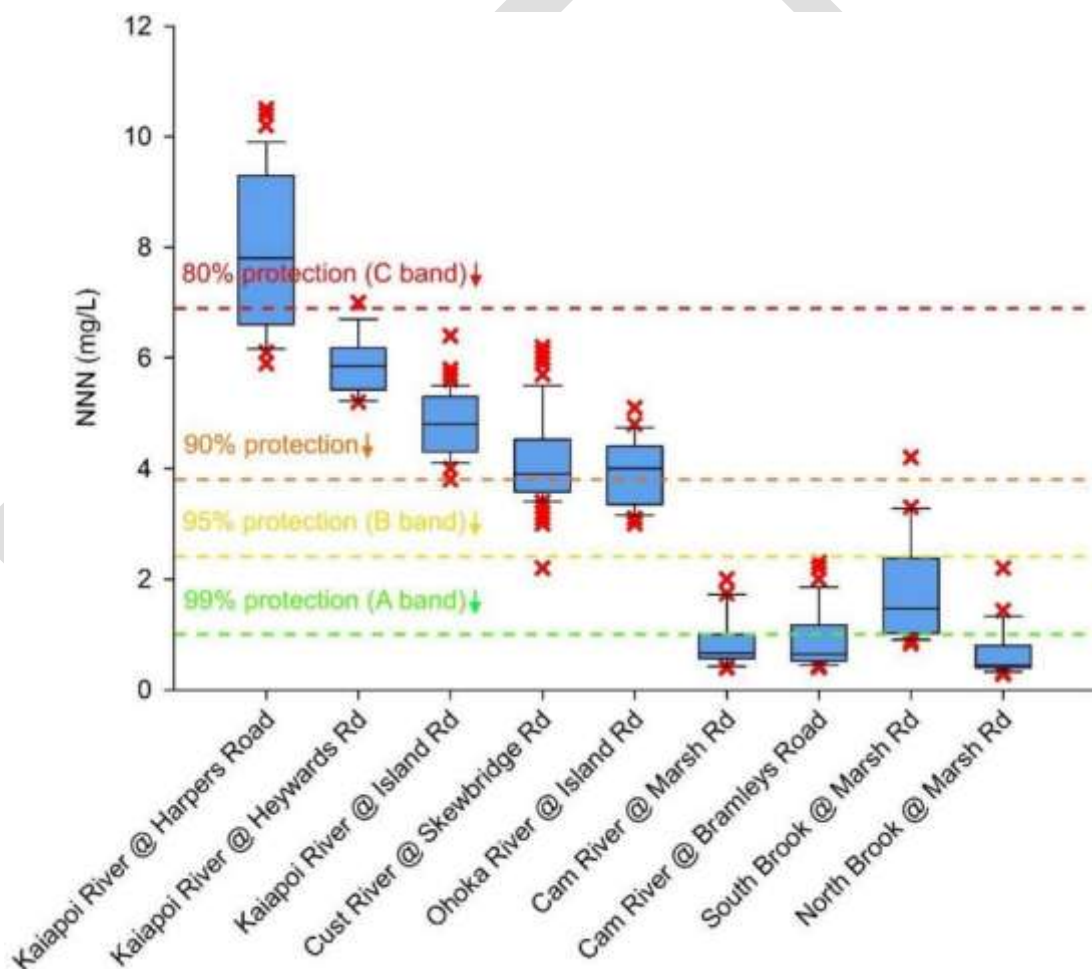


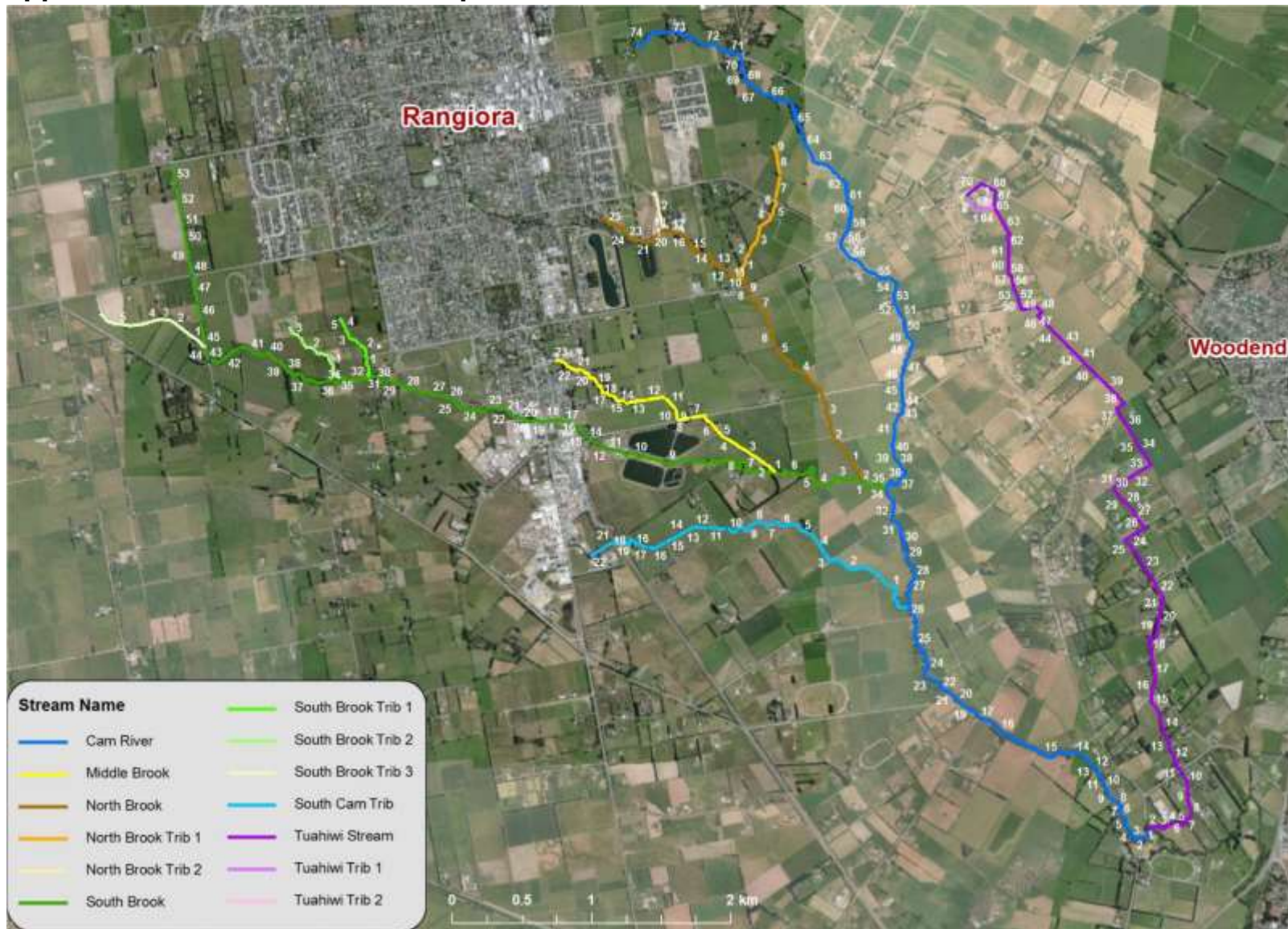
Figure A2: 1 Distribution of NNN concentrations, with thresholds for the protection of biodiversity from nitrate toxicity (Hickey 2013) and NPS (2014) bands.

