Karamu catchment

In-stream flows for oxygen

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Environmental Science - Hydrology

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Executive Summary

Water is abstracted from streams and aquifers for irrigation and town supply. Deciding how much water should be allocated, and when restrictions should come into force, will require information on flows required to sustain stream ecosystems. Dissolved oxygen is vital for safeguarding the life-supporting capacity of streams, but reduced flow can reduce oxygen in low-gradient streams that support high abundances of aquatic plants, like the Karamu. This means oxygen is an important consideration when setting in-stream flows for the Karamu catchment.

Oxygen is a critical issue for the Awanui Stream, with seventy-seven days of overnight anoxia measured during summer and autumn. There was more oxygen in the Raupare Stream, where dissolved oxygen was at least 4 mg/L for all but 5 days in 2013. Oxygen concentrations as low as 2.6 mg/L were observed in the Irongate Stream, coinciding with flows that were the lowest since records began 1978.

The System for Environmental Flow Assessment (SEFA) was used to predict the change in oxygen with flow. This model uses rates of photosynthesis, respiration and reaeration estimated from oxygen monitoring data. The Raupare and Awanui Streams were intensively monitored to characterise changes in oxygen, temperature, flow and aquatic plant abundance over a year. More conventional seven-day monitoring was undertaken at the Irongate Stream flow recorder site. Cross-sections were surveyed at all three sites for hydraulic modelling of the change in depth and velocity with flow. Quantile regression was used to determine the probability of a given oxygen concentration for a given flow, using recorded oxygen concentrations and flows for the Raupare and Awanui Streams.

This report presents the in-stream flows predicted to achieve specific oxygen targets for each site, which are summarised in the table below. These predictions were validated using observations for the Awanui and Irongate streams. For the Raupare Stream, observed results supported the Autumn Scenario model – representing conditions likely to occur during extreme low flows. However, the Summer Scenario model better represented oxygen-flow response at the peak of plant growth (Dec-Jan) than the Autumn Scenario. The Autumn Scenario and Summer Scenario models predicted the same oxygen concentrations at the existing minimum flow for the Raupare (4.6 mg/L at 300 L/s).

Flow is not the sole determinant of oxygen concentrations, but reduced flow may reduce oxygen concentrations. The validation data, together with the regression quantiles derived from the calibration data, are useful for understanding the variability in oxygen concentrations for a given flow. Setting minimum flows for these streams can now consider the consequences for oxygen limits. The policy process for setting minimum flows will involve stakeholders recommending appropriate limits to council, and what constraints should apply to water users when streams breach that minimum flow.

Summary Table: Flow requirements to achieve nominated dissolved oxygen targets for the study sites. Oxygen concentrations are specified as a daily minimum concentration in mg/L. Flows are given to two significant digits. * denotes flows extrapolated lower than the observed flow range. Pre-existing minimum flows are also listed from the 2006 Hawke's Bay Regional Resource Management Plan.

Stream	Scenario	Oxygen Conc.				Min. Flow
		3 mg/L	4 mg/L	5 mg/L	6 mg/L	(2006)
Raupare (Ormond Road)	Autumn	*160 L/s	240 L/s	350 L/s	510 L/s	300 L/s
	Summer	*110 L/s	*200 L/s	390 L/s		
Awanui (flume)	Summer	170 L/s	270 L/s	510 L/s	-	120 L/s
Irongate (Clark's weir)	Summer	21 L/s	33 L/s	67 L/s	190 L/s	100 L/s

1 Introduction

Freshwater in Hawke's Bay includes streams, rivers and lakes. Fish and other stream life depend on freshwater to survive. Water is taken from streams and aquifers for irrigation, industry and town supply. Hawke's Bay Regional Council manages freshwater resources under its Regional Resource Management Plan. Deciding how much water should be allocated, and when restrictions should come into force, will require information on flows required to sustain stream ecosystems.

Hawke's Bay Regional Council is developing policy approaches for the Greater Heretaunga area (Tutaekuri, Ahuriri, Ngaruroro and Karamu catchments) to manage the effects of land-use activities on freshwater. Regional plans conventionally set minimum in-stream flows as a basis for water allocation and to trigger irrigation bans. Setting minimum flows is an effective approach to manage the effects of multiple water takes that are spread over a wide area, particularly in the absence of dams large enough to affect flood flows or sediment regimes.

Stream flow requirements for aquatic ecosystems may depend on, amongst other things, stream temperature, oxygen and depth. This report examines the impact of reduced stream flow on dissolved oxygen concentrations for three sites. Subsequent reports will examine how oxygen stress varies across the riverscape.

The term "oxygen" is used throughout this report to refer to O_2 gas dissolved in water (dissolved molecular oxygen). Oxygen is vital for sustaining fish and other aquatic life. A lack of oxygen can suffocate fish, with numerous studies describing the tolerances of different species to low oxygen concentrations (Davies-Colley *et al.*, 2013; Dean & Richardson, 1999; Landman *et al.*, 2005; Urbina *et al.*, 2012).

