Forecasting rehabilitation outcomes for degraded New Zealand pastoral streams

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Abstract To understand the timescales and magnitude of responses that can be expected following catchment and riparian rehabilitation, we forecast changes to selected stream ecosystem attributes following tree planting in a pastoral catchment. All planting scenarios were predicted to lead to decreases in daily maximum water temperature after 15–20 years to levels that would be suitable for sensitive invertebrate species. Cooling and reheating were rapid so that most benefits to water temperature along the mainstem were forecast to accrue from shading all of the stream channel network. All planting scenarios were predicted to increase sediment yields over the status quo over the 25-year timeframe examined, with maximal sediment yield occurring about 15 years after planting due to expected erosion of the streambanks under the developing forest shade. Sediment yield was greatest for full catchment planting over 25 years, although sediment yield would be lowest with this scenario over longer timescales. A macroinvertebrate biotic index was predicted to increase by 25% over 15 years if whole catchment afforestation were implemented, compared to 9% if only the 4th order mainstem were planted with riparian trees. The use of ecological forecasting to predict likely outcomes for a range of scenarios should prove useful for prioritising rehabilitation actions.

Keywords: Agriculture; biodiversity; macroinvertebrates; riparian management; sediment yield; water temperature

Introduction

Wide-scale degradation of aquatic ecosystems in New Zealand is believed to have commenced 160 years ago with the onset of European colonisation and the development of large tracts of land for agriculture. The rate of degradation has been rapid with approximately 90% of wetlands drained, and unmodified indigenous forest cover reduced from 78% of land surface area prior to human colonisation to 22% today (Molloy, 1980; Howard-Williams et al., 1987). As a result of this landuse change, 70% of the length of larger rivers in New Zealand’s North Island now flow through catchments with modified vegetation cover (Collier et al., 2000).

There is now increasing desire in many countries to reverse stream and river degradation by restoring key habitat characteristics or ecosystem processes (e.g., National Research Council, 1992; Davies et al., 2000). In New Zealand, riparian management is becoming increasingly recognised as an important tool to mitigate the effects of land clearance and pastoral farming on small to medium-sized streams (Quinn, 2000). Technical guidelines for riparian management were published in 1995 (Collier et al., 1995), and since then several sets of guidelines have been produced for landowners (notably Ministry for the Environment, 2000). These guidelines were underpinned by the results of earlier case studies that demonstrated the effectiveness of riparian management in achieving environmental rehabilitation goals (Williamson et al., 1996), the temporal scales involved (Howard-Williams & Pickmere, 1994, 1999), and the utility of modelling to predict the outcomes of riparian planting relative to other management options (McBride et al., 1994).

Recent research has identified some adverse impacts that can also result from riparian planting depending on the attributes and timescales being assessed (Davies-Colley, 1997; Howard-Williams & Pickmere, 1999). To understand the timescales, direction and
magnitude of change that can be expected to follow planting, we used empirical and numeric models to forecast evolution of selected stream ecosystem attributes in a pastoral catchment near Hamilton, North Island, New Zealand. We compared forecasts for two riparian tree planting scenarios (4th order and >1st order riparian planting) and two catchment re-afforestation scenarios with the status quo over 25 years to provide a basis for rehabilitation planning in the catchment.

Methods

Study area

The upper Mangaotama Stream catchment has an area of 259 ha and is located 15 km west of Hamilton (Figure 1). The land was cleared of native forest about 75 years ago and revegetated with clover and pasture grasses. Occasional remnant native trees still occur sporadically in the catchment and some introduced poplars and willows have been planted in places along middle and lower reaches to stabilise eroding streambanks. Current landuse is sheep and beef grazing (average 12 stock units per hectare). The headwaters arise in steep hill-country with a maximum catchment elevation of 342 m asl. Elevation drops to 60 m asl at the catchment outlet where median annual flow is 43 l.s⁻¹. Fifty-nine percent of channel length in the stream network is taken up by 1st order streams, compared to 18, 8 and 15% for 2nd, 3rd and 4th order streams, respectively. The upper catchment comprises two sub-catchments that cover 49 and 95 ha.