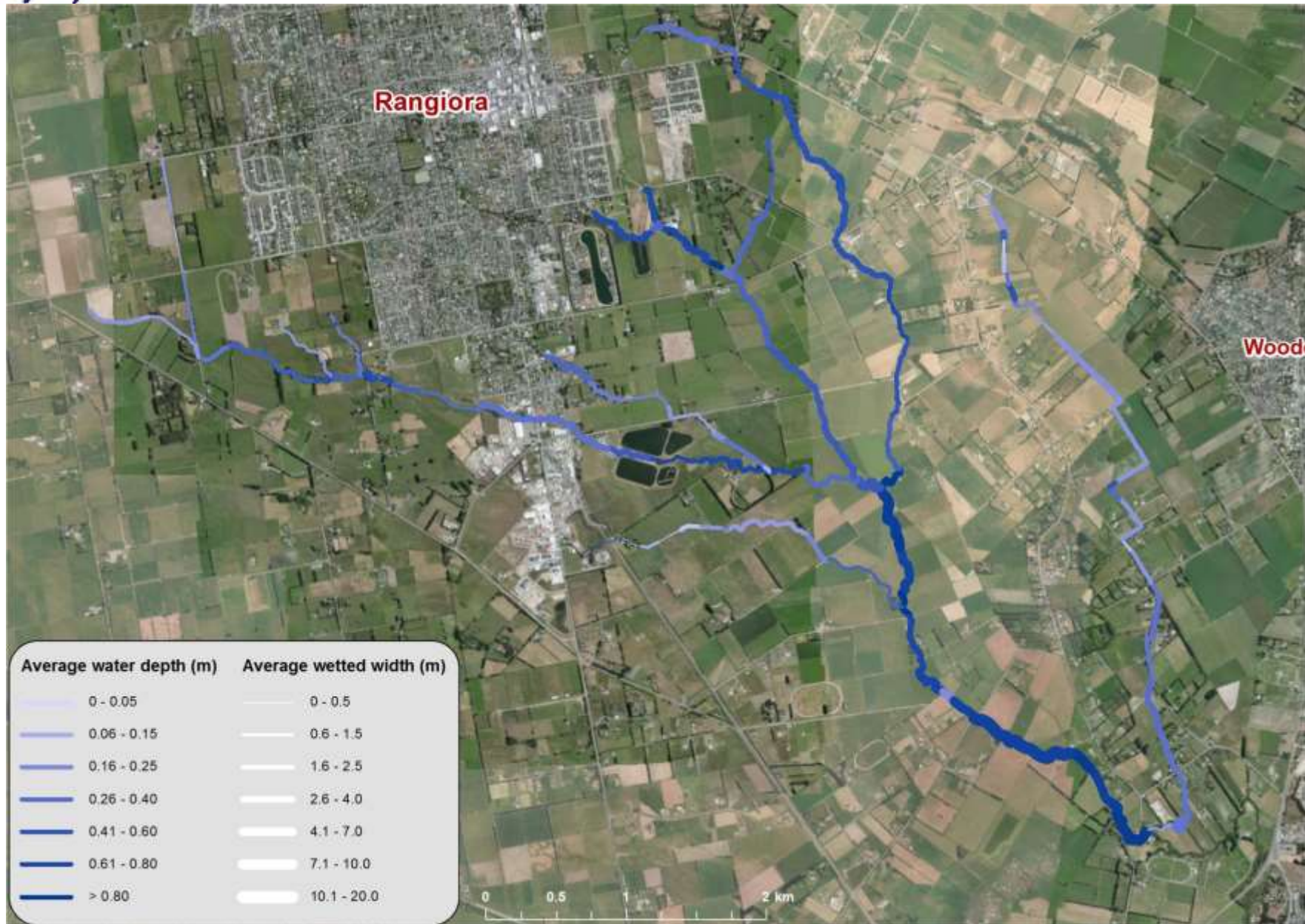
Recorded total suspended solid (TSS) concentrations are relatively low at the study sites (i.e. less than the 25 mg/L TSS threshold for onset of detrimental effects). However, it should be noted that it is likely that measurements were not taken during the rising stages of a flood when concentrations are expected to be greatest.

All of the sites in the Kaiapoi catchment are above the alert level for *E.coli*. Most of the measurements for the Cam at Marsh Road and Bramleys Road exceed the threshold at which a site is considered unsuitable for contact recreation. Some exceedances also occur on the South Brook and North Brook, but the majority of measurements are between the alert level and unsuitable for contact recreation level. The Cam sites are trending up for unadjusted flows whereas the South and North brooks are trending down for the period of record (1999-2016).