The term "aquatic plants" is used throughout this report to refer to macrophytes or weed, but excluding algae and moss. Streams with abundant aquatic plants typically experience increasing oxygen concentrations by day and declining oxygen concentrations overnight. Oxygen diffuses into water from the atmosphere in a process called reaeration. Decreasing the flow of water can decrease reaeration in some lowland streams. The more water flowing through the stream also increases the mass flow of oxygen available to replace the oxygen consumed by plants. Thus, decreasing the flow of a stream can reduce oxygen concentrations through reduced reaeration and reduced water volume. This report investigates the relationship between stream flow and oxygen. This information is intended to inform limit selection by the TANK Stakeholder Group (TANK - Tutaekuri, Ahuriri, Ngaruroro, Karamu), which was assembled for the Greater Heretaunga Plan Change.

The study examined lowland single-thread streams of the Heretaunga Plains, so excludes the large gravel-bed rivers originating from mountainous headwaters, including the Ngaruroro, Tutaekuri, and Tukituki rivers. The three study sites are within the Karamu catchment, which has a maritime-temperate climate, with about 800 mm of rainfall falling evenly throughout the year, and about 2150 sunshine hours per year (Chappell, 2013).

High evaporation rates through summer reduce stream flows and increase water demand for irrigation. Most irrigation water is sourced from groundwater. Intensive development of the Heretaunga gravel aquifer provides irrigation water for orchards, vineyards and crops, for town water supply and for industry (HBRC, 2014). Streams of the Heretaunga Plains are fed by the same aquifer. Artesian pressure produces springs through windows in the confining clays. In addition to these point-source springs, diffuse springs seep through streambeds along the boundary between the confined and unconfined aquifer. These types of spring supply the Raupare, Irongate and Tutaekuri-Waimate Streams. Springs arising from limestone in the surrounding hill country also feed the Awanui Stream.

The Karamu is characterized by low-gradient streams that support high abundances of aquatic plants, and these characteristics increase the risk of oxygen stress (Wilding *et al.*, 2012). Invertebrate monitoring indicates degraded conditions exist at many sites in the Karamu catchment (HBRC, 2014). Understanding dissolved oxygen is important for understanding the constraints on aquatic life in the Karamu catchment (Haidekker, in prep.).

2 Oxygen and Stream Flow

Fish and stream invertebrates depend on oxygen to survive because oxygen is required for cellular respiration which fuels life (e.g. muscle movement, protein biosynthesis). An absence of oxygen (termed anoxia) is fatal to most fish. Exposure to low oxygen (termed hypoxia) forces many fish to stop feeding and leave shelter to respire at the water's surface where there is more oxygen (Domenici *et al.*, 2007; Kramer, 1987; Landman *et al.*, 2005; Neilan & Rose, 2014). Therefore, the processes determining how much oxygen is available to stream life are important.

This report examines only gaseous oxygen that is dissolved in water (dissolved O_2 or DO), rather than oxygen bound to other compounds. At equilibrium, the pressure of gaseous oxygen in water is the same as the pressure of oxygen in the atmosphere, with a partial pressure of about 0.21 Pa/Pa (21%) at 1013 hPa, at sea level. But oxygen diffuses through water about 10,000 times slower than through air. This is why water movement, such as turbulent flow, is important for distributing oxygen through the water column (Cox, 2003). Oxygen diffuses at an increased rate if there is a steep oxygen gradient. For example, fish increase the oxygen gradient to their benefit using thin gill tissue between the high-oxygen water and their low-oxygen blood.

Oxygen diffuses through warm water at a faster rate than through cold water, which compensates for the lower saturation concentration of oxygen in warm water (Verberk *et al.*, 2011). But fish need more oxygen at higher temperatures because fish metabolism increases with temperature. Eventually a temperature is reached at which increasing metabolic demand surpasses the increasing oxygen diffusion rate (Verberk *et al.*, 2011).

The relationship between oxygen and stream flow is affected by both air-water diffusion and water-organism diffusion, because oxygen concentrations are reduced when respiration by plants and microbes exceeds the diffusion rate from air to water.

During the day oxygen is produced by aquatic plants as a by-product of photosynthesis ($H_20 + CO_2 => O_2 + CH_2O$). Respiration by the same plants, and other aquatic life, consumes oxygen ($C_6H_{12}O_6 + O_2 => CO_2 + H_2O$), and this respiration continues through the night after photosynthesis stops. As a result, streams dominated by aquatic plants can fluctuate from oxygen super-saturation by day (photosynthesis minus respiration) to hypoxic conditions at night (minus respiration).

Given the complexity of these processes, predicting the response of dissolved oxygen concentrations to stream flow requires estimates of the following:

- ***P*** - rate of oxygen production from plant photosynthesis (g/m^3/day)
- ***R*** - respiration rate of plants and microbes that consume oxygen (g/m^3/day) and
- ***K*** - reaeration coefficient for oxygen from the atmosphere (/day)

The rates of photosynthesis and respiration increase with the abundance of plants and microbes. The net reaeration rate increases from zero at saturation, to its maximum value when the water is depleted of oxygen (and negative values when super-saturated). Conceptually, the change in oxygen from day to night can then be modelled using equation 1:

$$\frac{dC}{dt} = K(C_{sat} - C) + P - R \qquad 1)$$

Where ***C*** is the oxygen concentration at time ***t***, and C_{sat} is the saturation concentration for a given temperature. To implement this equation, estimates of photosynthesis, respiration and reaeration can be derived from observed oxygen monitoring data using the Delta Method (Chapra & DiToro, 1991; McBride & Chapra, 2005) or the Metabolism Calculator (Wilcock *et al.*, 2011). This study uses SEFA (System for Environmental Flow Assessment) to implement the Delta Method.

