Ecosystem health in highly modified lowland catchments:

Karamū catchment, Hawkes Bay

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Executive summary

This report is a synthesis of information from a scientific workshop held in Hawkes Bay on "Ecosystem health in highly modified lowland catchments". The workshop was hosted by the Hawkes Bay Regional Council (HBRC) and Karamū catchment was used as a focus catchment to frame the discussion. This catchment is one of four catchments subject to a proposed plan change. The primary objective of the workshop was to identify which management actions would be most likely to improve stream ecosystem health in lowland catchments such as the Karamū, while also protecting other catchment and downstream values. Riparian management and nutrient reduction were options of particular interest. Information gathered at the workshop was intended to inform the TANK stakeholder group.

The Karamū catchment is characterised by streams that have been extensively modified, channelized and straightened for drainage and flood protection, and the land is widely tile drained. The streams are typically low gradient with a sandy or silty bed. The Karamū is one of three catchments that feed into the Waitangi estuary, which is classified as a Significant Conservation Area in the Regional Coastal Environment Plan. Land use in the catchment is predominantly dry stock farming in the upper catchment and a mixture of horticulture and urban development (including the city of Hastings) in the lower catchment.

The major ecosystem health issues of concern in the catchment streams are:

- chronically low dissolved oxygen levels
- high water temperatures
- elevated nutrient concentrations, and
- nuisance growths of aquatic plants (macrophytes and attached algae).

In the estuary, elevated sediment and nutrient inputs are of particular concern. The estuary periodically experiences planktonic algal blooms and nuisance growths of macroalgae, and large pulses of sediment.

Management options that were considered in the workshop included:

- riparian management (i.e., fencing and planting)
- nutrient reduction, and
- other tools to reduce aquatic plant abundance (i.e., herbicides, grass carp and manual/mechanical removal).

Riparian management was considered to be the option most likely to achieve long-term improvement in ecosystem health in the Karamū/Clive catchment. It is anticipated that planted stream banks in appropriate locations within the catchment would increase shading thereby reducing the abundance of instream plants and thus the oxygen they consume and it would also moderate water temperatures. Other benefits of this activity would likely include trapping of sediment and nutrients in land runoff and enhanced aesthetic appeal. In comparison the other management options that were considered seem likely to provide only limited and short-lived benefit, or benefits were highly uncertain, or could potentially result in more serious harm to

ecosystem health. However, low impact activities like cutting with rake removal and herbicide use could be used as interim measures to reduce instream plant abundance while riparian plantings establish.

Review of available literature combined with scientist observations suggest that a shading level of at least 70% would be required to reduce abundance of emergent, sprawling and floating plants and attached algae while a higher shading level (probably >90%) may be required to reduce the abundance of submerged plants. In smaller streams and drains, 70% shade is easily achieved by riparian planting.

The workshop group identified a number of priority locations in the catchment to target riparian management activities. These locations are those which: (1) frequently experience very low dissolved oxygen levels, (2) have low flows that cannot be increased to achieve oxygen targets, (3) have a channel that is narrow enough or orientated in such a way that sufficient shade can be created, especially with low stature plantings; (4) will not significantly impede flood control; (5) are in the headwaters to enable a contiguous riparian buffer to be created; (6) would enhance aesthetic, amenity and/or cultural values; (7) have supportive adjacent landowners; (8) where funding for the works can be more easily acquired; and (8) implementation costs are not prohibitive. This approach is consistent with the recently updated Te Karamū Enhancement Strategy.

We recommend implementing riparian management first as a number of case-study examples to confirm the anticipated benefits prior to widespread adoption. Ideally these case-studies should (1) involve the local community in planning, implementation and monitoring; (2) be carefully designed with appropriate scientific expertise to ensure that anticipated outcomes are realistic and can be satisfactorily demonstrated; and (3) be carried out in different land use areas to illustrate the diversity of potential benefits across the wider catchment.

1 Introduction

Many of New Zealand's lowland stream catchments are highly modified, macrophyte-dominated systems with poor ecosystem health as indicated by low dissolved oxygen, high water temperatures and low macroinvertebrate community indices. The Karamū/Clive catchment on the Heretaunga Plains is an example.

This report is a synthesis of information presented and discussed at a workshop on "Ecosystem health in highly modified lowland catchments" hosted by the Hawkes Bay Regional Council (HBRC) on 15 November 2016, focused on the Karamū/Clive catchment. Seven staff members from HBRC participated in the workshop along with seven external scientific experts from NIWA, Cawthron Institute and University of Canterbury. Several background reports were provided to external experts in advance. The workshop comprised a two hour fieldtrip through the catchment in the morning to familiarise external experts with the issues first-hand, followed by a five hour presentation and discussion session in the HBRC Works Group offices in Taradale.

The Karamū catchment is one of 4 catchments (TANK: Tutaekuri, Ahuriri, Ngaruroro, Karamū) for which HBRC is currently working through a proposed plan change (Greater Heretaunga and Ahuriri). It is also one of three catchments that feed into the Waitangi estuary, which is classified as a Significant Conservation Area in the Regional Coastal Environment Plan (2012). The Plan Change will consider the NPS-FM in the context of the Hawkes Bay Land and Water Management Strategy. The focus of the Plan Change is on water quality, flows and allocations in the four targeted catchments, including for wetlands and estuaries. This workshop was intended to assist HBRC to provide information on appropriate freshwater objectives, limits and management actions to the TANK stakeholder group to protect and improve stream ecosystem health in the Karamū catchment.

The Karamū/Clive catchment on the Heretaunga Plains is one of New Zealand's most productive horticultural areas. It has 238 lineal kilometres of streams, covering an area of 514 km^2, with 11 subcatchments (Rewcastle 2016). The streams have been extensively modified, channelized and straightened for drainage and flood protection (see Figure 1-1), and the land is widely tile drained. Many streams in the catchment have a low gradient with a sandy or silty bed, which provide ideal growing conditions for macrophytes. The streams have high nutrient concentrations and are currently suffering from nuisance macrophyte and algal growth. Poor ecosystem health is reflected by biological indicators such as the macroinvertebrate community index (MCI).

The major ecosystem health issues in the Karamū catchment are chronically low dissolved oxygen levels, elevated water temperatures and excessive macrophyte and algal growths in lowland streams. These issues are also relevant in a national context. While the NPS-FM has to date provided some draft national guidance on desirable dissolved oxygen and periphyton attribute states in rivers (the former downstream of point sources), advice on how best to manage these attributes to comply with specific attribute states is not yet available.

The primary objective of the workshop was to identify which management actions would be most likely to improve stream ecosystem health in the Karamū catchment, while also protecting other values in the catchment and in the Waitangi estuary. The focus was on riparian management and nutrient reduction but discussion included other potentially relevant management actions to reduce aquatic plant abundance.

Figure 1-1: A typical stream in the Karamū/Clive catchment. Source: Hawkes Bay Regional Council.

Specifically, the workshop sought to address the following questions:

- What are the possible management actions that can be applied to improve stream ecosystem health (e.g., sediment and nutrient reductions, riparian planting and shade creation, macrophyte control)?
- How effective and feasible are each of these actions likely to be?
- Where in the catchment should these actions be applied or prioritised?
- What information including relevant guidelines or research is there to support the TANK Group decision making about the appropriate freshwater objectives (i.e., attribute and attribute states) to improve stream ecosystem health in the Karamū catchment (e.g., temperature, dissolved oxygen, periphyton, macrophytes, sediment).

2 The Karamū/Clive catchment

2.1 Land use

Land use is predominantly dry stock farming in the upper catchment and a mixture of horticulture and urban development in the lower catchment (Figure 2-1).

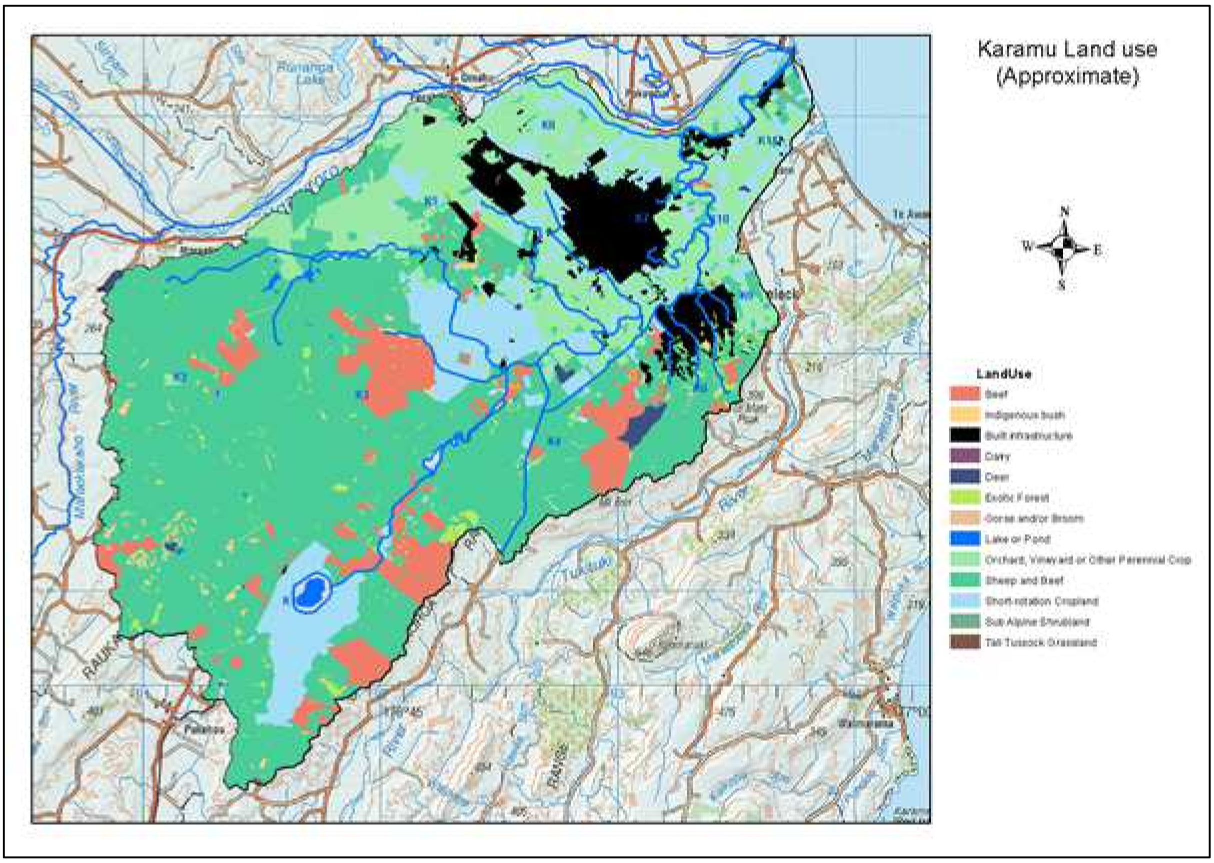

Figure 2-1: Land uses in the Karamū/Clive catchment. Source: Hawkes Bay Regional Council.

2.2 Stakeholder values

Ecosystem health is one of a number of stakeholder values that apply across the Karamū catchment. Several stakeholder values (i.e., cropping, orcharding, viticulture, industry, contact recreation, Operation Patiki: Flounder and inanga spawning habitat) apply only to the lower catchment (Table 2-1).

Table 2-1: Stakeholder values in the Karamū/Clive catchment. Source: Hawkes Bay Regional Council.

Upper catchment	Lower catchment (main stem)
Predominantly sheep and beef farming	Cropping, orcharding, viticulture, industry
	Contact recreation
	Operation Patiki: Flounder
	Inanga spawning habitat
Ecosystem health	
Fisheries, angling	
Food gathering	
Irrigation	
Household and urban water supply (drinking water)	
Flood protection	
Cultural: Mauri, Wairua, Taonga, Kaitiakitanga, Mana, Whakapapa, Waihi tapu	

2.3 Ecosystem health issues

2.3.1 Streams

The key ecosystem health issues in the catchment streams are considered to be:

- Excessive macrophyte & periphyton growth.
- Low dissolved oxygen.
- High water temperature.
- Sediments (as a potential source of phosphorus).
- Lack of habitat.

These have been identified from State of Environment (SOE) monitoring and other targeted scientific investigations within the catchment (see below). Faecal contamination (as indicated by *E.coli*) is a related issue with implications for contact recreation and water supply.

A summary analysis of SOE data by HBRC (Figure 2-2) indicates that for most or all monitoring sites data for macrophyte abundance, nutrients (particularly phosphorus), and clarity exceed recommended HBRC guidelines most of the time. Macrophyte abundance was compared to the 50% CAV provisional guideline recommended by Matheson et al. (2012). The toxicity guideline was used to evaluate nitrate concentrations. Stream phosphorus concentrations are ubiquitously high (and up to 0.4 mg/L) and exceed the 0.015 mg/L guideline at all sites. It is unclear whether this might be a natural or land management issue. Phosphorus concentrations are also high in deep groundwater. The macroinvertebrate community index (MCI) indicates poor ecosystem health at all but one site, even including gravel-bed streams. A targeted investigation carried out in summer 2014 in the Karamu catchment showed that water temperature can exceed 25°C (Figure 2-3) and dissolved oxygen can be significantly lower than 4 mg/L (Figure 2-4), which correlated with sites having particularly low MCI values (Haidekker 2016). Sensitive macroinvertebrates (e.g., EPT species) require a temperature of ≤19°C and DO >7.5 mg/L. Faecal contamination (indicated by *E. coli*) is an occasional problem.