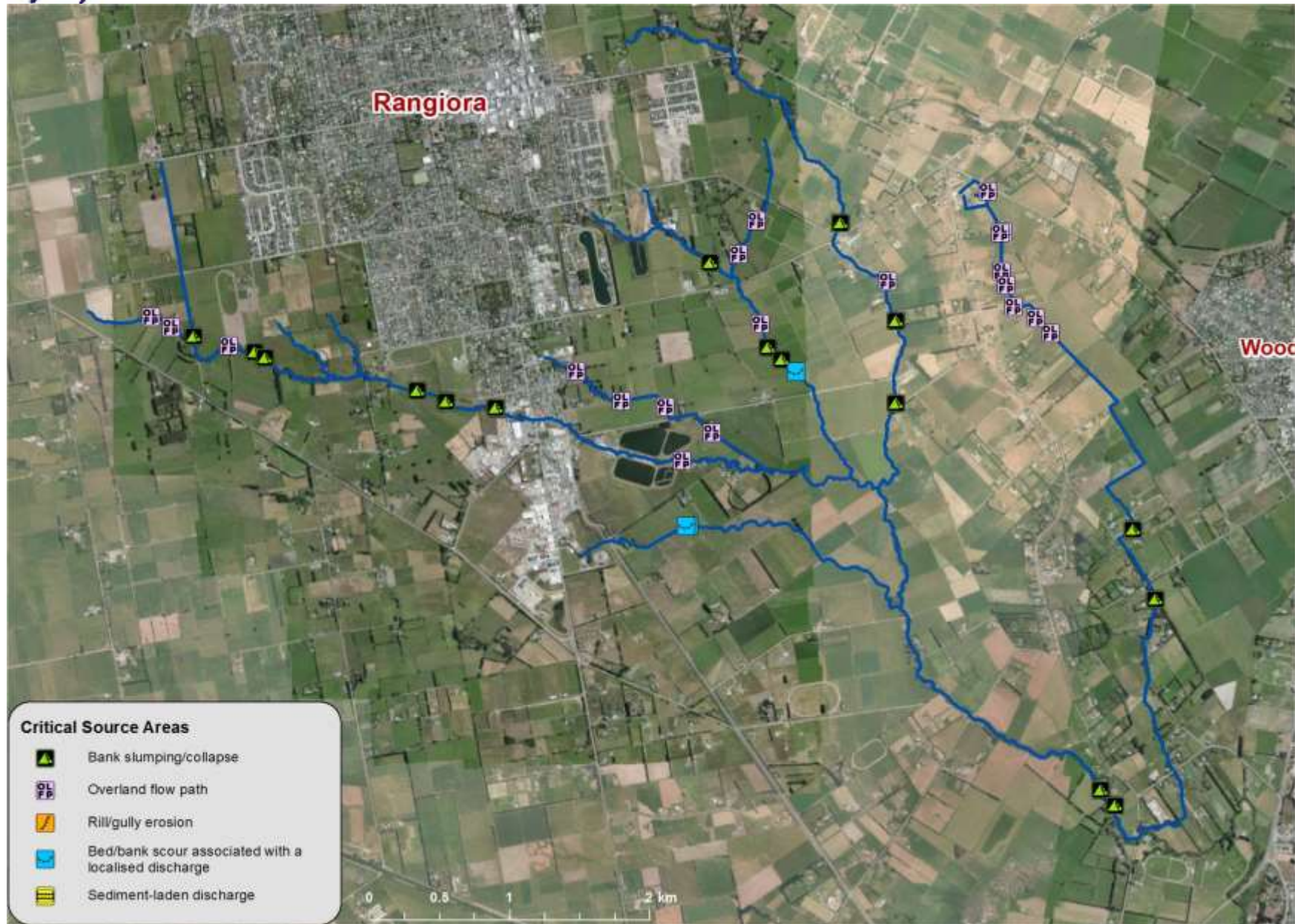
Greer & Meredith (2016) do not report on habitat grade; but Greer (2015) has done so in a memorandum to the Waimakariri Zone Committee. Only two sites in the study area were reported. The Cam River at Bramleys Road had an average grade of good and has been graded as fair or good for each of the last five years. For the same period, the South Brook at Marsh Road had an average grade of poor, ranging from fair to very poor.