For the Delta Method, the reaeration coefficient is estimated as a function of the time lag between solar noon and time of maximum oxygen (i.e. independent of P and R), with the photoperiod being the total hours of daylight (Equation 2). The SEFA model estimates hours of daylight for each date and location using latitude and longitude. Instantaneous reaeration rates are converted to a standardized value at 20 °C using a gas-transfer temperature coefficient ($1.0241^{20\text{-mean temp}}$), (Demars & Manson, 2013; Jowett *et al.*, 2014).

$$\mathrm{K} = 7.5\left(\frac{5.3\mathrm{n} - \mathrm{timelag}}{\mathrm{n.timelag}}\right)^{0.85} : \text{where } \mathrm{n} = \left(\frac{\mathrm{photoperiod}}{14}\right)^{0.75} \qquad 2)$$

The Delta Method works better in streams with low reaeration coefficients (less than 25 /d), such as those studied here, because error-sensitivity is reduced if the time-lag between solar noon and maximum oxygen is longer (Wilcock *et al.*, 2011). Alternative methods are available (Cox, 2003; Wilcock *et al.*, 2011), including the night-time regression method, which estimates reaeration from the rate of decline in oxygen after dark (Wilcock *et al.*, 2011; Young *et al.*, 2006). The night-time regression method is also sensitive to the timing of nightfall and dawn, and is not integrated in an oxygen-flow model, but provides a useful cross-check of reaeration coefficients. Gas tracer methods are used by some research organisations to estimate reaeration, but require considerable investment to achieve a single estimate (Riley & Dodds, 2013). Streams with waterfalls, rapids and riffles have a higher reaeration coefficient than low-gradient streams. But finer-scale resolution of changes in reaeration coefficient at a site over time has proven difficult to predict (Cox, 2003; Demars & Manson, 2013; Jowett, 2012). For this investigation, the decision whether to fix the reaeration coefficient, or to vary it with flow, was based on obtaining the best fit to observed data for each site.

The SEFA model calibrates respiration and photosynthesis rates to measured oxygen concentrations. SEFA can then predict oxygen concentrations for other flows using the predicted change in depth between this reference flow and the modelled flows.

This investigation focuses on streams where aquatic plants drive dissolved oxygen concentrations. Low stream gradients and high abundance of plants are factors increasing the risk of oxygen stress (Wilding *et al.*, 2012). In other streams, oxygen concentrations are affected by chemical and biological oxygen demand. For example, oxygen decreases downstream of point discharges of sewage effluent from decomposition of organic matter by bacteria. Some dissolved chemicals, such as ammonia, also consume oxygen. In the past, in-stream pollutants may have been important oxygen consumers when there were more point discharges of effluent. But aquatic plants and decomposing plant material are now likely to be the main consumers of oxygen.

Groundwater can also affect oxygen concentrations, both negatively and positively. The effect on oxygen can be negative at the spring source because groundwater often has little or no dissolved oxygen (Hall & Tank, 2005). The groundwater influence can then transition to a positive effect at some distance downstream of the discharge, as the increased stream flow reaches a new equilibrium oxygen concentration. That distance will depend on the rates of reaeration, respiration and photosynthesis. Studies by Hawke's Bay Regional Council in the Harakeke Stream revealed a net oxygen benefit just 400 m downstream from an anoxic groundwater discharge (see **File Note**). Neither SEFA nor the Metabolism

Calculator can account for the pre-equilibrium effect of groundwater inflows, which reduces the accuracy of the respiration parameter (Hall & Tank, 2005). The consequence of parameter errors for oxygen-flow predictions are yet to be established. The robustness of both models is not compromised downstream of the new equilibrium point.

3 Study Sites

The Karamu catchment includes part of the Heretaunga Plains and surrounding hill country (Figure 3-1). Different stream types on the Heretaunga Plains were selected for the study, including streams draining limestone hill-country and streams that are spring-fed from the Heretaunga gravel aquifer. Study sites were chosen at existing flow monitoring sites (Figure 3-1). Those flow monitoring sites provide flow data and telemetry options for this investigation, and are also locations where compliance with minimum flows can be monitored in future.

Raupare Stream

The Raupare Stream is a modified natural water course fed by springs in the Twyford area from the Heretaunga aquifer. Annual low-flows experienced at this site are more than at the other study sites, despite having the smallest surface catchment (Table 3-1), because the aquifer is recharged from a larger catchment. The Ngaruroro River is a major source of aquifer recharge (Dravid & Brown, 1997), and it is only between 0.5 km to 4 km from the Ngaruroro River to the springs that feed the Raupare (Figure 3-1). The smaller area of the surface catchment, compared to the groundwater catchment, means that floods in the Raupare are smaller compared to the average flow. This is significant, because smaller floods are less capable of scouring aquatic plants (Riis & Biggs, 2003). Land use in this catchment is mostly orchards and crops. Most irrigation water is sourced from groundwater bores (HBRC, 2014).