Site name	E.coli	NO_3	Amm-N	Chla	MPh	DIN	TN	DRP	TP	Bdisk	Turbty	MCI
Ruahapia Strm	C	A	B			D	D	F	F	E	C	poor
Karewarewa Strm	C	C	C			E	F	F	F	D	C	poor
Awanui Strm	B	B	B			E	F	F	F	D	B	poor
Poukawa Strm	A	A	A			C	F	F	F	D	A	poor
Herehere Strm	D	B	A			C	D	F	F	C	C	poor
Mangarau Strm Keirunga Rd	B	A	A	D		B	C	F	F	E	C	fair
Mangarau Strm at Te Aute Rd	B	B	A	C		F	F	F	F	E	B	poor
Clive Rv	B	B	A			D	D	F	F	D	B	poor
Taipo Strm	C	A	C			D	E	F	F	F	D	poor

A	all data below GL
B	90th %ile above one or more GL, median below all
C	75th %ile above all GL, median above some GL
D	median above all GL
E	25th %ile above all GL
F	10th %ile above all GL
	not applicable
	no data

MCI	
excellent	> 120
good	100 - 120
fair	80 - 100
poor	< 80

Figure 2-2: Summary of water quality, macrophyte and macroinvertebrate data for Karamū streams in relation to recommended guidelines. Source: Hawkes Bay Regional Council. These are HBRC guidelines prior to the Clean Waters proposed revisions of the NPS-FM.

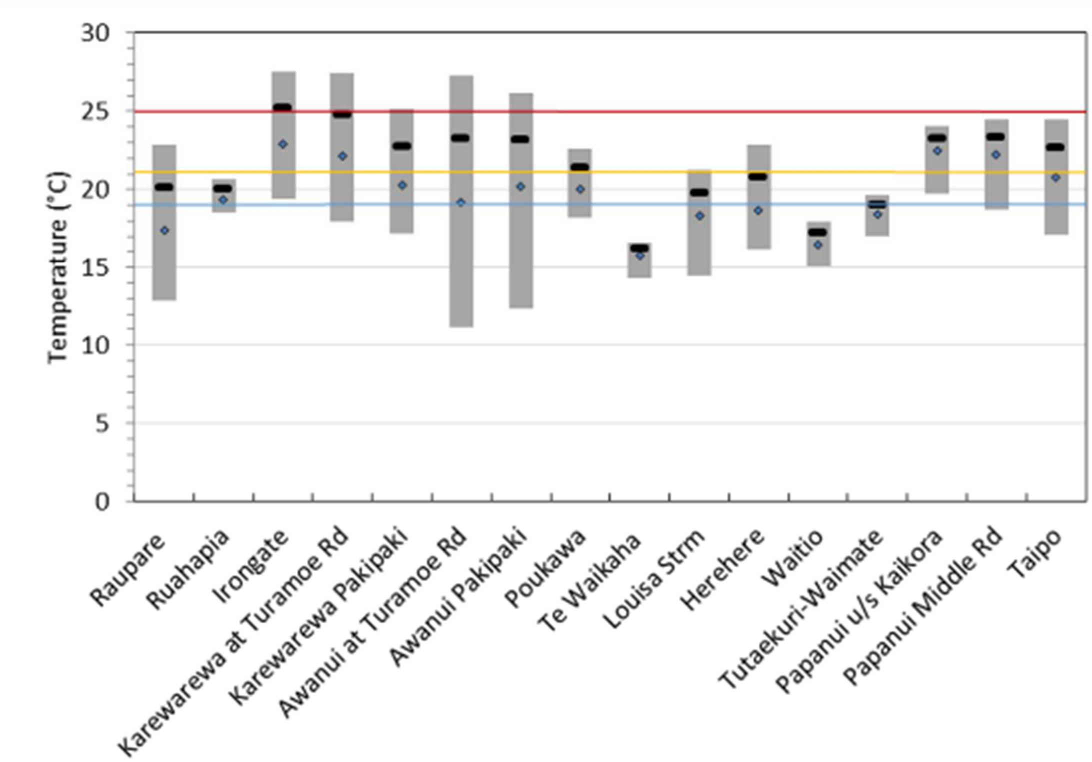

Figure 2-3: Water temperature across the lowland study sites in summer 2014. Source: Hawkes Bay Regional Council. Grey bars represent 2-hour minimum to 2-hour maximum water temperature from a continuous measurement over the period of logger deployment. Squares represent average water temperature. Black bars represent Cox-Rutherford-Index calculated as the average of the daily mean and maximum temperature. Lines represent proposed temperature regime thresholds for aquatic organisms using the Cox-Rutherford Index (Davies-Colley et al. 2013). Below blue line Band A: no stress caused on aquatic organisms; between blue and orange line Band B: occasional minor stress on sensitive organisms; between orange and red line Band C: some occasional thermal stress, with elimination of certain sensitive insects and absence of certain fish; above red line Band D: significant thermal stress on a range of aquatic organisms. Risk of local elimination of keystone species with loss of ecological integrity.

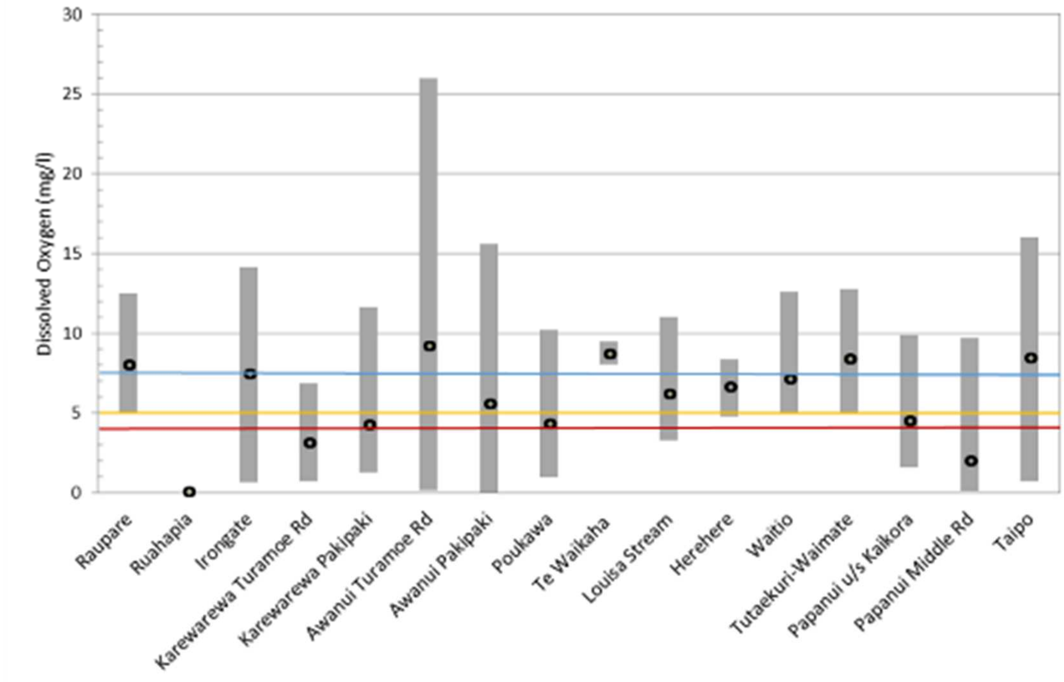

Figure 2-4: Dissolved oxygen concentration across the lowland study sites in summer 2014. Source: Hawkes Bay Regional Council. Grey bars represent 2-hour minimum to 2-hour maximum dissolved oxygen concentration from a continuous measurement over the period of logger deployment. Black dots represent average dissolved oxygen concentration. Lines represent proposed thresholds for ecological health (Davies-Colley et al. 2013). Above blue line Class A: no stress caused on aquatic organisms; above orange line Class B: occasional minor stress on sensitive organisms; above red line Class C: moderate stress on a number of aquatic organisms; below red line Class D: significant, persistent stress on a range of aquatic organisms, likelihood of local extinction of keystone species and loss of ecological integrity.

Most of the streams in the Karamū catchment have a low gradient and thus are 'soft-bottom' with mud or sand substrate. Only a small proportion of total stream length in the catchment consists of 'hard-bottom' substrates (Figure 2-5).

Springs dominate the flow of several streams on the Heretaunga Plains, including the Raupare, Irongate, Mangateretere and Tutaekuri-Waimate (see Figure 2-5 for locations). There are also large springs that make up much of the baseflow of the Karamu mainstem, downstream of the Mangateretere confluence (Wilding 2016). Most of the springs on the Greater Heretaunga Plains source their water from the Ngaruroro catchment. However, spring contributions are relatively small for the remainder of Karamu tributaries where nutrient levels are typically higher. Water conductivity (an indicator of total dissolved solids) is high in most of the stream length that has been measured in the Karamū/Clive catchment (Figure 2-6).

Modelling work has been performed to predict the percentage of stream mean annual low flow (MALF) required to maintain minimum dissolved oxygen concentrations at or above 40% of saturation (Wilding 2016). This analysis shows that MALF would need to be increased substantially (by 200% or more) in much of the catchment to keep minimum dissolved oxygen concentrations above 40% saturation (Figure 2-7).

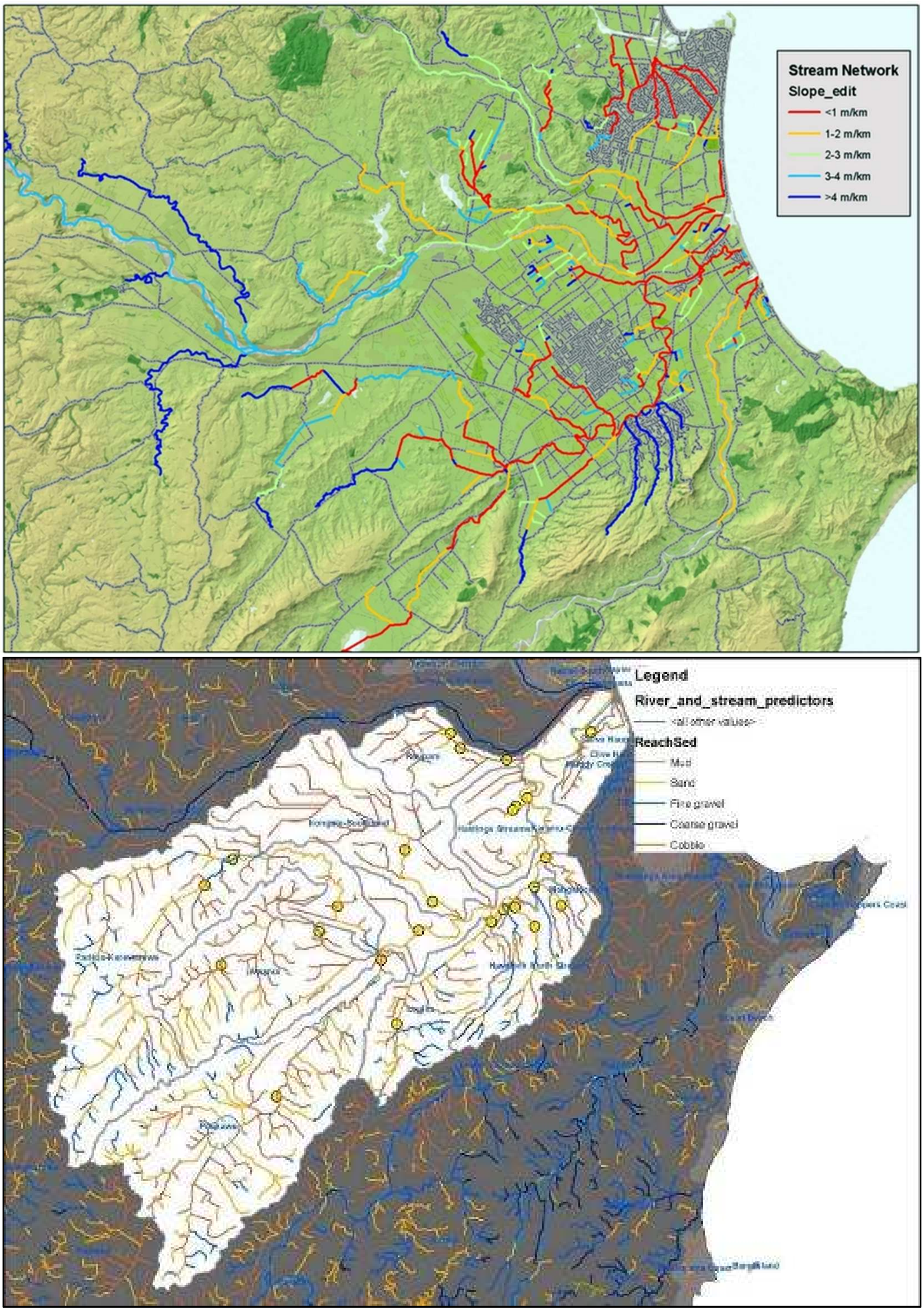

Figure 2-5: Stream gradient (top) and dominant bed substrate type (bottom) in the Karamū/Clive catchment. Source: Hawkes Bay Regional Council.