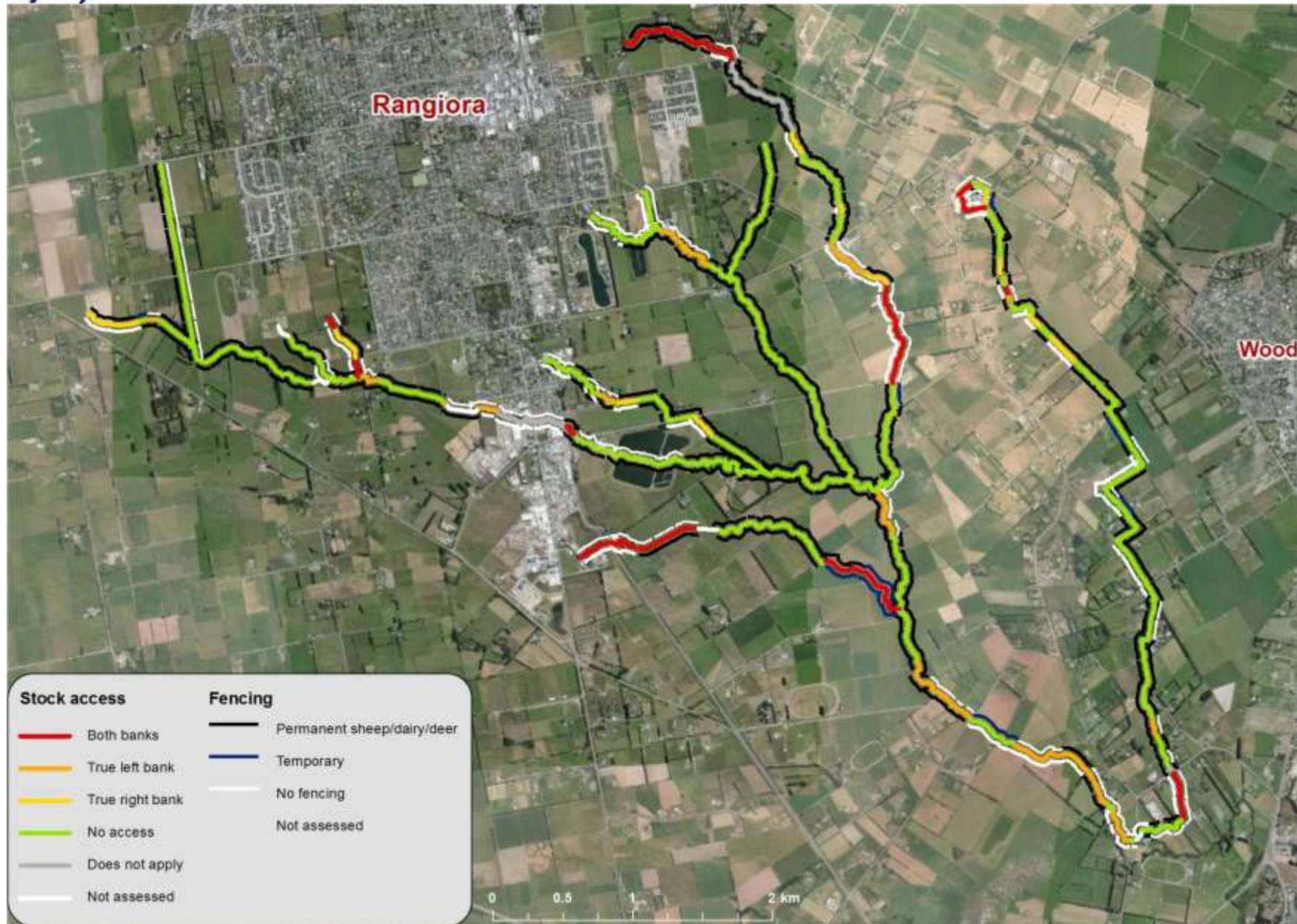
Appendix 3: ECan stream walk maps













Appendix 4: WDC waterway work maps

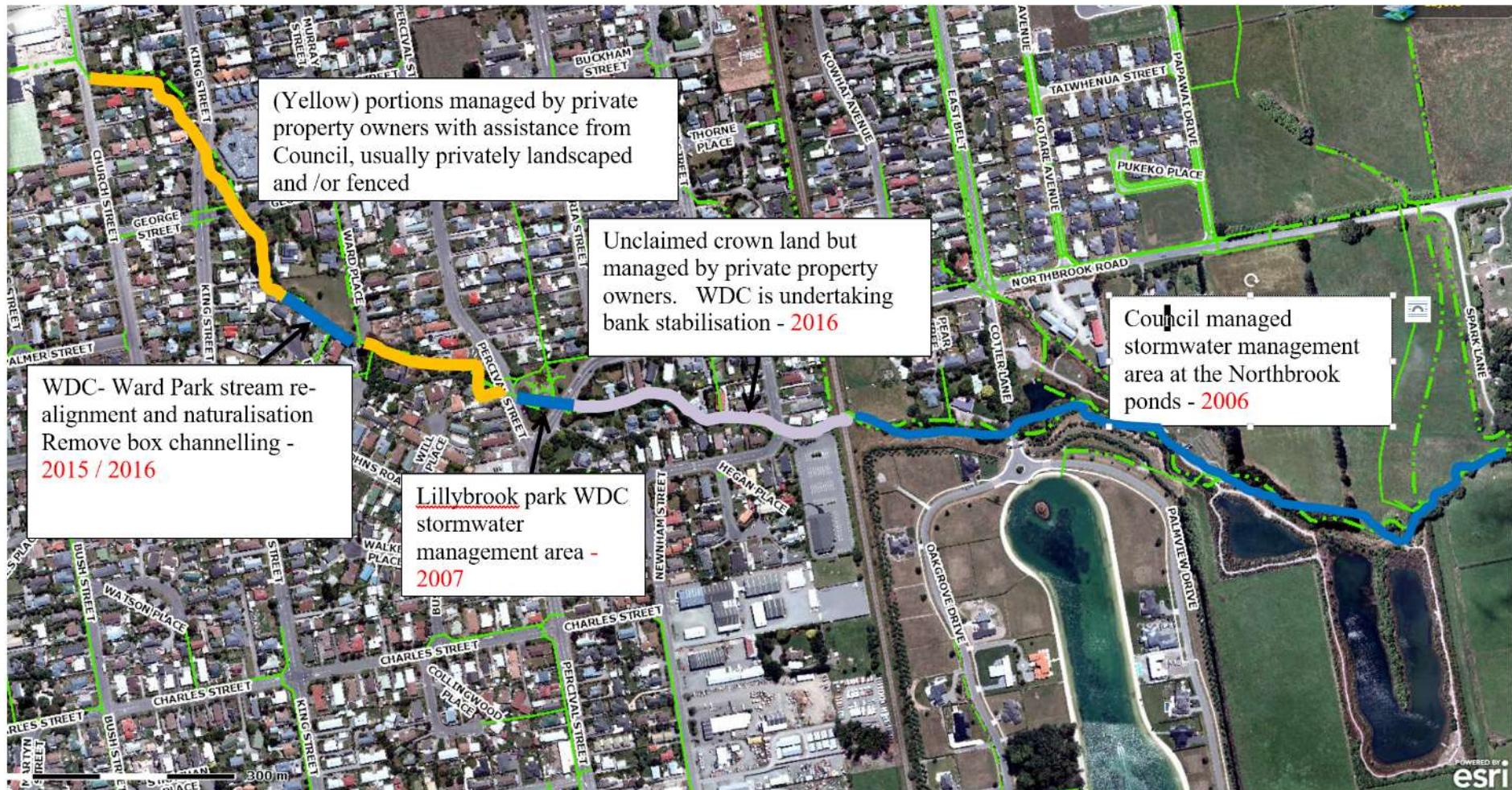
North Brook (Spring Heads originating at North West of Town) to Dudley Park

Legend

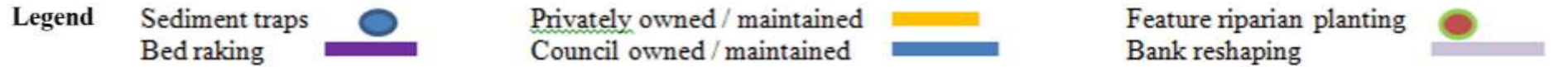
Sediment traps		Privately owned / maintained		Feature riparian planting	
Bed raking		Council owned / maintained		Bank reshaping	