In 1867 the course of the Ngaruroro River shifted, so that the Raupare catchment was no longer on the north bank of the Ngaruroro, but instead was situated on the south bank (NIWA events catalogue; HBRC, 2004). The river avulsions may have changed the location and magnitude of spring outflows. The natural springs and wetlands were modified to their present channel alignment at least 75 years ago. The stream network delineated in a soil map from 1938 (Bell *et al.*, 1938), and in 1950 aerial photographs, was substantially similar to today's network. Boyd (1984) mentions drainage by the early 1890's of Frimley Estate (J. N. Williams, p 102), which extended downstream of Ormond Rd, when dairy farming was a significant industry. This preceded several decades of rapid orchard expansion in the Hastings area (Boyd, 1984; Wright, 2001) that may have accelerated efforts to drain the Raupare catchment.

Discrete spring-heads with boiling sands are found in areas with imperfect confining layers, including the Raupare Road to Twyford Road area. Discussion with landowners reveals that these springs change over decades, in response to events such as earthquakes and removing tree stumps. Springs rising where the unconfined aquifer intersects the surface are typically more diffuse, as found west of Twyford Road and Trotter Road. These areas have been drained by networks of buried tile drainage pipes to enable deeper rooting of orchard trees. Some tile drains require pumping where the drain outlet is lower than the receiving surface drain. The quality of the emerging groundwater is generally excellent (HBRC, 2014), with 95% of nitrate samples less than 0.5 mg/L (from 71 samples collected between 1995-2014 from Monitoring Well 1674).

Spring water emerges from the ground at 14.5 °C, with 20% oxygen saturation measured in some springs. The emerging spring water is subject to reaeration in the tributaries before it reaches the main stem of the Raupare. Little or no groundwater emerges directly into the bed of the main stem of the Raupare, as demonstrated by concurrent gaugings through the catchment. The oxygen monitoring site is therefore more than 1 km downstream of significant inflows from the gravel aquifer. Channel substrates are predominantly fine material, with silt, sand and pumice-gravel deposited on a clay base. There are isolated sections with gravel substrate (e.g. adjacent to Nicholl Road; Pakowhai Country Park's pre-1969 Ngaruroro bed).

A diverse fish community inhabits the Raupare Stream, including inanga, longfin and shortfin eels, common bully, patiki (black flounder), yelloweye mullet, common smelt, rainbow trout, *Gambusia* and goldfish (HBRC, 2014). Torrentfish were recorded from a gravel reach upstream of the monitoring site (adjacent to Nicholl Road). Other conspicuous stream life observed included koura (crayfish) and freshwater mussels. Inanga and mullet were the most abundant fishes at the study site, from daytime observations when eels were probably undercover (Table 3-2). Both inanga and mullet are seasonal residents of the Raupare because part of their life-cycle is completed in estuaries and the ocean. Inanga were observed in the Raupare between late-November and February, with infrequent observations in March. Yelloweye mullet were observed from late-November through June, with larger schools observed toward the end of this period. Rainbow trout are present in the Raupare, but a recent RiVAS assessment ranked the Karamu catchment as "very low use" for trout angling (Booth *et al.*, 2012).

Aquatic plant communities cover most of the bed year-round, and *Elodea canadensis* and *Potamogeton crispus* were more common (Wells & Champion, 2003). Emergent water celery and watercress extend out from the margins through summer and autumn. Hawke's Bay Regional Council actively controls aquatic plants by periodic cutting. A weed boat is used to cut down the height of plants, but not their bed coverage, between Raupare Road and the Karamu confluence. A tractor-mounted boom-mower maintains grassed banks and also cuts emergent water celery. Herbicide (glyphosate) is typically applied once a year to emergent water-celery.

The monitoring site at Ormond Road is typical of the Raupare Stream, with a straight channel, high abundance of aquatic plants and steep mown banks (Figure 3-2). The reach represented by the Ormond Road monitoring site extends 850 m upstream to the Burns confluence, and 1700 m downstream, ending at the gravel-bed reach within Pakowhai Country Park. There are minimal inflows to the study reach; the channel is a relatively uniform U-shape; the riparian vegetation is relatively uniform (mown grass); and the stream has a northerly aspect (channel runs approximately west to east).