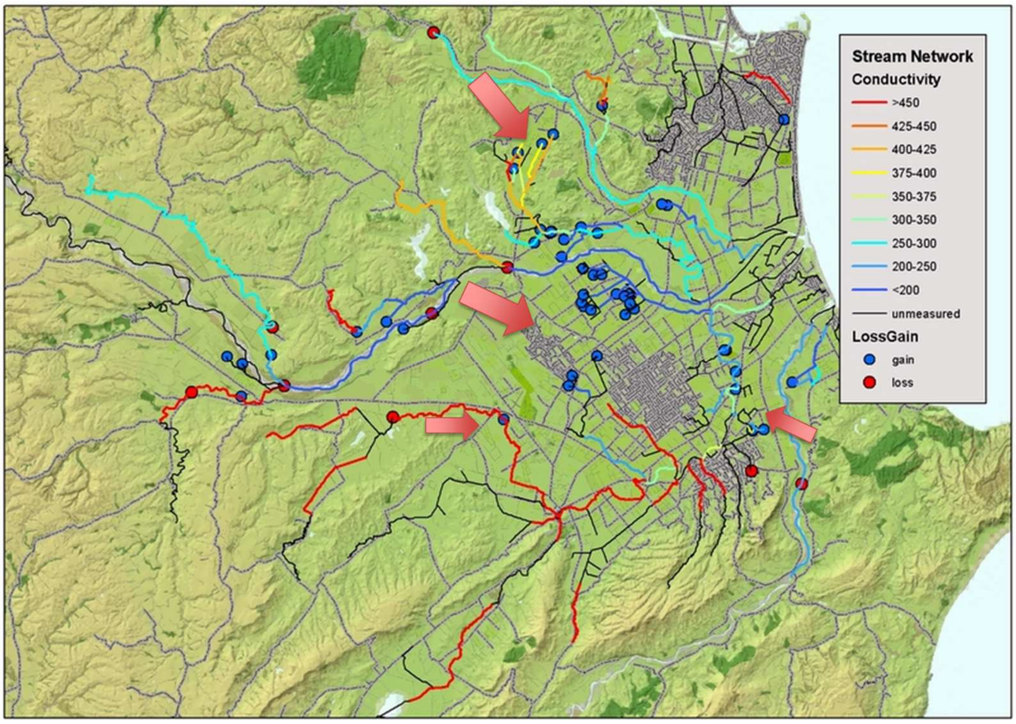

Figure 2-6: Location of springs (with loss or gain indicated) and stream electrical conductivity in µS/cm (top) in the Karamū/Clive catchment. Source: Hawkes Bay Regional Council.

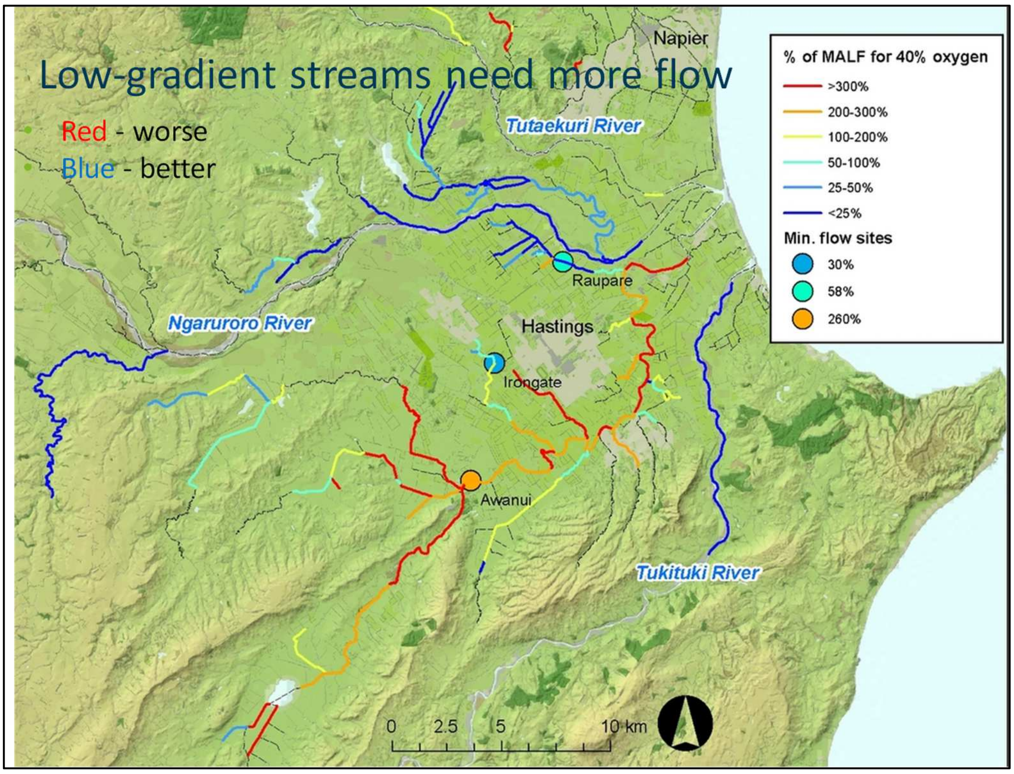

Figure 2-7: Percentage of stream mean annual low flow (MALF) required to maintain minimum 40% dissolved oxygen in Karamū/Clive catchment. Source: Hawkes Bay Regional Council.

Soil mapping shows variable accumulation of recent soil indicated by the depth to Taupo pumice layer (Figure 2-8). These indicate some of the more peaty areas in the catchment, particularly in the Upper Awanui and Louisa catchments. There are quite a few wetlands in the Louisa sub-catchment. These areas with higher recent soil accumulation correspond to streams with higher DIN levels. However the role that these soil deposits might play as a potential conduit for nutrients to these streams is unknown.

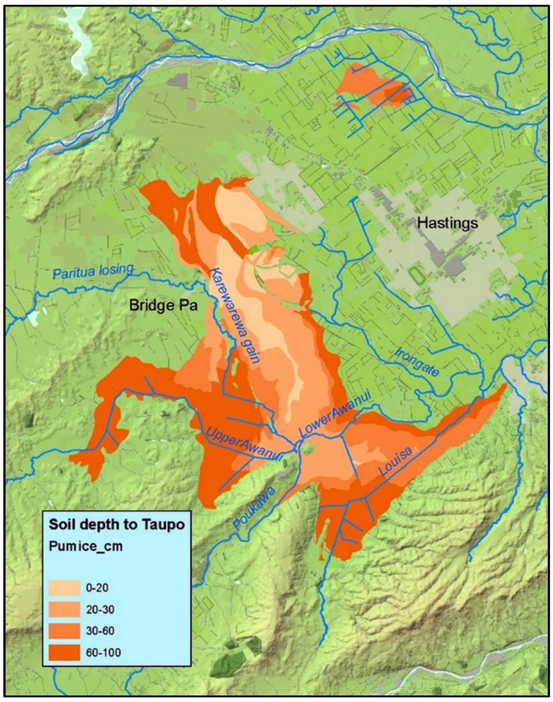

Figure 2-8: Soil depth overlying Taupo pumice layer for areas where soil mapping has been carried out in Karamū/Clive catchment. Source: Hawkes Bay Regional Council.

Continuous dissolved oxygen monitoring at selected sites in the catchment broadly supports the results of the modelling work (Wilding 2016). In the Raupare stream (see Figure 2-7 for location), modelling suggests that flows are generally sufficient to maintain minimum dissolved oxygen levels above satisfactory levels (Figure 2-9). Continuous monitoring of dissolved oxygen in this stream for one year showed concentrations above 4 mg/L (ca. 40% saturation) for all but 5 days. The lowest dissolved oxygen concentration recorded (3.7 mg/L) coincided with the lowest flow (283 L/s on 2 February 2013).

In the Awanui Stream (see Figure 2-7 for location), modelling indicated that flows at least twice the MALF would be required to maintain satisfactory minimum dissolved oxygen levels (Figure 2-9). Continuous field monitoring confirms that very low dissolved oxygen levels occur in this stream over the summer to autumn period. In fact zero oxygen was recorded at dawn for a period of 77 days and flows at this time were less than 50 L/s. Concurrent monitoring of aquatic plants shows that the period of low dissolved concentrations also coincides with the highest levels of cover of surface-reaching macrophytes (>50% cover) (Figure 2-10). These surface-reaching macrophytes are predominantly submerged species rather than emergent/sprawling marginal plants (Figure 2-11). Cover of the latter does not alter substantially over the summer-autumn period of low dissolved oxygen but cover of the submerged component does, indicating that these species have grown to the water surface and, consequently, are then designated as surface-reaching.

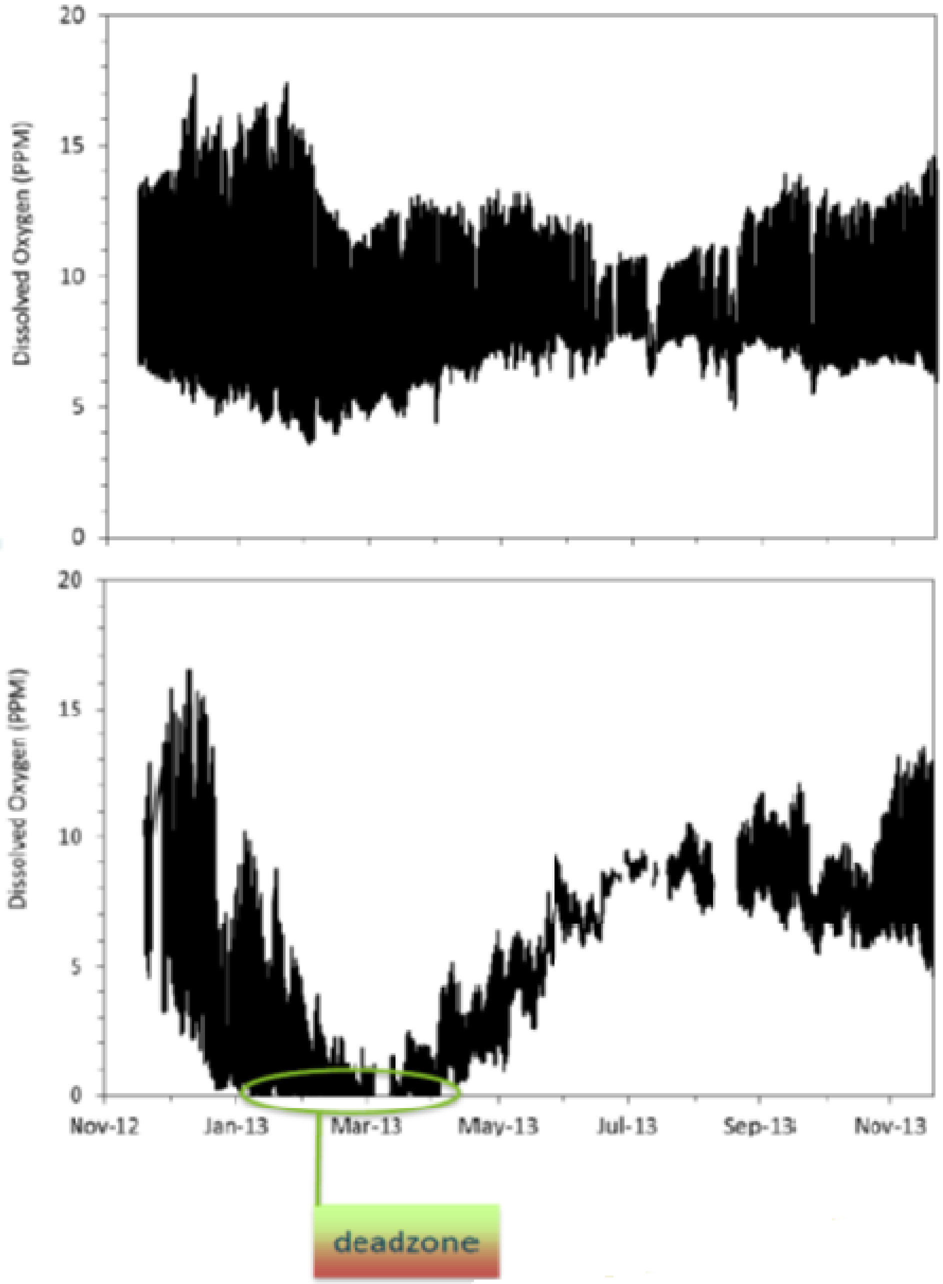

Figure 2-9: Dissolved oxygen concentrations measured continuously for one year in the Raupare Stream (top) and in the Awanui Stream (bottom). Source: Hawkes Bay Regional Council.

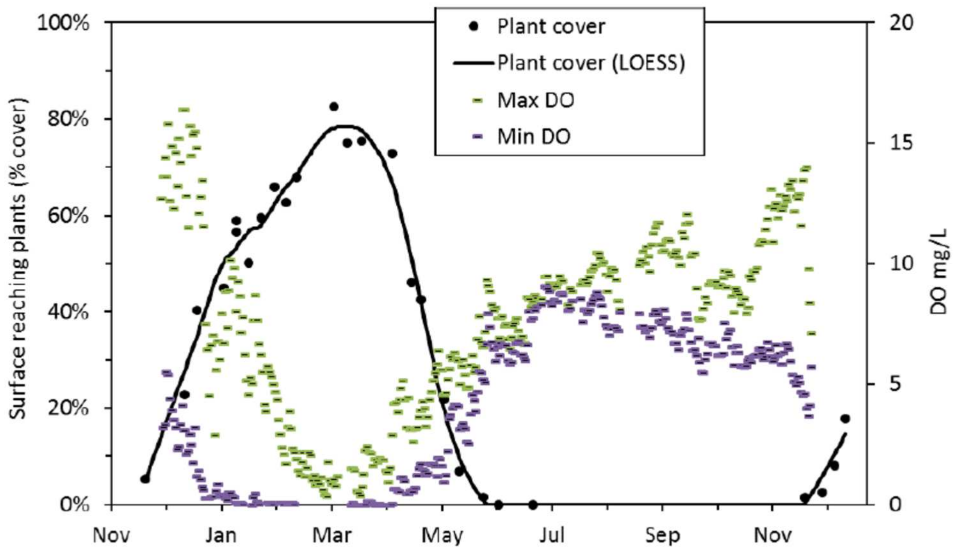

Figure 2-10: Daily maximum and minimum dissolved oxygen concentrations and cover of surface reaching aquatic plants from Nov 2012 to Dec 2013 in the Awanui Stream. Source: Hawkes Bay Regional Council.