Light exposure at the streamwater surface (~ 40% of ambient) is typically about 25 times greater than in comparable native forest streams nearby (1–2%; Davies-Colley & Payne, 1998). Suspended sediment concentrations measured at 3 sites average around 18 g.m⁻³, over twice those at nearby native forested sites (NIWA, unpubl. data). Mean monthly water temperatures in pasture streams are on average 2°C higher than those in native forest streams. Maximum summer temperatures can exceed 25°C in pasture streams, but in native forest streams these maxima are always below 20°C (Parkyn, 2000), a temperature approximating the thermal tolerance for sensitive stream invertebrates (Quinn et al., 1994; Cox & Rutherford, 2000).

Scenario forecasting

Forecasts were made of water temperatures, sediment yields and a biotic index (Macroinvertebrate Community Index; Stark, 1985) for 5 scenarios:
- Scenario 1: status quo (i.e., continuing pastoral land use)
- Scenario 2: fencing and planting of 15 m wide riparian zones along the 4th order mainstem (3.1 km of channel)
- Scenario 3: fencing and planting of riparian zones along 2nd order and larger channels (8.3 km)
- Scenario 4: re-afforestation of a headwater subcatchment (95 ha)
- Scenario 5: total catchment re-afforestation

These scenarios were formulated by a catchment management group charged with developing workable solutions for the management of this catchment (Quinn et al., in press). Our forecasts were carried out based on planting with introduced pine trees (Pinus radiata) since a large amount of information exists on their growth rate and shading levels, and they are a potential agroforestry species for farmers. Moreover, pine trees provide several of the desirable riparian functions of other tree species, including provision of shade and allochthonous inputs. However, growth rates are considerably faster than for native trees and responses of instream conditions to planting can therefore be expected to be more rapid. We used a 25-year timeframe as our forecasting horizon to approximate one human generation. Channel lengths were calculated by stream order from digitised GIS maps. The
scenario forecasts assume that there will be no change in pastoral activities on unplanted land.

Water temperature
The computer model STREAMLINE (Rutherford et al., 1997) was used for predicting changes in water temperatures. It quantifies shading by riparian vegetation, hillsides, and streambanks, and assumes steady flow but predicts diurnal variations of water temperature in the water column and underlying sediments. The model was calibrated for the upper Mangaotama Stream during summer low flows in January 1999 and tested during higher but steady flows recorded in December 1998. Data were derived from water temperature loggers (Onset Hobos or Stowaways) located at the outlets of the 95 ha subcatchment and the main catchment (Figure 1) where flow was also monitored continuously. Air temperature was recorded in an adjacent catchment. In addition, daily radiation and minimum/maximum air temperatures were recorded at a meteorological station 5 km away and cloud cover was recorded 30 km away. Surveys of channel widths and bank heights were made at 11 sites (5 transects per site), and water depths were measured at 5 points across each transect. Hillside and streambank topography and canopy angles (where riparian trees were present) were measured from the centre of the channel using an inclinometer.

The model was used to predict the effects of the various scenarios on water temperatures during worst-case, summer low-flow conditions. A riparian zone width of 15 m and a planting density of 200 stems per hectare were used when calculating shade levels. Water
temperatures in tributary streams bordered by plantings were assumed to reflect pasture conditions over the first 10 years and then to reflect forested conditions after 15 years following planting. Groundwater temperature (16.5°C), wind speed and humidity were assumed to be unchanged from the model calibration period. This assumption is likely to result in pessimistic predictions of water temperature changes for the various scenarios because it leads to underestimates of cooling. However, this underestimate may be balanced out to some degree by the fact that, for the purposes of the model, we considered wetland areas as equivalent to tributaries, and this would have overestimated the degree of shading that wetlands receive.