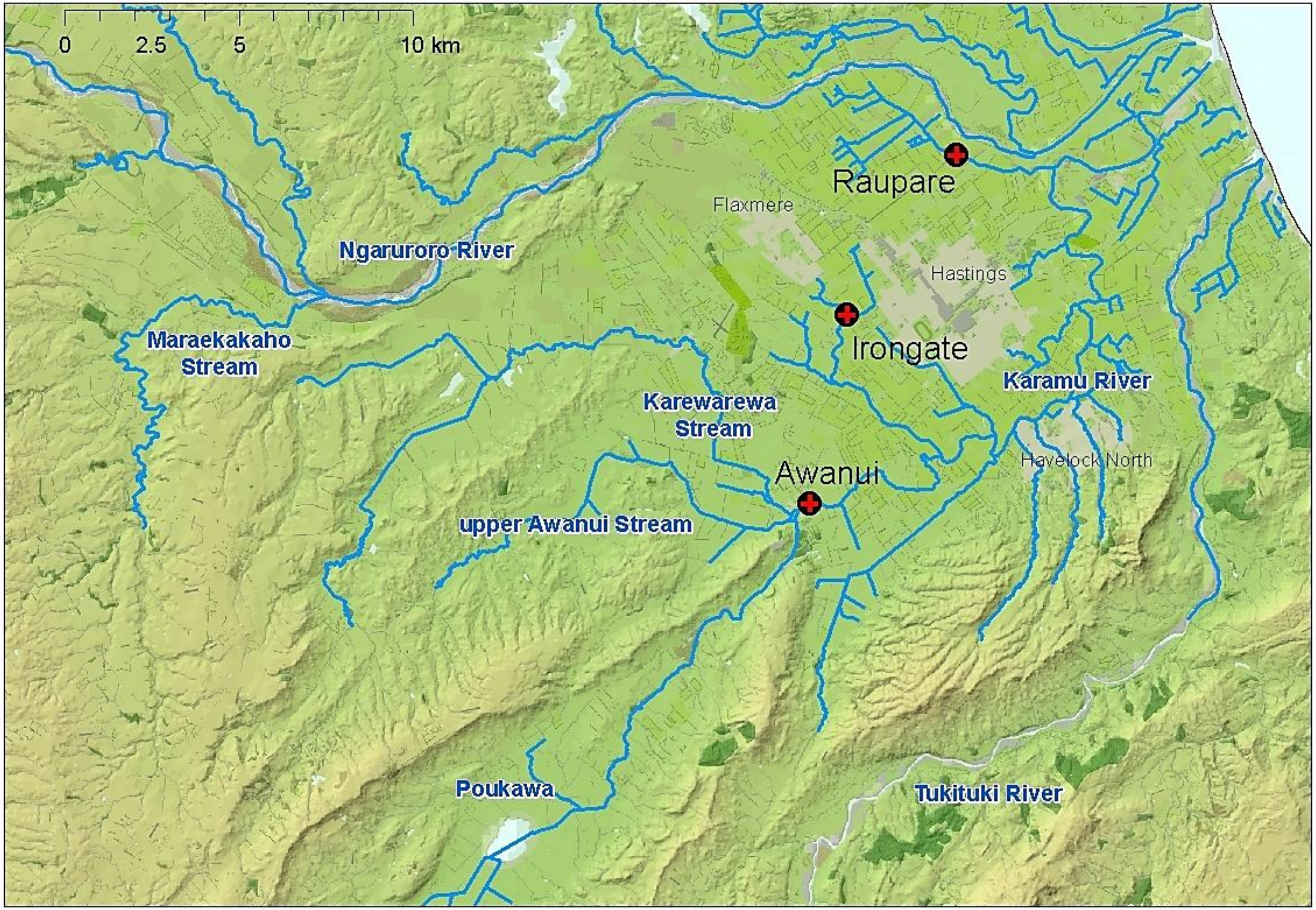

Figure 3-1: Map of study sites. Sites are shown as dots with a red cross in the centre and named.

Table 3-1: Flow and channel metrics for the study sites. Flow metrics were sourced from the Karamu Characterisation report (HBRC, 2014). MALF stands for mean annual low flow, calculated as the mean flow from a time-series of annual 7-day minima. Larger values for mean/median flow indicate more flow variability. Catchment areas are from the Envirosites Database, except the Irongate which is from the River Environment Classification. Stream gradient was calculated from a LiDAR terrain map over the reach length (1 to 3 km). Widths and depths are means from ten cross-sections at the time of cross-section survey, and would increase with flow (see section 4.4). The minimum flow pre-dating this report is from the 2006 Hawke's Bay Regional Resource Management Plan.

Stream	**Raupare**	**Awanui**	**Irongate**
Site	Ormond Road	Flume	Clark's weir
Mean flow (L/s)	646	768	379
Median flow (L/s)	631	395	341
MALF (L/s)	412	84	99
Catchment area (km^2)	18	302	37
Mean/Median flow	102%	194%	111%
MALF/area ($L/s/km^2$)	23.3	0.3	2.7
Width (m)	4.8	5.2	3.8
Depth (m)	0.55	0.64	0.22
Gradient (m/km)	0.8	0.4	1.4
2006 minimum flow (L/s)	300	120	100

Table 3-2: Species observed during site visits to the Raupare and Awanui Streams. Records were kept of the species observed during plant surveys and dissolved oxygen checks. Counts were converted to a relative abundance (% of total number of fish counted at each site). A total of 164 visits were made to these sites between November 2012 and June 2014. Species identifications are less certain from visual observations. Most were corroborated by catch data, with the exception of a rainbow trout in the Awanui. Benthic and nocturnal species, such as koura, eel and bully are probably underestimated by this method.