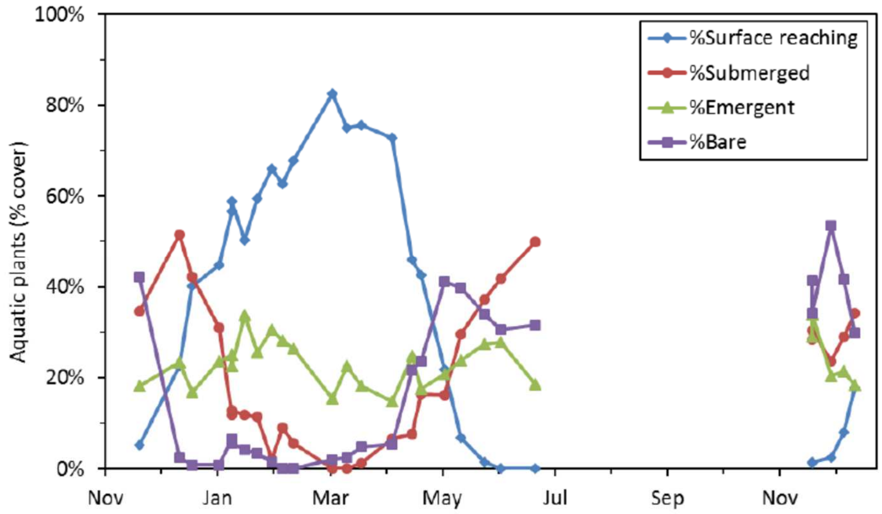

Figure 2-11: Cover of all aquatic plant life forms and bare sediment (below) from November 2012 to December 2013 in the Awanui Stream. Source: Hawkes Bay Regional Council. Surface reaching = submerged species that grow to the water surface, Submerged = submerged species that do not grow to the water surface.

In addition to the above, HBRC scientists have observed catastrophic mid-summer collapse of some macrophyte beds resulting in highly anoxic, fetid conditions in the affected areas. The cause/s of these macrophyte bed collapses are uncertain but potential contributing factors could include: (1) smothering of macrophytes by attached algae preventing photosynthesis; (2) anoxic conditions in sediments and watercolumn creating conditions toxic to roots (e.g., high levels of sulphide). Where the macrophyte community includes *Potamogeton crispus* an additional natural factor is the unusual growth cycle of this species that has been observed in some locations (e.g., Lake Horowhenua) compared to other introduced macrophytes, whereby substantial growth typically occurs early in the growing season and is followed by early dieback in summer.

Visual observations by HBRC suggest that increased riparian shading effectively reduces the cover of macrophytes in their streams. A photograph taken with a drone shows clearly the difference in surface cover of macrophytes in a riparian shaded versus unshaded reach (Figure 2-12). The unshaded reach has an almost complete surface cover of sprawling emergent plants while the shaded reach has more open water visible. HBRC have also found that shaded sections have 10-15% more dissolved oxygen than unshaded sections (Wilding 2016).

Figure 2-12: The difference in aquatic plant surface cover in a shaded versus unshaded section of a Hawkes Bay stream. Source: Hawkes Bay Regional Council.

2.3.2 Waitangi estuary

In the estuary, key issues are:

- Faecal microbial contamination indicated by *E. coli.*
- Nutrients.
- Sediments (as a potential source of nutrients, benthic smothering and impacts on water clarity).

The estuary periodically experiences blooms of macroalgae (*Ulva* spp.) and large pulses of sediment. Planktonic algal blooms occur in the Clive Arm. Beds of the native brackish water plant *Ruppia* provide important habitat in the estuary (Figure 2-13). Discharges from the Whakatū Industrial Estate contribute to poor water quality in the lower Clive river.

Figure 2-13: A bloom of Ulva on the mudflats (top left), a plume of sediment-laden water (top right) and a bed of Ruppia (bottom left) in the Waitangi estuary. Source: Hawkes Bay Regional Council.

Estuarine water quality monitoring by HBRC (Figure 2-14) shows that DRP concentrations in the estuary mostly exceed the guideline of 0.010 mg/L with high concentrations contributed by the Clive River. Dissolved oxygen concentrations are also mostly below guideline levels indicating depleted conditions. In contrast, dissolved inorganic nitrogen concentrations are mostly below the guideline level of 0.44 mg/L. This is consistent with estuarine waters being more often N-limited than P-limited (Howarth and Marino 2006).

High loads of sediment are often flushed through the estuary and deposits can be up to 40 cm deep after large floods. Dredging occurs within the Clive Arm only. However, suspended sediment concentrations in the Waitangi estuary are frequently higher than those measured in the Clive River. The Ngururoro and Tutaekuri rivers appear to be more significant sources of suspended sediment to the estuary than the Clive River (and thus the Karamū/Clive catchment) (Figure 2-15). Sednet estimates a sediment load of 33,000 T/y from the Karamū/Clive catchment but greater quantities from the other catchments that feed into the estuary, especially the Ngaruroro and Tutaekuri catchments (Figure 2-16). Deposited sediment is considered to be high in the Waitangi estuary on the basis of sediment particle size data which indicates very high percentages of mud (i.e., silt plus clay >60%). These levels greatly exceed a threshold indicated by HBRC data for a key benthic macrofauna species, the sand preferring spionid polychaete, *Aonides* spp. (Figure 2-15).

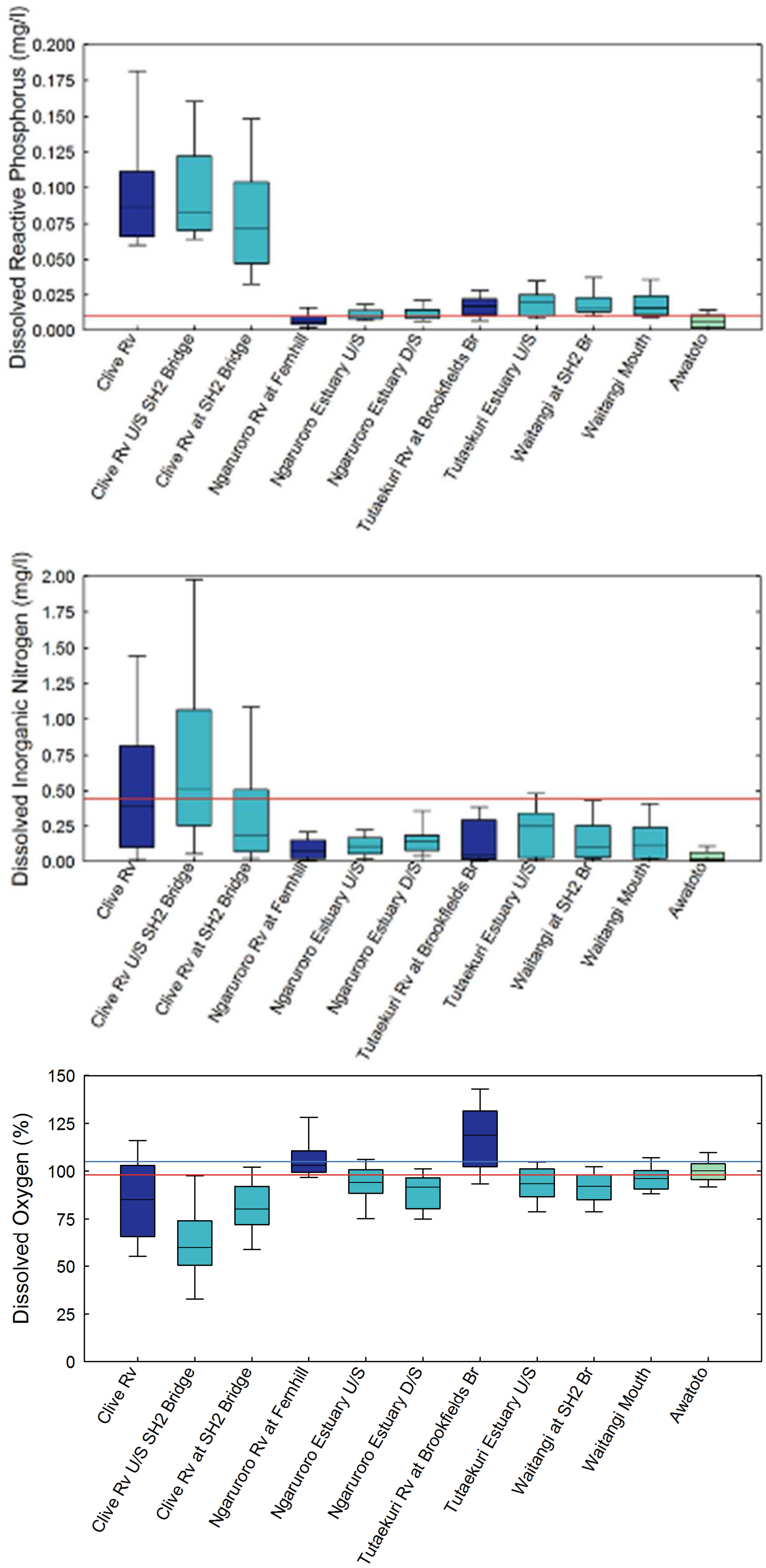

Figure 2-14: Dissolved nutrient and oxygen at Hawkes Bay Regional Council estuarine monitoring sites.
Source: Hawkes Bay Regional Council.

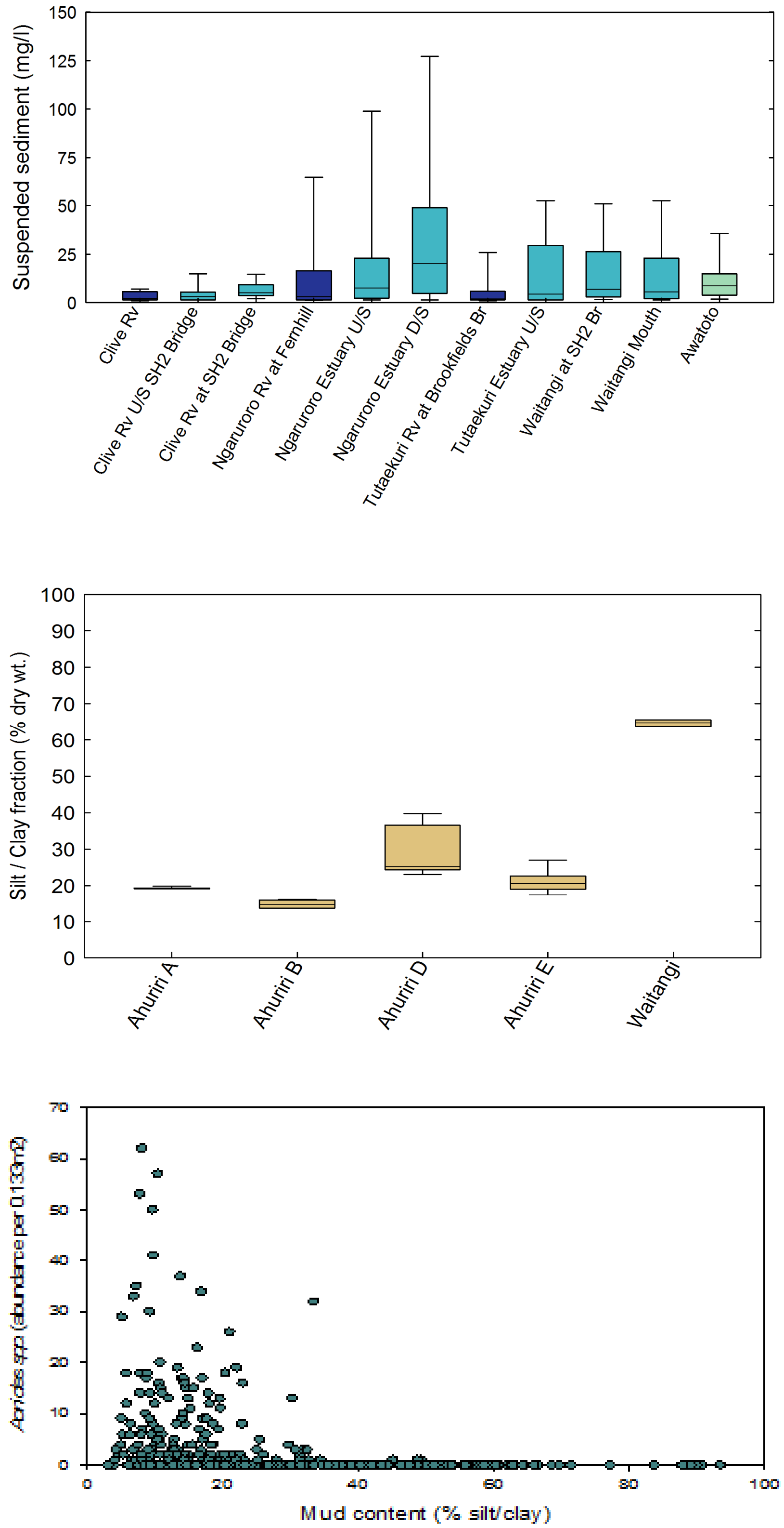

Figure 2-15: Suspended sediment at monitoring sites, particle size at sites in the Ahuriri and Waitangi estuaries and mud content vs. *Aonides* spp. abundance. Source: Hawkes Bay Regional Council.