Sediment yield
Most of the sediment entering Mangaotama Stream under the current pastoral land use regime is expected to be derived from hillslope erosion assuming steady-state channel morphology. Armouring of the streambanks to fluvial scour by pasture turf is believed to account for the average twofold lower channel width of pasture streams compared to native forest streams with comparable upstream catchment areas (Davies-Colley, 1997). Observations along streams draining previously pastoral catchments now planted in pines indicate that shading out of riparian grasses leads to destabilisation of streambanks and mobilisation of stored sediment, particularly during large floods, with consequent increases in channel width, sediment yields and turbidity (Quinn et al., 1997; Davies-Colley, 2000).

We calculated the mass of sediment stored in streambanks that could be eroded by floods after riparian grasses had been shaded out by plantings, and estimated the timescales over which this erosion was expected to occur. These calculations were based on expected channel cross-sectional area changes and observations in nearby (re-afforested) streams which were used to define expected sediment yield endpoints following planting. Cross-sectional channel area was determined from measured channel depths and widths, and from sketches of channel cross-sectional form at 60 locations throughout the Mangaotama Stream network. Channel cross-sections were plotted against the catchment area upstream to derive a regression equation for predicting average channel cross-section. This curve was combined with a distribution of stream length by catchment area so as to determine channel lengths in different ranges of channel cross-section. Stored sediment volume was then calculated by summing incremental stream length × channel cross-section (assuming an increase in cross-section by a factor of 2 following shading), and this volume was converted to mass assuming a bulk density of 1.2 tonnes.m⁻³. Based on spot observations of raw banks, it was assumed that pasture streambanks were composed mainly of fine-grained alluvium (<2 mm) that would be transported out of the catchment following mobilisation.

Riparian buffers are also expected to reduce the sediment in surface runoff from catchment hillslopes (Smith, 1989; Cooper et al., 1992). We used the procedures of Collier et al. (1995, guidelines volume pp. 51–55) to estimate removal of sediment for grass riparian buffers that will be formed rapidly following removal of animals from fenced riparian buffers. We further assumed similar sediment removal efficiencies in the litter layer of the eventual forest buffers.

Biotic index
The Macroinvertebrate Community Index (MCI) was originally developed for monitoring the impacts of organic pollution in stony streams. It is based on the cumulative tolerance scores of macroinvertebrate taxa occurring at a site divided by the number of scoring taxa and multiplied by a scaling factor (Stark, 1985, 1993). Values decline as the “health” of a site decreases. The quantitative derivative of the MCI has been found to be a useful
indicator of landuse impacts, with values in Waikato hill-country streams averaging less than half those in native and pine forest streams (Quinn et al., 1997).

For our biotic index forecasts, we used benthic macroinvertebrate data collected in spring 1995 from 3 pasture sites in the Mangaotama catchment, 3 similar-sized pine forest sites nearby, 3 native forest sites, 2 pasture sites with varying percentages of headwater catchment area in native forest, and several sites located in forest remnants but with upstream catchments in pasture. Samples consisted of 7 pooled 0.04 m² Surber samples (250 µm mesh) collected from randomly selected points in a 100 m reach at each site. A regression equation was developed to predict MCI score from the proportion of the catchment in forest. Riparian planting was assumed to restore MCI values to 85% of those measured in streams draining catchments entirely in native forest based on data collected in forest remnants with pastoral headwaters. The sites with catchments entirely in pine forest were 15 years old at the time of sampling, and had mean MCI scores almost identical to those at the native forest sites. Results were weighted by streambed area to account for changes in channel size along the stream network and the anticipated eventual doubling of channel width. Fourth-order streams occupy 40% of streambed area compared to 11% and 15%, respectively, for 3rd and 2nd order streams. For simplicity, we assumed a linear response in streambed-weighted MCI values from the start of planting to reach a steady state 15 years later (but see below).