Species	**Raupare**	**Awanui**
yelloweye mullet	66%	
inanga	27%	96%
black flounder	1%	
rainbow trout	3%	0.4%
koura	1%	
eel	1%	2%
common bully	0.4%	
Gambusia		1%

Figure 3-2: Raupare Stream at Ormond Road. View downstream of the dissolved oxygen and flow monitoring site, with emergent water celery visible growing over the stream and submerged plants in the stream. Image from Google Street View, January 2013 (© 2014 Google). Location E1929880 N5609666 metres NZTM NZGD2000.

Awanui Stream

The Awanui site was chosen to represent streams fed from limestone hill-country and peat wetlands, to contrast with the spring-fed Raupare. The Awanui and Raupare study reaches are otherwise similar in channel width, gradient (Table 3-1), and realignment. The surface catchment is seventeen times larger than the Raupare, producing larger flood flows. But the MALF is smaller than the Raupare, reflecting less groundwater input from the Heretaunga Aquifer. The Awanui drains grazed hill country via three sub-catchments – the Poukawa, Karewarewa and upper-Awanui (Figure 3-1). More intensive cropping takes place on flatter alluvial soils. The Poukawa has two large peat wetlands (Lake Poukawa and Pekapeka Swamp) that are presumably the source of tannin coloured water in winter. These wetlands increase the residence time for runoff, which probably buffers the flood peaks (Clode, 2007). Other wetlands in the catchment were drained, including the Turamoe Wetland.

Baseflow in the Poukawa catchment is probably sustained by small springs originating from limestone aquifers (Cameron *et al.*, 2011). The Paritua (a Karewarewa tributary) appears to receive spring inflows from limestone, but there have been occasions when this inflow was lost to the Heretaunga Aquifer before reaching the Awanui (Waldron *et al.*, 2007). The Karewarerewa gains flow from the Heretaunga Aquifer further downstream where it intersects the water table (Waldron *et al.*, 2007).

The stream bed composition at the monitoring site is mostly clay, with some silt, sand and pumice-gravel. Concentrations of calcium bicarbonate in the Awanui are about 4 times the concentration in the Raupare, reflecting the Awanui's limestone geology. Conductivity is about 600 µS/cm, compared to 180 µS/cm in the Raupare. The influence of peat from Poukawa and Pekapeka wetlands increases the organic carbon concentrations, to a median of 13 g/m^3 for Awanui, compared to 0.7 g/m^3 for Raupare, from seven pairs of same-day measurements.

Fish inhabiting the Awanui include inanga, common bully, *Gambusia*, goldfish, longfin and shortfin eels, as observed from fyke netting, daytime observations, and earlier records (HBRC, 2014). Inanga were the most abundant fish at the study site, from daytime observations when eels were probably undercover (Table 3-2). Inanga were observed in the Awanui between late-November and mid-March, though only two inanga were observed after mid-January 2013.

Aquatic plant communities in the Awanui are more seasonal than the Raupare, with *Ceratophyllum demersum* proliferating during summer. Other species present are *Elodea canadensis*, *Stuckenia pectinata* and *Potamogeton crispus* (Wells & Champion, 2003), and are scoured to low abundance by high flows in winter. Emergent sweet grass (*Glyceria maxima*) extends out from the margins year round.

The Awanui Stream was surveyed at the flow monitoring site adjacent to Te Aute Road (Figure 3-3). The reach represented by the monitoring site extends 400 m upstream to the Poukawa confluence, and 3300 m downstream to a tree shaded reach, over which there are minimal inflows from surface water or groundwater. The channel meanders between grassed stop-banks and has a northerly aspect (channel flowing generally west to east).

Figure 3-3: Awanui Stream at the flume (Te Aute Road). View upstream of the dissolved oxygen and flow monitoring site (8 January 2014), showing prolific aquatic plant growth reaching the surface and emergent sweet grass along the banks. Location E1925675 N5599637 metres NZTM NZGD2000.

Irongate Stream

The Irongate Stream is spring-fed from the Heretaunga Aquifer, as is the Raupare, but the Irongate has a lower flow (Table 3-1). Riparian conditions are more variable for the Irongate, than the Raupare, with more shading at the study site (Figure 3-4). The Irongate Stream flows through an old bed of the Ngaruroro River, after a major flood moved the Ngaruroro to its current path in 1867 (NIWA events catalogue; HBRC, 2004). Cobble substrates are more widespread here than in the Raupare, but silt tends to smother the cobble and gravel during summer/autumn low-flows, when aquatic plants spread. Urban runoff from Flaxmere is piped directly to the Irongate Stream, and hence peak flows here are more than in the Raupare.

Only introduced goldfish were recorded in the Irongate Stream (HBRC, 2014), though eels and koura were observed at the study site during this investigation. *Elodea canadensis* was the dominant aquatic plant at the monitoring site, with Wells and Champion (2003) observing *Stuckenia pectinata* and *Potamogeton crispus* in the Irongate.