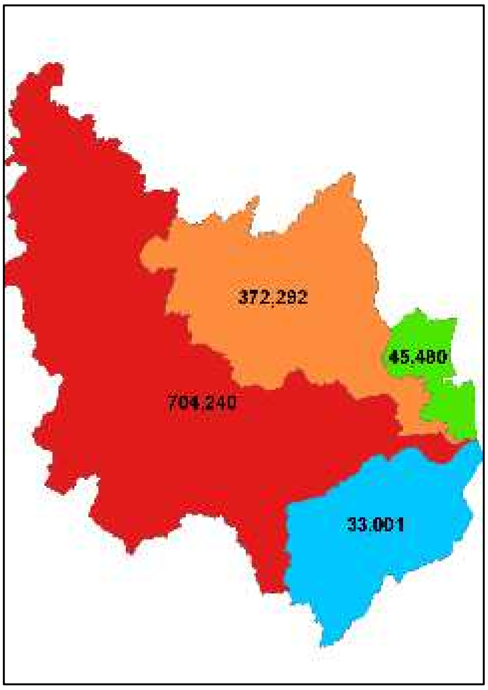

Figure 2-16: Sednet predictions of sediment loads (Tonnes/y) to the Waitangi estuary from the four contributing catchments. Source: Hawkes Bay Regional Council.

Sampling for faecal contamination in the Waitangi estuary using *E. coli* as an indicator shows that concentrations sometimes exceed safe contact recreation levels (Figure 2-17). Faecal source tracking by HBRC suggests that plant matter is a source of *E.coli* in the Karamu catchment. Aquatic vegetation, along with soils and sediments, are regarded as secondary reservoirs for *E.coli* (Badgely et al. 2011) and not usually primary sources. Most likely non-human sources are ruminants and birds. The human infection rate is generally lower from avian sources (Soller et al. 2010).

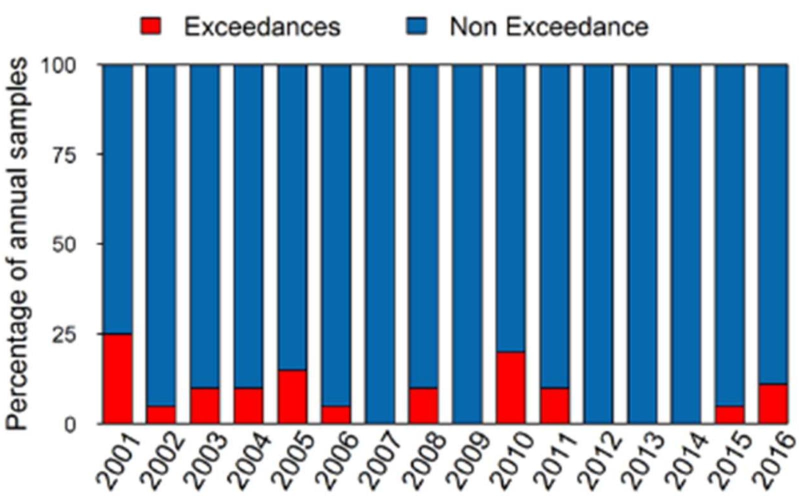

Figure 2-17: Percentage of annual *E. coli* samples in the Waitangi estuary that exceed levels safe for contact recreation. Source: Hawkes Bay Regional Council.

There are two known important sites for inanga spawning adjacent to the estuary (Figure 2-18). One site is located in the lower Clive river. In addition large tracts of stream bank in the lower Clive, lower Ngaruroro and lower Tutaekuri rivers are identified as potential inanga spawning habitat (i.e., may already be used for spawning).

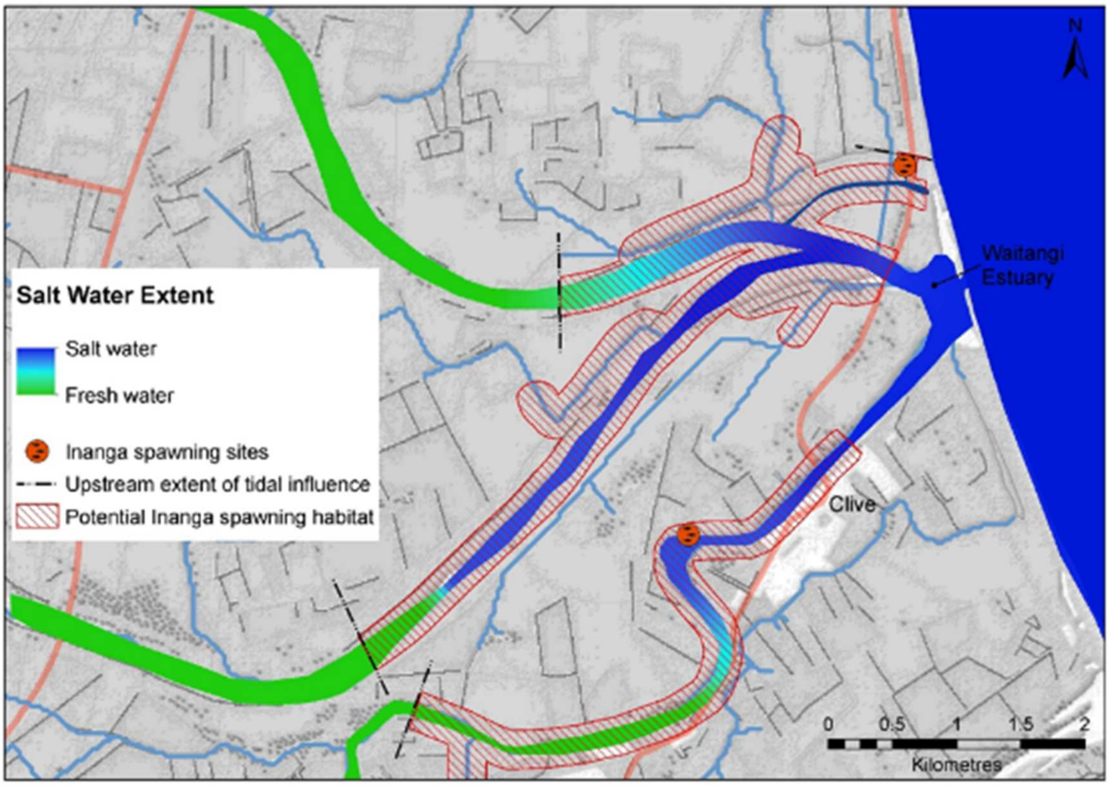

Figure 2-18: Inanga spawning sites and potential spawning habitat is the lower Clive, Ngaruroro and Tutaekuri rivers. Source: Hawkes Bay Regional Council. Salt water extent at high tide is shown.

2.4 Summary of key catchment issues

In summary, the key catchment issues are:

(1) Low dissolved oxygen and high water temperatures limiting the life-supporting capacity of streams as indicated by an impoverished macroinvertebrate community.

(2) Excessive growth of stream macrophytes and attached algae creating chronically low dissolved oxygen during summer via respiratory oxygen consumption (by macrophytes and algae, and microbes in sediments trapped within the macrophyte beds).

(3) Low stream flows exacerbating the above detrimental effects by reducing the reaeration rate, and increasing water heating rate.

(4) The potential for phosphorus release from stream sediments under anoxic conditions, high water temperatures and elevated pH levels, contributing to stream (and possibly estuary) eutrophication.

(5) In the estuary, elevated concentrations of faecal contamination, nutrients and sediments are of concern. Thus, management actions to improve ecosystem health in the catchment streams should also aim to reduce these contaminants in waters flowing into the estuary.

Important to note is that macrophytes provide valuable habitat for stream insects and fish in soft-bottomed streams, so maintaining a moderate abundance is desirable. Low macroinvertebrate community health in the catchment streams is also associated with a lack of habitat.

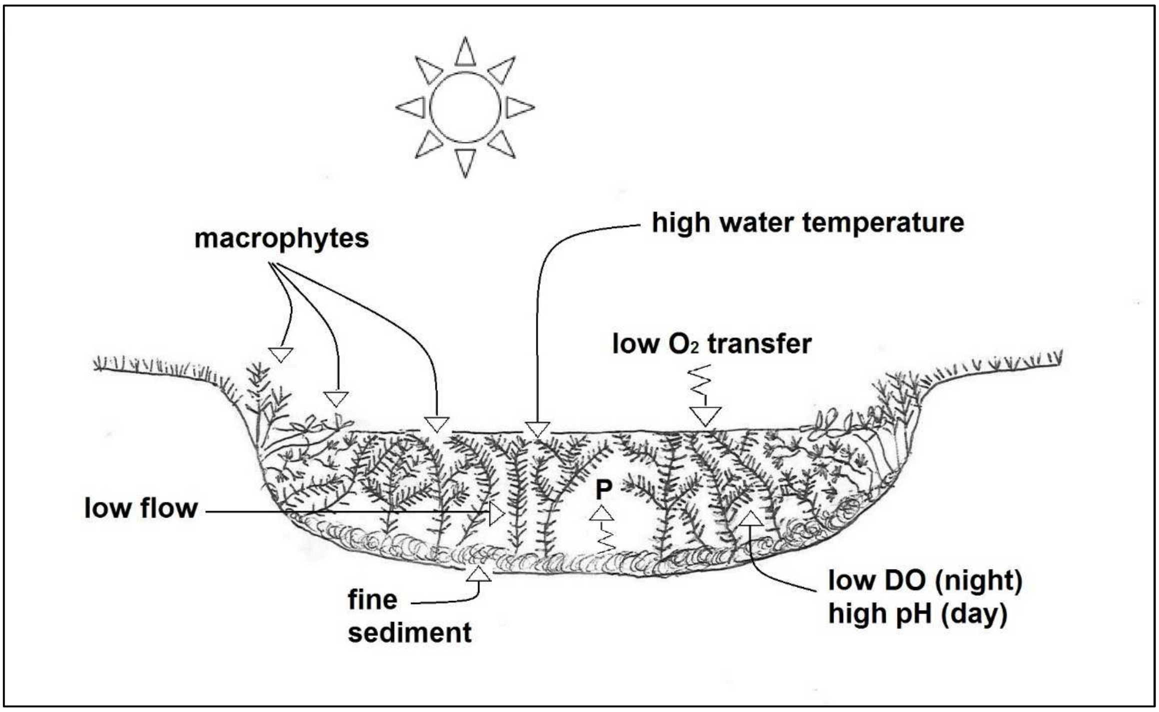

Figure 2-19: Schematic showing interactions leading to low dissolved oxygen and, potentially, P release in unshaded macrophyte-clogged lowland streams.

3 Management options

3.1 Riparian planting

3.1.1 What is this likely to achieve?

Fencing off and planting the banks of small to mid-size streams in the Karamū/Clive catchment with suitable riparian sedges, shrubs and trees would be expected to shade the stream channel, thereby reducing stream water temperatures (Rutherford et al. 1997, Quinn & Wright-Stow 2008) and the abundance of nuisance aquatic macrophytes and attached periphyton.

We anticipate that these changes would increase dissolved oxygen concentrations in these streams. Cooler waters contain more oxygen, and lower macrophyte abundance should reduce oxygen consumption via ecosystem respiration (e.g., Burrell et al. 2014) and increase flow conveyance (Wilcock et al. 1999, Champion & Tanner 2000). In addition, increased dissolved oxygen levels in the stream could potentially reduce phosphorus release from bed sediments which typically occurs under anoxic conditions. These effects are likely to be most pronounced where high levels of shading are achieved (i.e., narrower streams with taller, denser riparian vegetation) and where longer lengths of stream margin are subject to planting.

Data compiled from Waikato streams suggests that reducing macrophyte cover to ≤35% would likely maintain minimum dissolved oxygen levels above 5 mg/L (Matheson et al. 2012). This is also consistent with a recommendation to maintain an intermediate level of macrophyte abundance in lowland streams to provide sufficient habitat for biota (Collier et al. 1999).

At least 50% shading is recommended to achieve a reduction in abundance of emergent and sprawling plants and periphyton, while shading of 70% or more is likely to be effective at achieving an intermediate level of macrophyte cover (McBride et al. 1991, Canfield & Hoyer 1998, Julian et al. 2011, Burrell et al. 2014). High levels of shade (i.e., >90%) may be required to reduce the abundance of some low light adapted submerged species. This is consistent with observations from HBRC shading trials using 4 m high vegetation (tall grasses on the north side of the stream bank) which show that some macrophytes are still present in the sections shaded by 50-70%. It is also consistent with the observed relationship between macrophytes and shade on the Heretaunga Plains (Wilding 2016).

Shading levels of 50% or more are most likely achieved in streams that are less than 6-7m wide based on New Zealand data and modelling comparing shading levels amongst native forest, pasture and plantation forestry sites (Davies-Colley & Quinn 1998, Davies-Colley et al. 2009).

Additional benefits of riparian planting would likely include:

1. Increased inputs of leaves (and eventually wood) into streams providing a more diverse instream habitat for fish and invertebrates and a labile source of carbon to support stream food webs and heterotrophic nutrient processing (e.g., denitrification).