Results and discussion

Water temperature forecasts

Daily maximum water temperature, under summer low-flow conditions, was predicted to decrease significantly as a result of shading the stream (Figure 2). The magnitude of cooling was similar for all planting scenarios so that maximum temperatures were predicted to decrease by 5–6°C, reaching levels well below the threshold for the survival of sensitive invertebrate species. Thus, temperature maxima in shaded reaches were typically between 16 and 18°C for the various planting scenarios following the attainment of steady-state shaded conditions, compared with average daily maxima of up to 24°C in open pasture streams measured during the model calibration period. Daily maximum temperatures were predicted to be comparable to those measured in native forest streams within about 30 years of planting.

If riparian planting were implemented only along the 4th order mainstem (scenario 2), cooling would be rapid and temperature maxima less than 20°C were predicted within 15 years of planting along the lower 3 km of stream channel (Figure 2). The rapid cooling following the onset of riparian planting reflects the shallow depth of the stream and the high heat conductance of the gravel bed. Indeed, in this scenario, the first 150 m of shading decreases temperature maxima by 3°C. For scenario 3, the increase in shade along the second order and larger channels led to significant reductions in water temperatures after 15 years (Figure 2). Water temperatures were close to equilibrium along all the mainstem sites in that scenario.

Forecasts for the two re-afforestation scenarios predicted the same changes in water temperatures in the upper subcatchment with reductions in daily maxima of c. 4–5°C within 15 years. However, if only the headwaters were re-afforested (scenario 4), rapid reheating was predicted to occur below the forested section so that only the upper 1.5 km of stream benefited from the increased riparian shade. Reheating was particularly rapid over a 600 m stretch of channel that was only partially shaded, shallow (mean depth 0.12 m), and had a long water residence time (c. 3 hours). In contrast, re-afforestation of the entire catchment (scenario 5) was predicted to lead to temperature reductions of the same magnitude over the entire length of the main channel, as also predicted for scenario 3 (Figure 2).
As mentioned earlier, the water temperature modelling did not explicitly consider changes in microclimate conditions other than shade as a result of planting. Growth of pines in riparian zones will reduce solar radiation inputs, and if the riparian strip of forest vegetation in pasture is wide enough it may also reduce air temperature and wind speed, and increase humidity. If replanting reduces riparian air temperatures significantly, then water temperatures could decrease by a further 1°C over that predicted when microclimate conditions were ignored. Recent studies have shown that wind speed and air temperatures decrease over a distance of 40 m when going from pasture into native forest (Davies-Colley et al., 2000), providing an improved basis for determining appropriate riparian zone widths to maintain microclimate conditions. Microclimate conditions may be important for the survival of the adult stage of some stream insects (e.g., Collier & Smith, in press), suggesting they should be a consideration in future forecasting exercises.

Sediment yield forecasts
We estimated that the total mass of sediment stored in streambanks in the Mangaotama catchment is about 13,000 tonnes, equivalent to around 21 years of current annual sediment yield which we assumed to be all from hillslope sources. We also assumed that this sediment would be eroded in an approximately Gaussian pattern over a period of about 20 years, with peak erosion occurring at about 15 years after planting (Figure 3). Shade levels from pine trees were predicted to be sufficient to extinguish riparian grasses within 10–15 years of planting, so that smoothed curves of predicted sediment yield peak at about 15 years (Figure 3). Sediment yield peaks were highest for scenarios 3 and 5 with the entire mainstem shaded, and lower for scenarios 2 and 4. In reality, the smoothed curves shown in Figure 3, indicating the general trend of sediment yield, will be a series of sharp spikes during storms at which times most sediment stored in banks will be mobilised. Our re-afforestation forecasts assumed a linear decline in the inputs of hillslope sediment from
c. 600 tonnes y\(^{-1}\) currently to 135 tonnes y\(^{-1}\) after 25 years of tree growth, based on observations of 4–5 times greater average sediment yields in pasture than in forest (Davies-Colley 2000). A linear decline is a pessimistic assumption, made for simplicity, since hillslope sediment yield seems likely to decline rapidly following removal of animals, perhaps in an exponential pattern.