The Irongate Stream was surveyed at the flow monitoring weir ("Clark's weir") that is located upstream of Maraekakaho Road (Figure 3-3). The Irongate Stream is more variable than the Raupare and Awanui. Shading from riparian trees extends 150 m upstream of the dissolved oxygen probe, and shaded sections are scattered along the stream, representing about 15% of the total stream length (from aerial photographs). The monitoring site was about 1500 m downstream of the stream's starting point during the 2013 drought. Most of the flow from the Irongate Stream originates upstream of the monitoring site, presumably as diffuse springs, and about 30% more flow is gained downstream of the site. Gaugings after the oxygen study (2 December 2014) indicated groundwater inflows continue through the monitoring site. The channel was enlarged and straightened in the late 1960s, including the sections studied (page 62 in HBRC, 2004). The valley retains the meandering form from earlier river beds, so solar aspect varies (see Figure 3-1).

Figure 3-4: Irongate Stream at Clark's weir. View upstream of the dissolved oxygen and flow monitoring site (9 Jul 2013) near Maraekakaho Road. Location E1926740 N5605071 metres NZTM NZGD2000.

4 Methods

4.1 Dissolved Oxygen Monitoring

Long-term deployments (Awanui and Raupare)

Continuous dissolved oxygen data were measured using a Zebratech D-Opto probe, which uses a fluorescent sensor. This type of sensor can hold calibration longer than conventional membrane type sensors (Almeida *et al.*, 2014). The optic sensors measure fluorescent quenching by oxygen, and the probe incorporates algorithms to correct for increased quenching at higher temperatures (Stokes & Somero, 1999; Tengberg *et al.*, 2006; YSI, 2009). Conversion from fluorescent quenching to percent saturation of oxygen is performed by the D-Opto, as is the conversion from saturation to concentration (using measured temperature). The post-processing correction for atmospheric pressure is described later in this section (subsection: Oxygen data processing). Oxygen concentrations are expressed as mg/L throughout this report, which are equivalent to g/m^3. The D-Opto probes recorded oxygen in ppm (parts per million), which are exactly equivalent to mg/L at 4 °C in freshwater, and within 0.2% at 20 °C.

Oxygen monitoring started at the Awanui site on 27 November 2012 and at the Raupare site on 15 November 2012. Monitoring is ongoing as at winter 2014. The monitoring period captured extreme low-flows and extended periods without floods. In particular March 2013 saw the lowest flows in the Ngaruroro River since 1983, which was ideal for investigations into the consequences of reduced flows for dissolved oxygen. The D-Opto probes sampled dissolved oxygen and temperature every 15 minutes in the Awanui and every 30 minutes in the Raupare. The interval at the Raupare was reduced to 15 minutes from 27 November 2013, with all measurements recorded in New Zealand Standard Time (i.e. not daylight savings time).

Plots of telemetered data were checked visually most weekdays. In addition, on-site maintenance was typically performed weekly, including calibration checks, clearing weed from the housing and cleaning of sensors (see the field procedures, and the inspection form). This maintenance was reduced in frequency to fortnightly during the cooler months (May to November 2013), when dissolved oxygen suppression was less pronounced. Calibration checks included a spot measurement of stream oxygen concentrations, using a portable oxygen meter (Hach HQ40d with optic LDO probe) that was calibrated weekly in the laboratory, together with a check on site in a solution of 100% dissolved oxygen. The double check against both the portable probe and the 100% solution provided important redundancy, given the potential for either check to be incorrect. The first task on-site was placing the Hach probe in the stream to ensure the sensor had cooled to stream temperature. Laboratory trials demonstrated that 10 minutes was adequate for stabilisation (see appendix in field procedures).

After taking a spot reading, the D-Opto was removed from the stream, cleaned and placed in a 100% saturated calibration solution. Saturation was achieved using 20 tips of stream water from bucket to bucket, as recommended by Wilcock *et al.* (2011). The D-Opto was re-calibrated if it deviated from 100% by more than 3%. A third check was made after returning the D-Opto to the stream, using the portable Hach. A two-point calibration was performed typically every month, using Na_2SO_3 to create a solution with 0% dissolved oxygen, followed by a calibration check in 100% solution. The aim was to keep both probes at stream temperature throughout the process, with the exception of the 0% solution, which necessitated a longer stabilisation period because adding Na_2SO_3 increased the water temperature.

The National Environmental Monitoring Standard (NEMS) for dissolved oxygen monitoring (Wilcock *et al.*, 2013) were still being developed at the start of the Karamu study, with the final NEMS report not finalised until June 2013. Our monitoring protocols were developed with the aim of achieving the draft National

Environmental Monitoring Standard. To this end, some improvements to monitoring protocols were made over the study period. Initially, the D-Opto was transferred to the 100% solution and left for five minutes to stabilise, together with an air bubbler that was intended to keep the solution at 100%. The stabilisation period was later reduced to less than two minutes and the bubbler was omitted from calibrations after 20 July 2013, because laboratory trials demonstrated the calibration solution was closest to 100% immediately after saturation. Warming of the solution on a hot day can cause minor super-saturation. The bubbler exacerbated warming more than it stabilised gas saturation. Note, the magnitude of super-saturation was still within the National Environmental Monitoring Standard. More than 6% super-saturation could not be achieved, even going directly from a fridge to room temperature. A long stabilisation period was not necessary for the 100% solution because the D-Opto sensor was already stabilised at the solution temperature. Stream water was used for the calibration solution, which typically warmed only 0.2 °C after 20 tips.