2. Reduced contaminant inputs to streams as riparian vegetation will trap sediment and associated nutrients (particularly phosphorus) in overland runoff. But note that wider strips with a high proportion of (ungrazed) grasses and low-growing vegetation would likely be required to maximise sediment retention. There is also some uncertainty about the longevity of this sediment trapping function as trapped material is likely to

accumulate through time. In locations without tile drains and without steep banks and an incised stream channel, the riparian plant root zone could also be expected to intercept, transform and assimilate some dissolved nutrients from shallow groundwater.

3. Reduced runoff water entering waterways as a result of enhanced infiltration into higher porosity riparian soils and evapotranspiration from riparian vegetation thus reducing peak flood flows.

Sufficient shading for temperature and nuisance instream plant control, and sufficient inputs of leaves and wood, can likely be achieved with a relatively narrow riparian planted buffer (i.e., 5 to 10 m) but interception, trapping and transformation of surface runoff and shallow groundwater is likely to be more effective with a wider buffer (i.e., 10 to 20 m or more). Note that a buffer width of c. 20 m is probably need to ensure the riparian forest stability and there must be room for channel movement during floods.

3.1.2 What are the potential downsides?

Riparian planting and fencing will restrict access to the stream channel which might be desirable for channel clearance activities and fencing may be damaged and vegetation uprooted by large floods. There may also be a period of stream widening and release of sediment held in stream banks as the abundance of pastoral grasses is reduced by shading (Davies-Colley 1997) and changes in bank erosion processes and channel morphology occur (Hughes 2016). In the early years of establishment, the riparian zone may be a haven for terrestrial weeds (e.g., blackberry), requiring regular maintenance to maintain plantings. Thus establishment costs, which include fencing (usually full conventional fencing is required) and planting, can be relatively high.

If instream plant abundance is reduced then fewer dissolved nutrients will be taken up from stream water and/or bed sediments during spring and summer to support their growth. This has the potential to increase nutrient concentrations in the stream water during these seasons if the plants assimilate a large quantity of nutrients relative to the reduction of nutrients within the enhanced riparian system (see Parkyn et al. 2005). However, during autumn and winter, the nutrients assimilated into plant tissues may be released through scour by high flows and decay, and transported downstream. Nevertheless a portion of the nutrients assimilated into plant tissues is likely to be converted into refractory (i.e., biologically unavailable) forms. Studies in the Whangamata Stream near Taupo have shown that uptake by sprawling macrophytes (notably watercress, *Nasturtium* spp.) can lower stream dissolved nutrient concentrations and that this function is reduced with riparian planting and shade creation in that system (Vincent & Downes 1980, Howard-Williams & Pickmere 1999, 2010). However, a recent study in Canterbury showed that nutrient uptake by macrophytes (*Potamogeton cheesemanii, Elodea canadensis*, *Nasturtium* spp.) had little impact on the high nutrient concentrations in these lowland streams (O'Brien et al. 2014). Thus, for Hawkes Bay streams there is uncertainty about the impact of reduced instream plant abundance on stream nutrient concentrations during the growing season. However, reduced nutrient uptake capacity by instream plants could conceivably be offset by increased nutrient retention in the planted riparian zone and reduced release of phosphorus from bed sediments as noted above.

3.2 Herbicides

3.2.1 What is this likely to achieve?

Like shade creation by riparian planting, herbicides are another tool that could be used to limit or reduce the biomass of macrophytes in Karamū/Clive streams to enhance dissolved oxygen levels. Several New Zealand studies have demonstrated that the aquatic herbicide diquat can be effective at reducing or halting growth of instream macrophytes during the growing season (Young et al. 2004, Wells & Smith 2006, de Winton et al. 2016).

Diquat and endothall are the only two herbicides registered for aquatic use on submerged macrophytes in New Zealand. Endothall has only recently been registered. These are contact herbicides that desiccate the plant material that they contact. Glyphosate is a translocated herbicide that is often used to control marginal plants adjacent to waterways but it cannot be applied in water. Other herbicides currently available to control marginal plants include triclopyr amine, imazapyr and metsulfuron.

3.2.2 What are the potential downsides?

There are often public concerns about the toxicity of herbicides. However, these herbicides are considered non-toxic to aquatic biota and people if applied correctly at label recommended rates (e.g., 30L/ha diquat to achieve target conc. 1 mg/L). Results of local investigations with diquat on freshwater biota generally support the manufacturers claim (Wells & Clayton 1996, Tremblay et al. 2004, Young et al. 2004, Wells & Smith 2006).

There is often concern about deoxygenation of waters following herbicide application due to rapid decay of plant material. However, no significant deoxygenation effects have been observed in local studies (Young et al. 2004, Wells & Smith 2006), and decay of plant material often occurs slowly over weeks or months which reduces this risk. However, to minimise risk further, applications of herbicide in spring or autumn when temperatures are cooler, and thus decay rates slower, are typically recommended (de Winton et al. 2016).

Diquat is rapidly bound to organic and inorganic particles so its efficacy to control below-surface plants is often reduced in turbid water or where plant surfaces are covered by epiphytes or deposited sediment (Clayton & Matheson 2010). These factors could reduce diquat efficacy if it were used in Karamū streams.

3.3 Grass carp

3.3.1 What is it likely to achieve?

Grass carp are another potential tool that could be used to reduce macrophyte abundance, and thus enhance dissolved oxygen in Karamū/Clive streams. With management of fish stocking rates they might be able to maintain macrophyte abundance at intermediate levels.

3.3.2 What are the potential downsides?

There are a large number of potential downsides associated with grass carp use, particularly the difficulty of containment in a river subject to flooding. Consequently introduction/use of grass carp requires approvals from Ministry of Primary Industries and Department of Conservation (Hofstra et al. 2014). They are currently being used, and effects closely monitored, in the Hawkes Bay's Tutira Lakes for the eradication of *Hydrilla verticillata*, a national interest aquatic plant pest.

Grass carp will eat virtually all submerged, and then emergent, plants (Rowe & Schipper 1985, Wells et al. 2003) so complete devegetation of waterways is possible at higher stocking rates. Grass carp are sensitive to low dissolved oxygen, high water temperatures and polluted water (Hofstra et al. 2008, 2014) so they probably would likely find conditions challenging for survival in lowland streams with these issues, like those in the Karamū/Clive catchment. Nevertheless, they have previously been stocked to control aquatic macrophytes in Muddy Creek near Clive but appear to have been ineffective with numbers of fish rapidly declining probably due to capture for food by locals and perhaps unfavourable water quality conditions for their longer term survival.

3.4 Mechanical macrophyte removal

3.4.1 What is it likely to achieve?

Mechanical removal using a digger can be an effective way to substantially reduce macrophyte abundance in lowland streams for up to six months or more (Young et al. 2004) but perhaps less in other places (e.g., Canterbury streams, where used three times per year). However this approach does come with a number of downsides. Cutting the material (without removal) is another option with other downsides but it tends to be less effective at reducing macrophyte abundance. Currently in the Karamū/Clive catchment cutting by weed boat is carried out at key sites seven times per year to maintain flow conveyance for flood control. Harvesting would mitigate some of the problems associated with cutting the macrophytes.

3.4.2 What are the potential downsides?

Manual and mechanical removal of macrophytes is more labour intensive than herbicide and removal via digger is potentially more damaging to the ecosystem health. Detrimental impacts include removal of biota trapped in weed (especially eels and invertebrates), disturbance of bottom sediments, nutrient mobilization and increased water turbidity (Hudson & Harding 2004, James 2013). A recent PhD study has shown that the sediment resuspension and associated anoxia had detrimental effects on fish (Greer et al. 2014). However, a study of Marlborough spring-fed waterways showed that the invertebrate community recovered within one month following mechanical macrophyte removal (Young et al. 2004).

The cutting of macrophytes needs a higher frequency than the removal by digger, as the macrophytes grow back relatively quickly when the roots remain in the sediment. Although the immediate disruptive effect on the aquatic environment by cutting is less severe than by digging, other negative effects are a risk, as observed in the Karamu catchment: cut plants tend to accumulate in depositional zones and break down rapidly, increasing the risk of pronounced local dissolved oxygen deficit. Cut macrophytes also float downstream and recreational users in the lower Clive, particularly rowers, have raised complaints. Faecal source tracking has also shown that about 30% of *E. coli* found in the lower Karamu comes from plant material, raising the question if accumulated decaying plant material can be a source. *E.coli* has been shown to accumulate in epiphytic material (Drummond et al. 2014, 2015) but it is unclear whether the bacteria can grow and proliferate in these circumstances.

3.5 Nutrient reduction

The tools available to reduce nutrient concentrations (aside from land use change or destocking) include riparian fencing and planting to exclude direct livestock contamination, reduce surface runoff (for P in particular) and intercept shallow groundwater in locations without tile drains (mainly for DIN). In addition, denitrifying bioreactors installed at the end of tile drains may be able to reduce DIN (primarily nitrate) concentrations. These are currently being trialled in Canterbury. Targeting any point source discharges of nutrients in the catchment (both rural and urban) with more stringent compliance requirements might potentially be another option.

3.5.1 What is it likely to achieve?

Reducing nutrient concentrations in stream water has the potential to reduce macrophyte (and attached algal) abundance but it is likely that quite low concentrations would be required. An additional complication is that macrophytes that root into the bed of the stream can acquire nutrients from sediments as well as the water (Chambers et al. 1989, Madsen & Cedergreen 2002). Most of the nuisance submerged species in New Zealand have the capability of root uptake, the only possible exception is hornwort (*Ceratophyllum demersum*) which does not have true roots but might still acquire nutrients in this way via modified leaf structures laying on the sediment surface. Most sprawling emergent species produce roots on their floating stems (e.g., watercress, *Nasturtium* spp.,) so are able to assimilate nutrients from water in this way.

Several international studies suggest that it may be possible to reduce stream macrophyte abundance via nutrient reduction (i.e., Soziak 2002, Carr et al. 2003, O'Hare et al. 2010) and some nutrient thresholds are indicated (<1 mg/L DIN, Soziak 2002; <0.1 mg/L DRP O'Hare et al. 2010). However other studies (e.g., Terrell & Canfield 1996), including a local example, suggest that much lower thresholds are likely to be required. The local study of Matheson et al. (2009) suggests that TN concentrations <0.2 mg/L would be unlikely to affect a reduction in macrophyte cover but may be sufficient to moderately reduce the abundance of attached algae (i.e., *Compsopogon* spp.). Further information about each of the studies reviewed is provided in Appendix A. Based on this review the evidence for nutrient control of macrophytes is weak. The studies provide conflicting and, at times, non-intuitive findings, and so at present there is no clear evidence that macrophyte control in the Karamu catchment could be achieved with nutrient limitation. Nutrient reduction may have to be considered to protect the Waitangi estuary, but more research is recommended to identify robust thresholds for this objective.

3.5.2 What are the potential downsides?

Achieving nutrient reductions in streams of the Karamū/Clive catchment to the water concentrations likely to reduce macrophyte abundance would likely be very difficult. Even if selecting relatively optimistic targets based on the information above (e.g., DIN <0.2 mg/L) these concentrations are considerably lower than existing concentrations in the Karamū/Clive streams. Stream DIN concentrations are typically 1 to 2 mg/L at many sites and DRP concentrations are in the range of 0.1 to 0.2 mg/L across much of the catchment. The DRP concentrations are surprisingly high, and ubiquitously so, across the catchment. In future, stream sediment geochemical investigations including use of the Compound Specific Stable Isotope (CSSI) sediment tracing method (Gibbs 2008) may be able to help identify the source of phosphorus.

4 Conclusions & recommendations

Riparian fencing and planting is the management option that is considered most likely to achieve long-term improvements in ecosystem health within the streams and the estuary of the Karamū/Clive catchment. This is primarily through anticipated improvements in stream dissolved oxygen concentrations as a result of reductions in aquatic plant abundance and moderated stream temperatures. In comparison the other management options that were considered seem likely to provide only limited and short-lived reductions in aquatic plant abundance (i.e., herbicide use and manual removal), or benefits were highly uncertain (i.e., nutrient reduction) or could potentially result in more serious harm to ecosystem health (i.e., grass carp and mechanical removal). Nevertheless lower impact activities like herbicide use and macrophyte cutting and removal by rake could be used as interim measures to reduce instream plant abundance while riparian plantings establish.

Riparian management also has a number of important likely co-benefits for the Karamū/Clive catchment including:

- provision of more diverse stream habitat and carbon resource to support the food-web through enhanced leaf and (eventually) wood inputs
- improved aesthetic appeal of waterways
- enhanced interception and trapping of contaminants within riparian zones, particularly in overland flow, from adjacent land, and
- potentially, reduced phosphorus release from the stream bed.

Priority locations for the implementation of this management option within the catchment are those:

- Which frequently experience zero or very low minimum dissolved oxygen concentrations.
- Where managing flows is insufficient to achieve oxygen limits.
- Where the channel is sufficiently narrow to enable a sufficient level of shading to be achieved, ideally using lower stature plantings.
- Where riparian planting will not significantly impede flood control.
- In headwaters where a contiguous riparian buffer could be created.
- Where planting will enhance aesthetic, amenity and/or cultural values.
- Where adjacent landowners are supportive.
- Where funding can be more easily acquired to implement the works.
- Where the costs of implementation are not prohibitive.

We recommend implementing a number of case studies to confirm the anticipated benefits of this management option prior to widespread adoption. It would be desirable for these case-studies to:

- Involve the local community in planning, implementing and monitoring of outcomes.
- Be carefully designed in conjunction with scientific experts to ensure that anticipated outcomes are realistic and can be appropriately monitored and measured.
- Be carried out in contrasting land use areas (i.e., arable, orchard, pasture and urban) to illustrate the diversity of potential benefits across the wider catchment.