For the riparian planting scenarios (2 and 3), we allowed for sediment removal by riparian buffers based on removal efficiencies for optimal grass filters predicted using the guidelines of Collier et al. (1995). For conditions in the Mangaotama catchment (“high” slopes (20 to >35°), “moderate” infiltration rate (20–40 mm h\(^{-1}\); pers. comm. Sandy Elliott, NIWA), “moderate” clay content (20–40%) for the clay-loam soils), these guidelines predict that an “optimal” grass buffer of 7% of the hillslope length would remove 50% of the inflowing sediment. This figure corresponds to an average grass buffer width of 8.3 m along 4th order streams (scenario 2) that receive 8.9% of the total drainage through adjacent riparian areas, and an average 7.9 m width along 2nd order and larger streams (scenario 3) that receive 41% of the total drainage through riparian areas. Lank grass, ideal for sediment buffering, is expected to develop rapidly in 15 metre wide buffer strips once livestock are fenced out. The litter layers that will eventually develop under planted trees in the buffers may be less effective than grass in retaining sediment, but the assumption of continued 50% removal efficiency may be reasonable given that these buffers will be appreciably wider than the “optimum”. The net effect of the 15 m wide buffers, due to their filtering action and the reduced grazed hillslope area, was estimated to reduce hillslope sediment yield by 5.5% in scenario 2 and 24% in scenario 3.

Forecasts of the mass of sediment exported from the catchment after 25 years are shown in Table 1. These calculations suggest that all rehabilitation scenarios investigated would result in an increase in sediment yield compared to the status quo over the 25-year timescale as stream channels widen in response to shaded conditions. Least impact was forecast for re-afforestation of the headwater subcatchment (scenario 4), largely because of the stabilisation of hillslopes and the relatively short length of streambank erosion brought about following shading. Highest sediment yield was for scenario 5 in which the whole length of the main channel is shaded, because of the high bank erosion contribution despite the lowest hillslope inputs. Nevertheless, considering the uncertainties involved in forecasts of this sort, the differences in sediment yield between the scenarios examined were only minor over 25 years. Over the longer term, however, once this stored bank sediment has been exported, banks can be expected to stabilise as channels reach a new steady-state “forest” morphology and sediment yield will eventually decline to a lower level than currently experienced (Figure 3).

Biotic index forecasts
Forecasts of changes in the MCI weighted by streambed area indicate that total catchment re-afforestation will result in a 25% increase in MCI values by 15 years compared to the status quo (Figure 4). Re-afforestation of the headwater subcatchment and riparian planting of 2nd order streams and larger was predicted to increase MCI by around 14% over the same timeframe, whereas 4th order riparian planting led to a 9% increase on a streambed area-weighted basis. These changes reflect an overall increase in the diversity of sensitive invertebrate species.

The predicted timeframe to achieve steady-state MCI values corresponds with the timeframe that water temperatures were predicted to decrease to levels suitable for sensitive species. However, this timeframe also corresponds with the forecast period of significant sediment export as channels widen during large floods under shaded conditions, and this could potentially have an adverse impact on biotic index scores. However, observations in
Figure 3 Hypothetical curves indicating trends in sediment yield for the 4 planting scenarios. For each scenario a straight-line trend in hillslope erosion, and a Gaussian trend in channel erosion (peaking at 15 years) were assumed.