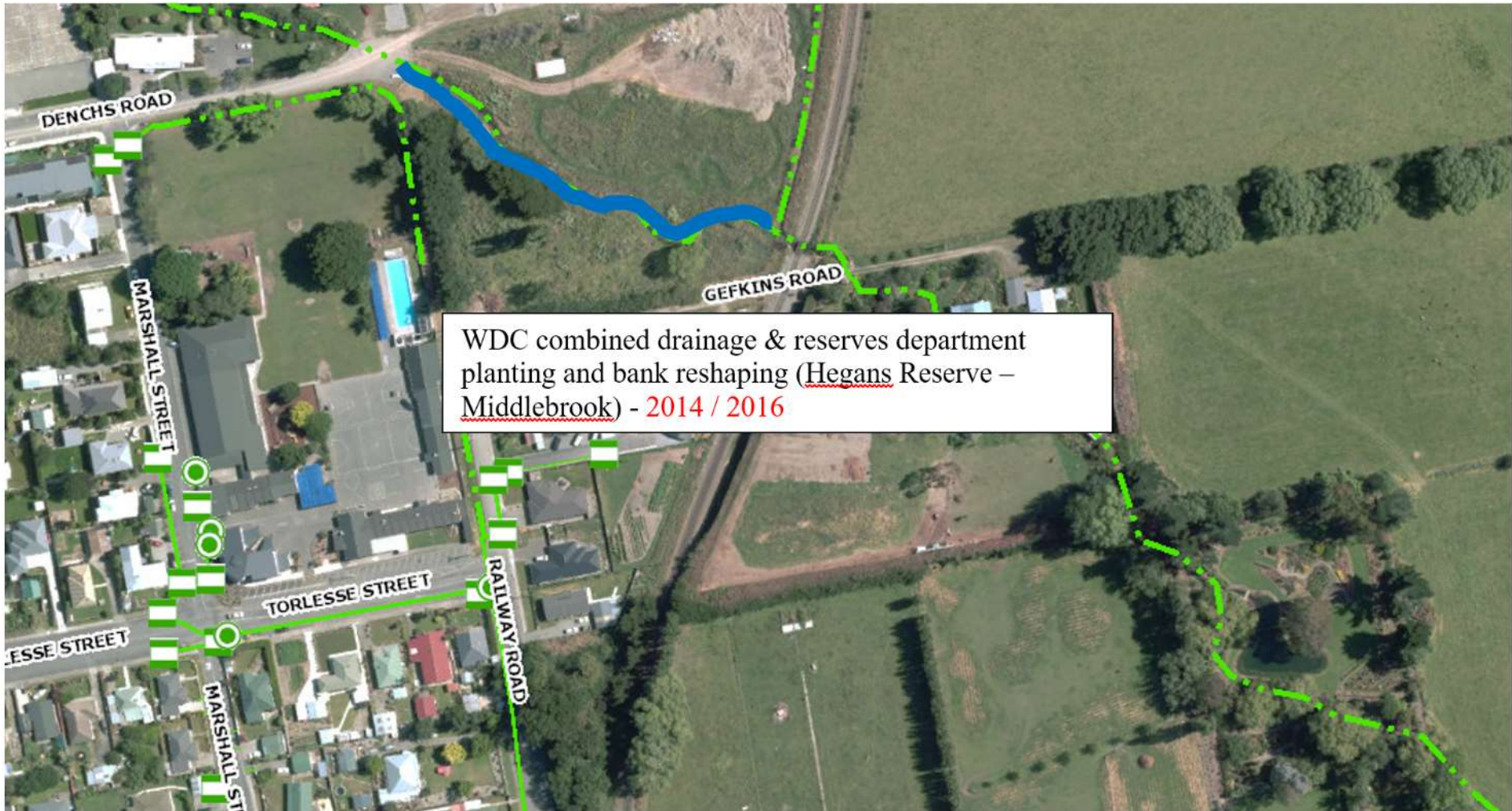
North Brook Dudley Park to Northbrook Ponds