The above approach is consistent with the recently updated Te Karamū Enhancement Strategy (Rewcastle 2016). The overarching objective of the strategy is to improve habitat and ecosystem health whilst providing flood and erosion protection.

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6 Glossary of abbreviations and terms

Attribute	According to the NPS-FM this is defined as: is a measurable characteristic of fresh water, including physical, chemical and biological properties, which supports particular values.
CAV	A macrophyte abundance metric introduced by Matheson et al. (2012) which is similar to the channel clogginess index of Collier et al. (2014) . CAV refers to the percentage of the wetted stream channel cross-sectional area (or volume, if a 1m swathe is assessed) that is occupied by macrophytes.
Ecosystem health	According to the NPS-FM this is defined as: The freshwater management unit supports a healthy ecosystem appropriate to that freshwater body type (river, lake, wetland, or aquifer). In a healthy freshwater ecosystem ecological processes are maintained, there is a range and diversity of indigenous flora and fauna, and there is resilience to change. Matters to take into account for a healthy freshwater ecosystem include the management of adverse effects on flora and fauna of contaminants, changes in freshwater chemistry, excessive nutrients, algal blooms, high sediment levels, high temperatures, low oxygen, invasive species, and changes in flow regime. Other matters to take into account include the essential habitat needs of flora and fauna and the connections between water bodies. The health of flora and fauna may be indicated by measures of macroinvertebrates.
EPT	Ephemeroptera, Plecoptera and Trichoptera; sensitive species of freshwater macroinvertebrate species.
Freshwater objective	According to the NPS-FM this is describes an intended environmental outcome in a freshwater management unit.
HBRC	Hawkes Bay Regional Council.
Limit	According to the NPS-FM this is the maximum amount of resource use available, which allows a freshwater objective to be met.
Macrophyte	A macrophyte is an aquatic plant that grows in or near water and is either emergent, submerged, or floating.
MALF	Mean Annual Low Flow.
MCI	Macroinvertebrate community index.
NIWA	National Institute of Water and Atmospheric Research.
NPS-FM	National Policy Statement for Freshwater Management (2014).
Periphyton	Periphyton refers to communities of algae in aquatic systems that are attached to the sediment surface or to aquatic, macrophyte vegetation.
TANK	Tutaekuri, Ahuriri, Ngaruroro and Karamū catchments.

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Appendix A Supporting material from published literature

Figure 3-1 from Matheson et al. (2012) shows the relationship between minimum dissolved oxygen concentrations and macrophyte cover in Waikato lowland streams.

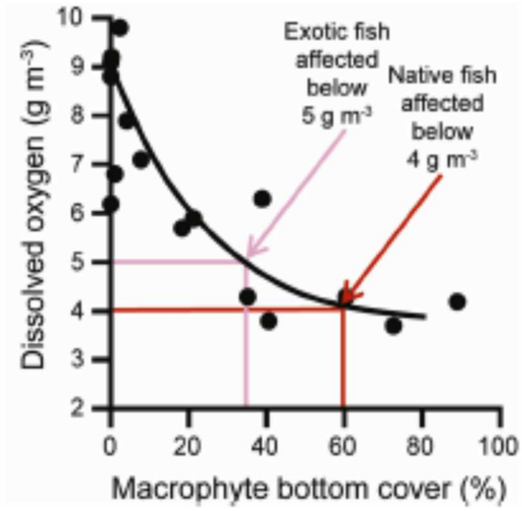

Figure 3-1: Relationship between dissolved oxygen minima and macrophyte bottom cover in 16 Waikato lowland streams during summer. Data from Collier et al. (1998) and Wilcock et al. (1998). Pink and red lines show the dissolved oxygen concentrations below which detrimental effects on sensitive fish species are likely. This corresponds to a macrophyte bottom cover ranging from around ca. 35-60%.

Table II from Julian et al. (2011) shows the stream lighting levels (transmitted PAR, inverse of shade) and associated levels of macrophyte cover in stream transects in forested, mixed and grassed land use areas of Big Spring Creek in the USA.

Table II. Habitat characteristics of forested, mixed and grassed transects in Big Spring Creek.

	Forested (mean ± SD)	Mixed (mean ± SD)	Grassed (mean ± SD)	ANOVA (*p*-value)
Transmitted PAR (% of E_{can})	26 ± 10	52 ± 7	80 ± 7	<0·001
Benthic PAR (mol m^{-2} day^{-1})	6·5 ± 3·0	13·5 ± 2·9	21·5 ± 2·3	<0·001
Macrophyte coverage (%)	21 ± 22	62 ± 27	90 ± 10	<0·001
Active channel width (m)	6·8 ± 1·5	7·8 ± 1·3	8·7 ± 1·7	0·007
Baseflow water depth (m)	0·64 ± 0·23	0·59 ± 0·24	0·53 ± 0·17	0·369
Bed sediment depth (cm)	10 ± 8	12 ± 8	22 ± 15	0·014
Bed sediment size, D_{50} (mm)	0·27 ± 0·32	0·17 ± 0·02	0·18 ± 0·03	0·772
Bed sediment OM (%)	2·5 ± 1·3	2·1 ± 1·1	2·1 ± 0·8	0·837
SRP net uptake (μg m^{-2} h^{-1})	−81 ± 291	N/A	322 ± 151	0·032*

Mixed transects have one forested bank and one grassed bank. Forested SRP uptake was derived from sites with 0% macrophyte coverage. Grassed SRP uptake was derived from sites with 80–100% macrophyte coverage.
* *t*-test.

Figure 2 from Julian et al. (2011) provides illustrative photographs of the above transects.

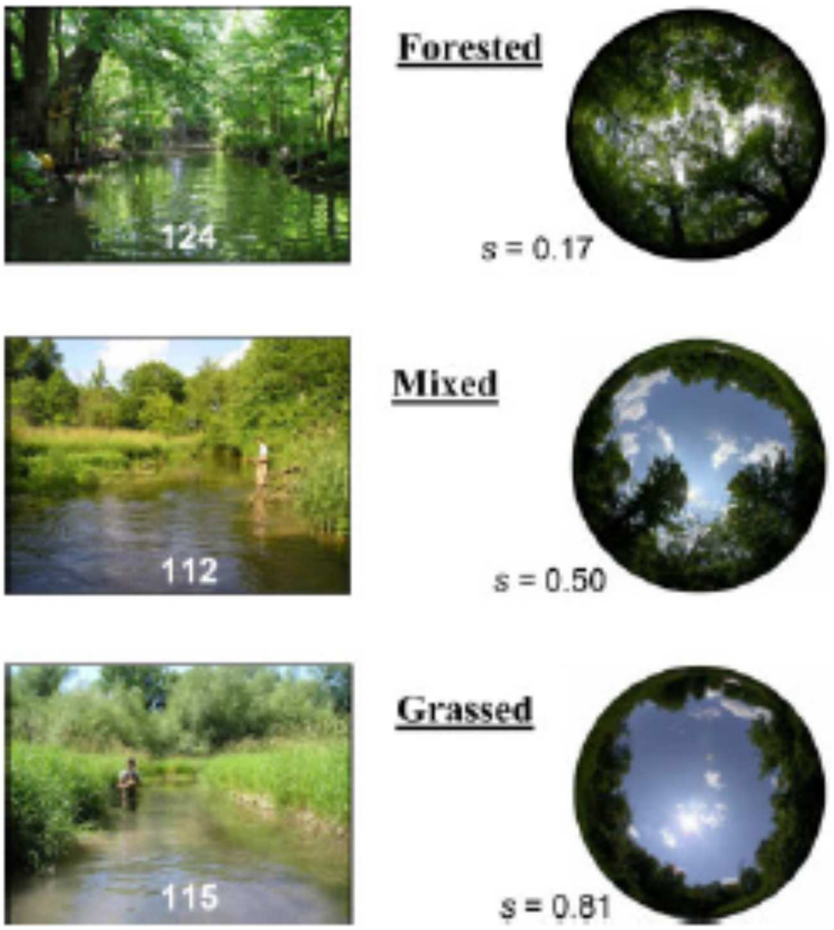

Figure 2. Longitudinal (left) and hemispherical canopy (right) photos of transects in Big Spring Creek with different riparian communities. Transect numbers (Figure 1) are located on the longitudinal photos. Shading coefficients (*s*—the proportion of above-canopy PAR that reaches the water surface) are located next to the canopy photos from which they were derived. The submerged aquatic macrophyte bed in the grassed transect (bottom left), with ~80% coverage, can be identified by its dark colour contrasted with the light-coloured sand bed of the stream. (This figure is available in colour in the online version of this article).

Figure 3 from Julian et al. (2011) shows the relationship between light measured at the stream bed (benthic PAR) and submerged macrophyte cover. A target submerged macrophyte cover of 35% corresponds to approximately 8 mol m^{-2} d^{-1} of benthic PAR, approximately 30% of the maximum benthic PAR which was measured. Assuming the maximum benthic PAR corresponds to minimum stream shading this relationship suggests that submerged macrophyte cover of 35% could be achieved with ca. 70% shade.

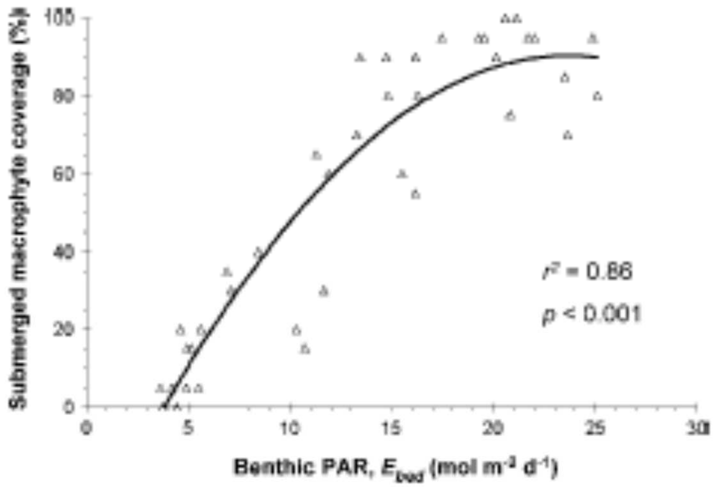

Figure 3. Submerged macrophyte coverage versus benthic PAR in Big Spring Creek on 27 June 2006. The regression equation is: $y = -0.23x^2 + 10.83x - 37.88$.

Canfield and Hoyer (1988) found that aquatic macrophyte biomass and riparian canopy cover (i.e., shade) where related by the following significant relationships:

$$\log(SC_{avg}) = 1.06 - 0.026\,(\%C) \qquad R^2 = 0.93$$
$$\log(SC_{max}) = 1.54 - 0.014\,(\%C) \qquad R^2 = 0.94$$

where SC_{avg} and SC_{max} are the average and maximum standing crop of aquatic macrophytes (kilograms fresh weight per square metre), respectively, and %C is the percent canopy coverage by riparian vegetation.

Figure 2 and Tables 2 and 3 from Burrell et al. (2014) show that gross primary production and ecosystem respiration increase with agricultural land use and macrophyte abundance but decrease with shade in Canterbury lowland streams

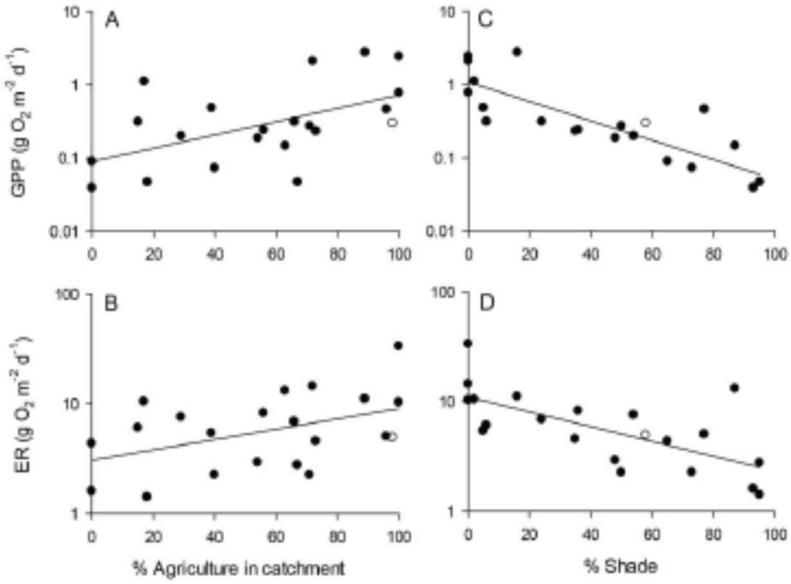

Figure 2. Regressions for gross primary production (GPP) (A, C) and ecosystem respiration (ER) (B, D) with respect to % agriculture in the catchment (A, B) and % shade at the stream reach (C, D). At the landscape level, GPP and ER were closely correlated with % agricultural land use in the catchment, whereas at the local level GPP and ER were closely correlated with shading by riparian vegetation.

Table 2. Correlations between stream metabolism (GPP = gross primary production, ER = ecosystem metabolism) and independent variables. Bold correlation coefficients are statistically significant. SRP = soluble reactive P, chl *a* = chlorophyll *a*, D_{50} = median particle size, FPOM = fine particulate organic matter. * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.