Table 1 Summary of predicted sediment yield (tonnes; rounded to the nearest 1000) from the upper Mangaotama catchment over 25 years following planting of Pinus radiata. Four rehabilitation scenarios are compared with the status quo.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Streambank</th>
<th>Hillslope</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Status quo</td>
<td>0</td>
<td>15,000</td>
<td>15,000</td>
</tr>
<tr>
<td>2. 4th order riparian planting</td>
<td>6000</td>
<td>14,000</td>
<td>20,000</td>
</tr>
<tr>
<td>3. &gt;1st order riparian planting</td>
<td>10,000</td>
<td>11,000</td>
<td>21,000</td>
</tr>
<tr>
<td>4. Headwater re-afforestation</td>
<td>5000</td>
<td>13,000</td>
<td>18,000</td>
</tr>
<tr>
<td>5. Total re-afforestation</td>
<td>13,000</td>
<td>9000</td>
<td>22,000</td>
</tr>
</tbody>
</table>

Figure 4 Streambed area-weighted MCI forecasts over 25 years for the 4 rehabilitation scenarios. The status quo is indicated at 0 years.
nearby streams bordered by 15-year old pine trees indicate that MCI scores are quite high, suggesting that changes in water temperatures and allochthonous inputs, for example, are more important in determining stream health than high sediment yields (see also Quinn et al., 1997).

Temporal considerations

This forecasting exercise has emphasised the need for a long-term perspective when attempting to define the likely benefits from planting pastoral catchments and riparian areas in trees. Although some benefits may accrue relatively rapidly, such as declines in hillslope erosion due to the removal of animals, others may take many years. For example, our forecasts indicated that water temperature regimes would take around 15 years to become suitable for sensitive aquatic species if pine trees were planted. Even longer timescales (>20 years) were predicted for the stabilisation of sediment yields from eroding banks, and water clarity may actually deteriorate for a period prior to this. The timeframes over which these processes operate will depend on the growth rates of the trees planted, and responses may be delayed if slow-growing native tree species are used. Forecast scenario outcomes can be ranked according to their expected benefits to provide a basis for prioritising rehabilitation options (Table 2). Based on the scenarios described above and using a 25-year timeframe, no action (status quo) may be favoured if the primary goal were to rehabilitate a sensitive estuary downstream by minimising sediment inputs, whereas total catchment re-afforestation or riparian planting of the 2nd order and larger streams may be favoured if onsite ecological characteristics were most highly valued.

Conclusions

The approach we have presented, using numerical and empirical models to forecast likely outcomes for a range of different scenarios, should prove useful for prioritising rehabilitation actions. The option selected from the balance of outcomes will reflect the pre-defined rehabilitation goals. The length of time required to achieve positive returns for some key ecological characteristics following planting is likely to exceed the length of tenure of many property holders. In addition to aquatic ecological characteristics, other attributes, including aspects of terrestrial ecology, aesthetics, recreation, public health and landowners’ goals will ultimately influence stream restoration planning. Another issue that warrants consideration at the landscape scale is defining the spatial arrangement of planted patches that maximises the probability of recolonisation by sensitive aquatic species at a particular locality. The dilemma of how to prioritise locations for rehabilitation, given the limited funding available, requires tools to predict a cost-effective spatial arrangement of patches to optimise environmental returns. These considerations highlight the need for realistic expectations concerning (i) the timescales of improvements, (ii) the fact that some conditions may deteriorate before they get better, and (iii) the suite of aquatic species that can be expected to establish at a site over the long term.

Table 2. Ranks of forecast beneficial effects (1=highest) on 3 aspects of stream health for 4 rehabilitation scenarios and the status quo over a 25-year timeframe

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Temperature</th>
<th>Sediment</th>
<th>Biotic index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Status quo</td>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>2. 4th order riparian planting</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>3. &gt;1st order riparian planting</td>
<td>1=</td>
<td>4</td>
<td>2=</td>
</tr>
<tr>
<td>4. Headwater re-afforestation</td>
<td>4</td>
<td>2</td>
<td>2=</td>
</tr>
<tr>
<td>5. Total re-afforestation</td>
<td>1=</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>
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