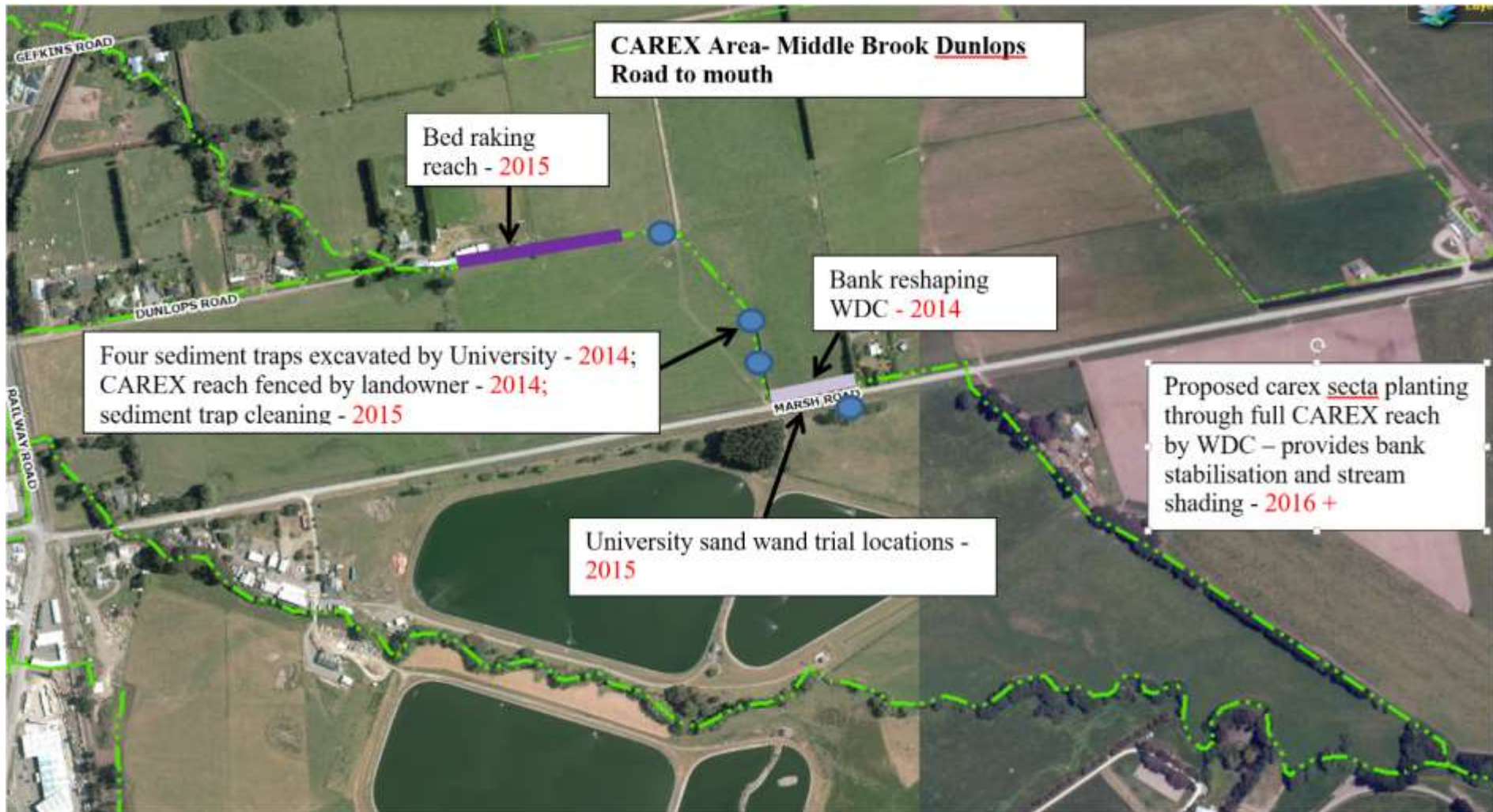
Middle Brook



Middle Brook Denchs Road to above Dunlops Road



Middle Brook CAREX reach



Southbrook West of Rangiora

Sediment traps



Bed raking



Privately owned / maintained



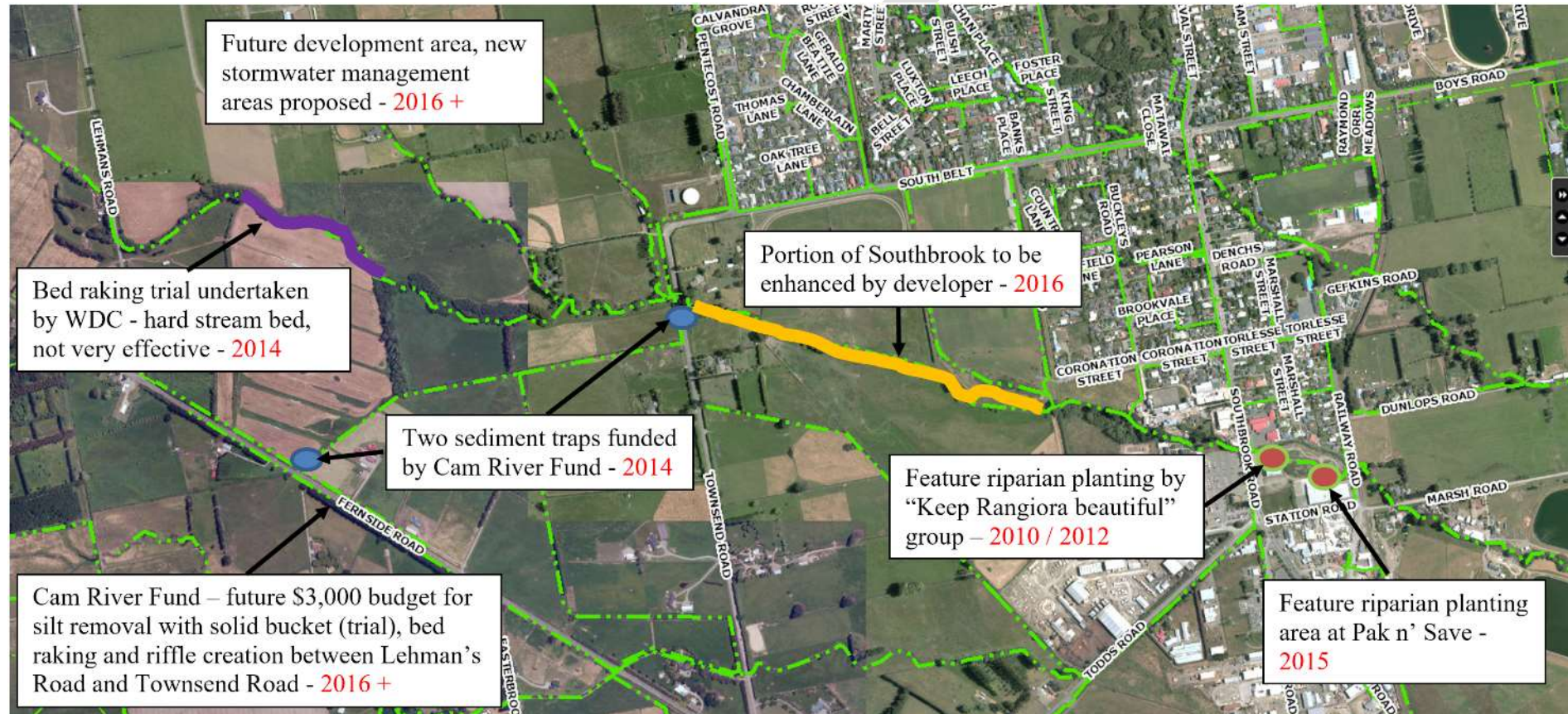