Category	Variable	Log(GPP)	Log(ER)
Landuse variables	% agriculture	0.567**	0.462*
	Fine sediment	0.393	0.362
	Log(NO_3^-)	0.428	0.184
	SRP	−0.316	−0.215
	Region	−0.368	−0.172
Local variables	% shade	−0.841***	−0.678***
	√(% macrophytes)	0.687***	0.521*
	√(chl *a*)	0.161	−0.052
	D_{50}	−0.590**	−0.538*
	FPOM	0.256	0.049
	Temperature	0.407	0.167

Table 3. Multiple linear regression model selection for gross primary production (GPP) and ecosystem respiration (ER) using Akaike's Information Criteria for small sample sizes (AIC_c).

Model	AIC_c	$\Delta_i\ AIC_c$	Model R^2
Log(GPP) = % shade + % agriculture	6.23	0.00	0.823
Log(GPP) = % shade + % agriculture + (% shade × % agriculture)	7.93	1.70	0.834
Log(GPP) = % shade	14.04	7.81	0.707
Log(GPP) = % agriculture	31.33	25.10	0.322
Log(ER) = % shade + % agriculture	6.86	0.00	0.537
Log(ER) = % shade	7.39	0.53	0.460
Log(ER) = % shade + % agriculture + (% shade × % agriculture)	9.94	3.08	0.537
Log(ER) = % agriculture	15.26	8.40	0.214

The figure below sourced from McBride et al. (1991) shows the relationship between macrophyte cover and shade for three Auckland lowland rivers.

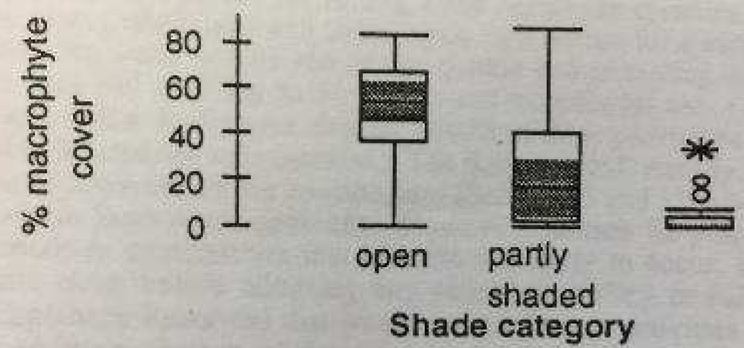

Figure 12: Comparison of percentage macrophyte cover of the streambed during summer amongst 74 sites with different levels of riparian shade on the three lowland rivers near Auckland. Box represents interquartile range, bar the median, and whiskers the range. Outliers (o) and extreme outliers (*) are identified. Shaded areas are approximate nonparametric 95 percent confidence intervals for comparison of medians. From McBride *et al.* (1991).

Data from Davies-Colley and Quinn (1998) show the relationship between channel width and shade under native, pasture and pine land use.

Shade decreases as channels widen above 6 m

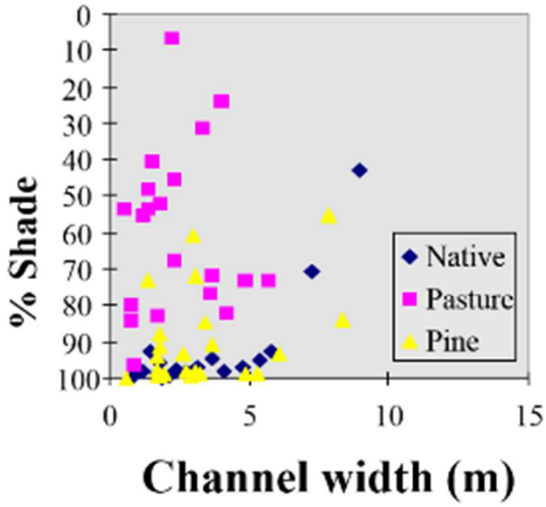

Figure 6 from Davies-Colley et al. (2009) shows the predicted time course of light reduction (i.e., shade creation) in streams of varying width under various riparian vegetation regeneration scenarios (i.e., native regeneration, pine reversion and active riparian planting).

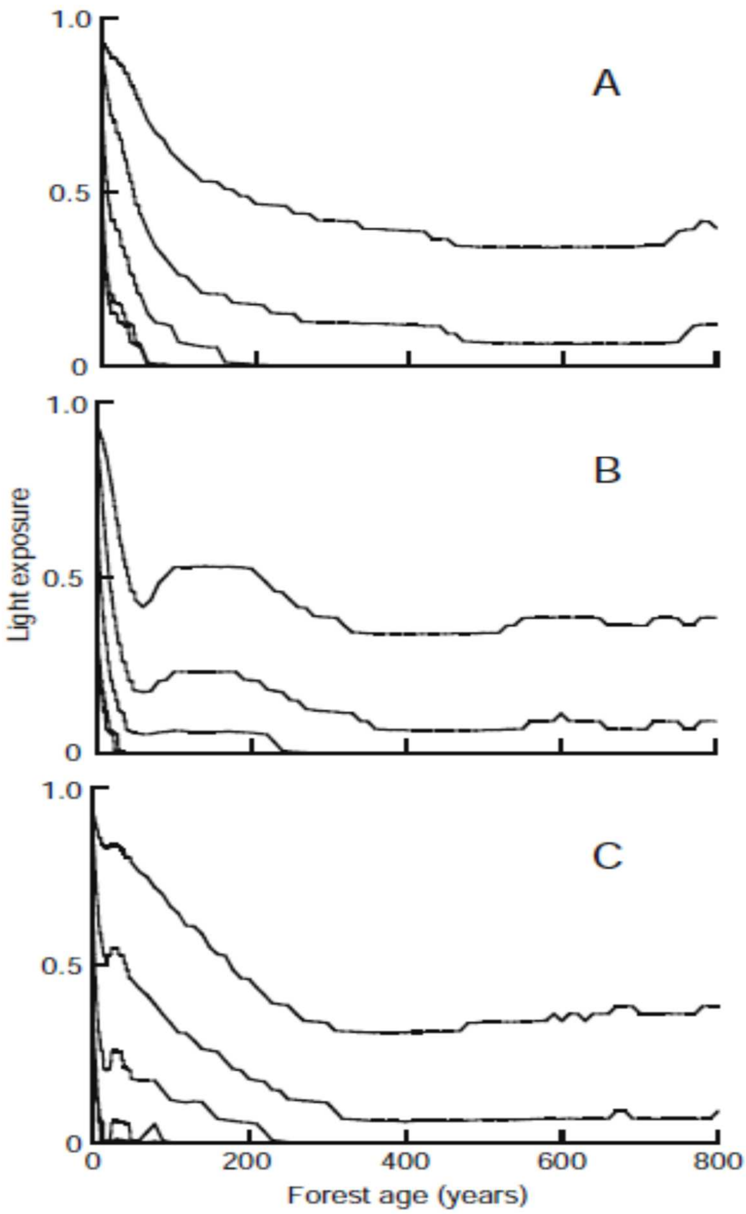

Fig. 6 Stream light exposure (proportion of sunlight in the open received by stream water) at baseflow water level, as simulated through time by the sWAIORA model (http://www.niwa.co.nz/our-science/freshwater/tools/waiora) for three scenarios: **A**, native regeneration; **B**, pine reversion; and **C**, active native tree planting. Curves are for different channel widths (from top to bottom in each panel: 14.0 m, 6.6 m, 3.3 m, 1.6 m, and 1.3 m).

Summary of literature investigating nutrient control of macrophyte and attached algae

In Bow river USA, Soziak (2002) found that macrophyte abundance (*Potamogeton vaginatus* and *P. pectinatus*) was greatly reduced following nutrient reductions from a wastewater treatment source. They associated this primarily with reductions in dissolved inorganic nitrogen to concentrations below 1 mg N/L. This study also produced a relationship which indicated that a concentration <0.0064 mg P/L would be required to reduce periphyton biomass to <150 mg/m^2.

The following year a study of 28 rivers in Ontario, Canada (Carr et al. 2003) reported weak but significant relationships between macrophyte biomass and nutrient concentrations (N & P). On that basis they concluded that nutrient abatement programs, especially focused on N, may be successful in reducing nuisance biomass.

And finally, a more recent study found a significant relationship between macrophyte biomass (*Ranunculus penicillatus*) and DRP concentrations in United Kingdom rivers (O'Hare et al. 2010). The authors considered that the 0.1 mg/L DRP Environment Agency Target would likely to be effective in reducing macrophyte biomass. Their data suggest that concentrations below 0.05 mg/L would be even more effective.

However, not all studies concur with the above findings. In Crystal river USA, Terrell & Canfield (1996) found that improved wastewater treatment reduced TN from 0.6 to 0.2 mg/L & TP from 0.105 to 0.027 mg/L yet there was no overall change in nuisance macrophyte & filamentous algal abundance. However, the macrophyte species in this study either do not occur (i.e., *Myriophyllum spicatum, Vallisneria americana*) or have a very restricted distribution (i.e., *Hydrilla verticillata*) in New Zealand freshwaters. The filamentous alga was *Lygnbya* spp.

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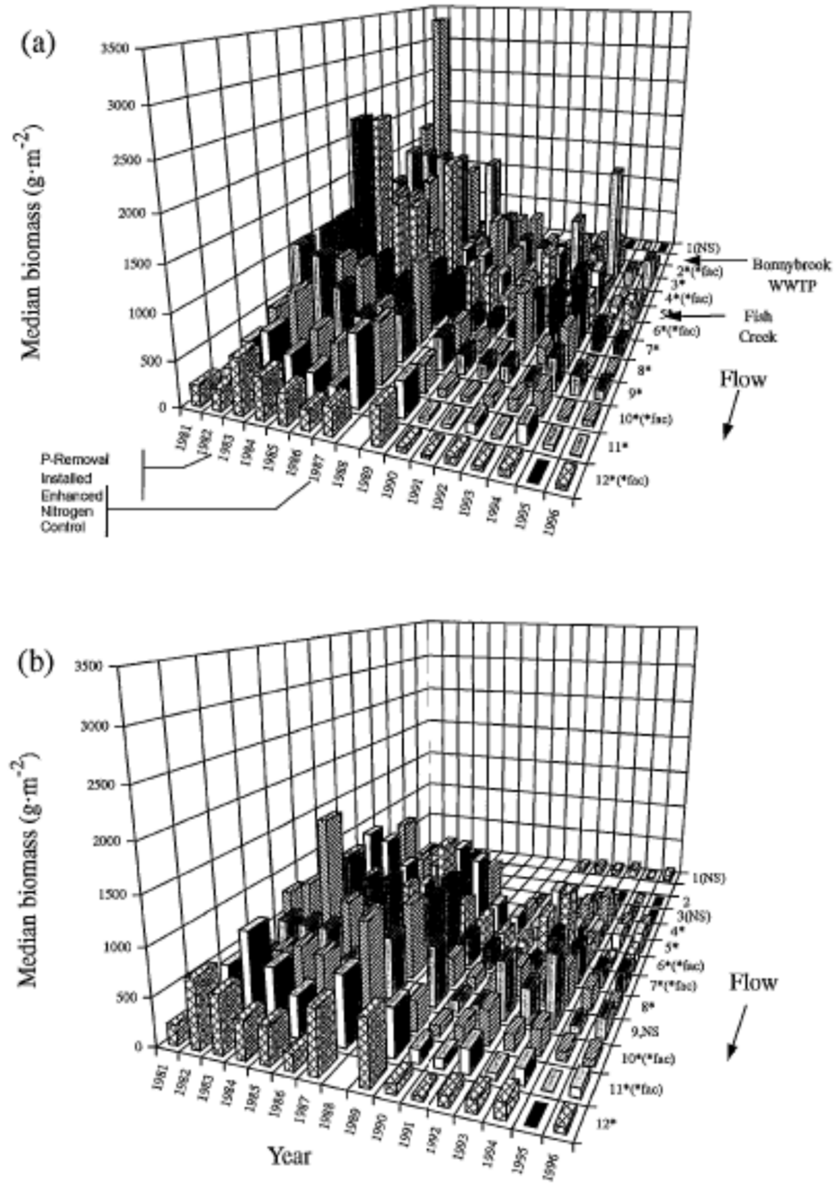
Nevertheless, a local study in the Piako river near Morrinsville showed no change in summer-time macrophyte abundance downstream of the town's wastewater treatment plant discharge which increased DIN from 0.2 to 2 mg N/L and DRP from 0.05 to 0.66 mg/L with no detectable change in shading level (both reaches with ca. 50% shade) or water clarity (ca. 1.1 m) (Matheson et al. 2009). Key macrophyte species were *Nitella aff. cristata*, *Potamogeton crispus* and *Egeria densa* and total cover was <25%. This concurs with the Crystal river study and suggests that macrophyte abundance may not be limited by DIN concentrations of 0.2 mg N/L or even less (as TN > DIN). However a moderately large increase in periphyton (dominated by *Compsopogon* spp.) was detected in the Piako river study suggesting that some reduction of periphyton abundance might potentially be achievable with these concentrations.

Figure 9 from Soziak (2002) shows the response of macrophyte biomass in the Bow river, USA to reductions in P and N inputs to the river associated with enhanced treatment of wastewater discharges.

Fig. 9. Macrophyte biomass in the Bow River, 1981–1996: (*a*) right bank and (*b*) left bank, both facing downstream. *Significant declining trend; NS, not significant; fac, flow-adjusted concentration; black bars indicate zero values.



The graph below from O'Hare et al. (2010) shows the relationship between biomass of the aquatic macrophyte *Ranunculus penicillatus* and water DRP concentrations in 14 UK rivers.