Council owned / maintained



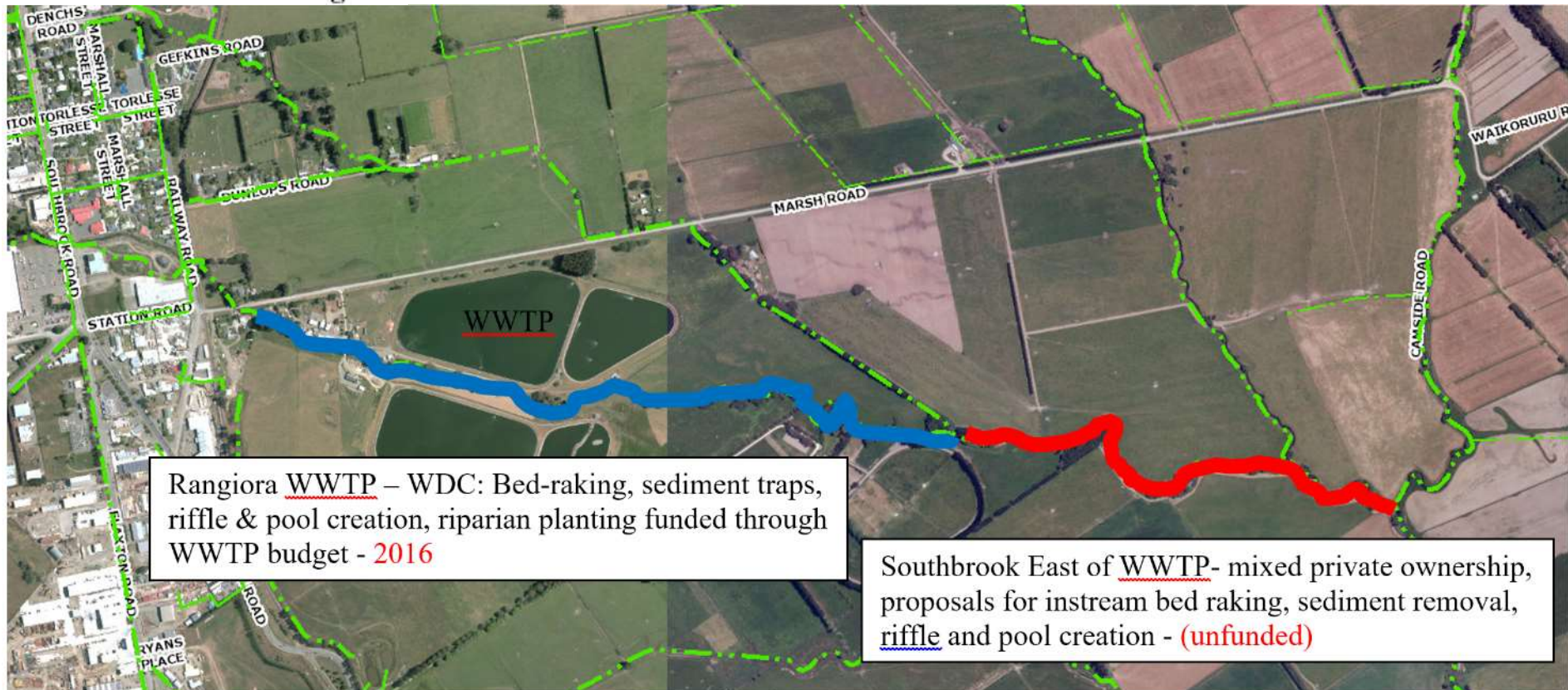
Feature riparian planting



Bank reshaping



South Brook East of Rangiora



Tuahiwi Drain: Rangiora Woodend Road to Okaihau Road



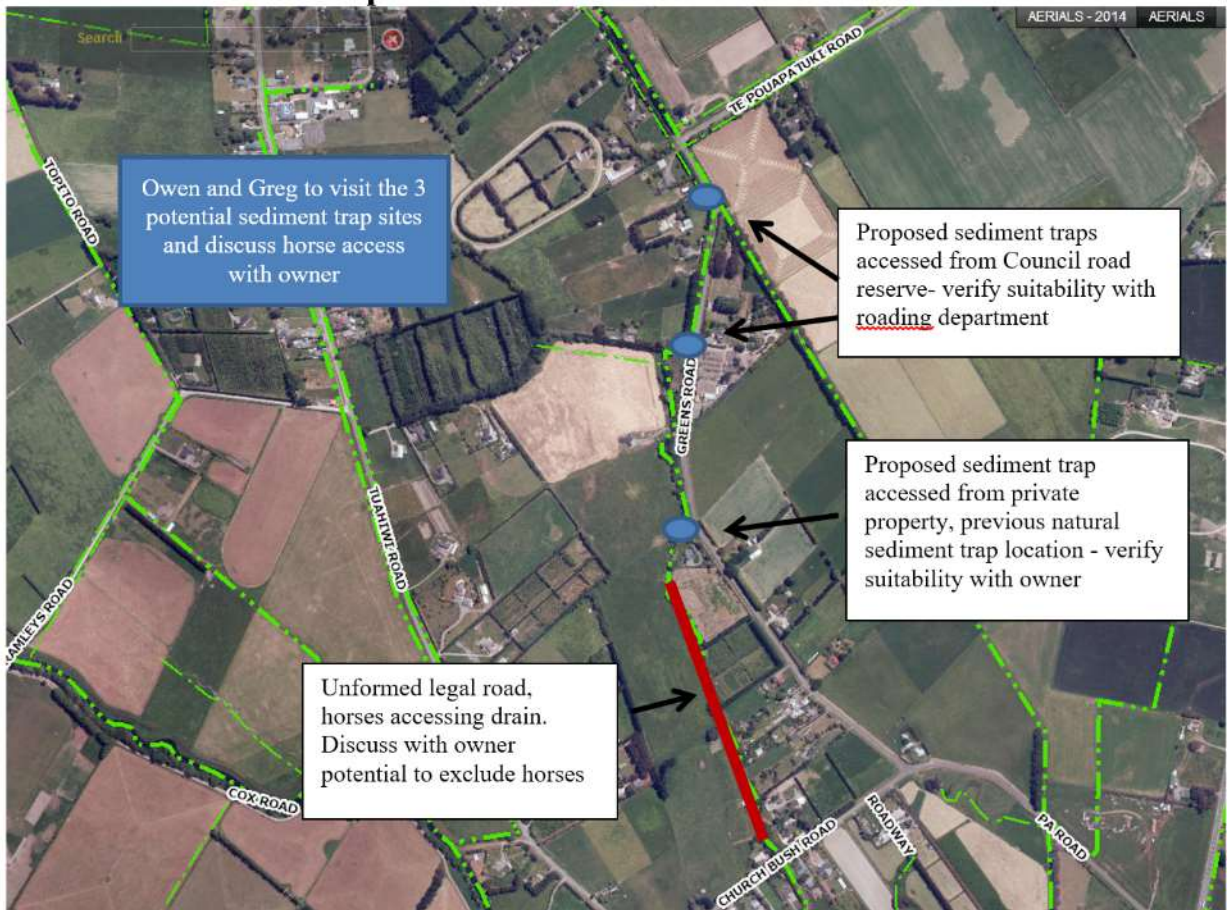
Tuahiwi Drain: Okaihau Road to Turiwhaia Road



Tuahiwi Drain: Turiwhaia Road to Te Pouapatuki Road



Tuahiwi Drain: Te Pouapatuki Road to Church Bush Road



Appendix 5: Tuahiwi Stream (Maori Drain)

Citation: Hudson, H.R. 2013. Drainage rehabilitation and low impact development: issues and options for Maori Reserve 873. Environmental Management Associates, Christchurch, Report 2013-01 for Waimakariri District Council. 110 pages.

Abstract

Waimakariri District Council (Council) is exploring options for a District Plan Change to provide the opportunity for additional housing and related living activities on Maori Reserve 873. As part of the proposed consultation and discussion, existing surface water drainage related issues of the 6.2 km Maori Drain are reviewed and management options are recommended.

Maori Drain is in a degraded state with limited aesthetic and ecological values. The objectives are to protect and enhance these values, while retaining drainage efficiency and lowering long term maintenance costs. Proposed measures are to control generation of sediment and contaminants from the catchment and channel, to trap and treat sediment and contaminants with buffers, bank reshaping and planting, and by removing excessive fine sediment deposits from the drain bed. Performance based management measures are required.

In addition, options to selectively rehabilitate elements of a natural watercourse are recommended, and management measures to protect the watercourse and receiving waters with future development of the 1068 ha Reserve are proposed. These measures include creating wetlands, green corridors and low impact development.

Maori Drain has been a notable source of sediment and contaminants; hence the measures proposed for the drain are an important element of the rehabilitation of the Cam and Kaiapoi rivers. These recommendations are also consistent with the Kainga-Nohoanga concept and scoping report for development of the Reserve and with the urban development strategy for greater Christchurch.

The greatest hurdles are not technical, but socio-economic. Clearly there are significant costs associated with extensive riparian planting, bank reshaping and channel works. The recommended actions may be at least partially funded through existing initiatives. However, the biggest hurdle may prove to be social. Maori Reserve 873 consists of multiple small holdings and owners and it may be difficult to achieve a common vision to enhance and rehabilitate the aquatic environment in a catchment context.

This report acknowledges the partnership Council has with Ngai Tuahuriri.

Conclusions and recommendations

Maori Drain is degraded because of excessive fine sediment and contaminants; and this situation is likely to continue unless further action is taken. It is futile to attempt to enhance or rehabilitate the drain unless inputs of sediment and contaminants are controlled. Specifically, to protect and enhance the existing drain the following are recommended:

1. **Catchment management:** Reduce inputs of sediment and contaminants from existing land uses by applying upland runoff, erosion and sediment control measures; and improved land use management practices.

2. **Riparian management:** Reduce inputs of sediment and contaminants with more extensive buffer strips; stabilise channel banks with reshaping and plantings; and control stock access to waterways (to prevent bank collapse and bed disturbance and prevent livestock defecation in watercourses).

Site investigations are required to identify and prioritize critical sites for the establishment of riparian buffers, bank reshaping and streamside planting.

Even if inputs are significantly reduced, existing extensive fine sediment deposits will probably continue to limit aquatic habitat and amenity values for decades. Flushing flows are limited in this groundwater dominated drain, but bed disturbance and minor increases in flow cause plumes of sediment to be resuspended and move downstream. A continued management focus on weed control in the lower two thirds of Maori Drain will not in itself address these issues. To improve habitat and amenity values, and optimize drainage management, the following enhancements are recommended (once recommendations 1 and 2 have been given effect to and sediment inputs are under control):

3. **Sediment removal:** Remove excessive fine sediment deposits from Maori Drain.
4. **Drainage efficiency management:** Performance based management criteria should be developed to determine drainage outfall requirements, and work windows should be used to determine the most appropriate time for drainage maintenance.

Maori Drain was constructed to dewater extensive swamps, with a focus on hydraulic efficiency. The drain is typified by long straight sections, steep sides, a flat base and shallow slow moving water. Although the removal of fine sediment from the drain will be an enhancement (recommendation 3), there is an opportunity to rehabilitate aspects of a natural stream and trap and treat sediment and contaminants. The objectives are to improve aeration and habitat, create threads of higher velocity to maintain a weed and fine sediment free corridor, and to trap and treat sediment and contaminants in selected areas to limit downstream spread. Specifically:

5. **Channel naturalisation:** Selectively create pool-riffle bed forms and a more asymmetric, sinuous channel pattern.
At one end of the spectrum this may be an extension of the sediment removal recommended in 3, involving redistributing bed material with a weed rake within the existing channel corridor.
A greater level of naturalisation would be construction of linear wetlands in two stage channels with linear wetlands to trap and treat sediment and contaminants in Maori Drain. These linear wetlands may be incorporated into the bank reshaping and riparian planting (recommendation 2).
At the upper end of the spectrum a meandering channel could be constructed along the existing alignment or in a different position.
6. **In-channel trap and treatment:** Control downstream movement of sediment and contaminants with traps and filters. Deep pools can be constructed as sediment traps (as part of recommendation 5) and several existing pools can be enhanced and managed as sediment traps.
7. **Tributary wetlands:** Construct wetlands to trap and treat sediment and contaminants from tributary surface and subsurface drains.

The viability of any of these measures is dependent on controlling the generation of runoff and sediment and contaminants from the rural landscape and with urban development. These measures are central to low impact design. Creating a naturalised stream corridor of channels and wetlands would be an integral component of the green infrastructure connections for the built environment.

The proposed measures are an important element of the rehabilitation of the Cam and Kaiapoi rivers, and are consistent with the concepts underlying the Kainga-Nohoanga proposal for the Reserve and the urban development strategy for greater Christchurch.

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