Short-term deployment

Only the Awanui and Raupare streams were targeted for long-term monitoring. For the Irongate Stream, a battery powered D-Opto probe was deployed for a week and data were logged to onboard memory. The battery logger was calibrated in the field prior to deployment using 100% solution, as described for long-term deployments. The D-Opto logger was installed in flowing water and anchored to an existing structure. A validation measurement was taken on installation using a hand-held oxygen probe, and also prior to removal from the stream. After removal, the probe calibration was checked in 100% solution.

Oxygen data processing

Processing raw data included removing erroneous data spikes, including when the probe was out of the stream for cleaning and calibration. Data was also omitted for periods when the sensor was smothered. In-stream validation measurements from a laboratory-calibrated portable probe were used to assess compliance with the National Environmental Monitoring Standard, together with checks in the 100% solution. For the Raupare, there were 30 calibration checks, of which three exceeded the National Environmental Monitoring Standard, including:

- Deviation on 12 December 2012 was attributed to rapid changes in ambient dissolved oxygen concentrations at the time of the spot measurement. Readings in the 100% calibration solution were satisfactory. No data were omitted.
- Deviation on 22 March 2013 was attributed to calibration error. Data were omitted from SEFA calibration back to 14 March 2013, which was the last good validation.
- Deviation on 26 June 2013 was attributed to weed fouling, given the D-Opto read correctly in the calibration solution. Oxygen data were deleted back to 24 June 2013, when indications of weed fouling first appeared.

For the Awanui, there were thirty-one calibration checks made (see processing file). Four of these checks exceeded the National Environmental Monitoring Standard, including:

- A deviation on 12 December 2012 was attributed to sensor calibration drift, with both the spot measurement and check in 100% solution outside tolerance. A ramp correction was applied ranging from 0% change on 27 November 12 to -13% change by 12 December 12. The two point check both in-stream and with the 100% solution supported a linear correction.
- A deviation on 17 January 2013 was attributed to calibration error of the portable probe, given the D-Opto measured satisfactorily in the 100% solution both on this occasion and at the next check.

- A deviation on 22 March 2013 was attributed to sensor fouling, as readings were within calibration after cleaning. Data were omitted from SEFA calibration back to 14 March 2013, which was the last good validation.
- A deviation on 23 August 2013 was attributed to smothering of the sensor. Data were deleted back to 11 August 2013 at the first indication of noisy readings.

The D-Opto deployed in the Irongate Stream held calibration within the National Environmental Monitoring Standard.

The raw data for percent oxygen saturation from the D-Opto required correction for changes in atmospheric pressure because the D-Opto assumes constant sea level air pressure. The correction for atmospheric pressure (hPa) used Equation 3 (following Table 7 from Wilcock *et al.*, 2013). The resulting correction was small, with a typical absolute correction of 0.5% oxygen for the Raupare record, and the95th percentile correction was 1.6% oxygen. Correcting for the displacement of oxygen by dissolved salts was not necessary because the monitoring sites had negligible salinity. A typical conductivity of less than 200 µS/cm for Raupare would reduce oxygen by less than 0.01 %.

$$correctedDO\% = DO\% \times {}^{1013.25}\!/_{airpressure} \qquad 3)$$

Air pressure data were sourced from Hobo loggers on site. Gaps in the air pressure data record were filled using monitoring results from Ahuriri Estuary, and Napier Airport. These two sites are at slightly lower elevations than the Raupare site, so were corrected to Ormond Road pressure using the overlapping record from the two sites, resulting in a very minor correction of 1 hPa, on average.

All processed data were archived, including validation data, which was entered as check data, and NEMS quality coding. The National Environmental Monitoring Standard QC600 for dissolved oxygen was pursued using best practices, but it is impossible to achieve this once concentrations exceed 100%. All values more than 100% are categorised at the lower QC500 by NEMS because no super-saturated calibration solution is available to test the accuracy claims of instrument manufacturers. This requirement does not impact on the quality of daily minimum oxygen concentrations, which are the focus of this report, because these minima were always less than 100%.

4.2 Aquatic Plant Monitoring

Aquatic plants were surveyed using monitoring protocols adapted from Waikato Regional Council (Collier *et al.*, 2009). Aquatic plant cover was estimated by visual survey, with plant cover categorised into:

- **submerged plants** that do not reach the surface (e.g. *Elodea canadensis*, *Potamogeton crispus*)
- **surface-reaching plants** that do not break the water surface
- **emergent plants** that emerge from the water surface (e.g. sweet grass, water celery)
- **no plants**

At each cross-section, plant abundance was estimated as a width of channel covered by each plant category (e.g. 2 metres of submerged plants, 1 metre of no plants). The aim was to obtain proportional cover data, with the conversion from metres to proportional cover completed during post-processing. Ten cross-sections were sampled, with each cross-section describing a 1 m wide transect across the stream. The cross-sections were randomly spaced along the 100 m section of stream, with a new set of random locations obtained for each survey using the Microsoft Excel 2007 function randbetween(0,100).

The change in aquatic plant abundance over time was investigated for the Raupare and Awanui Streams, with weekly surveys through summer-autumn, reducing in frequency to fortnightly during the cooler months of May to November 2013. A daily time-series of plant abundance was interpolated using a LOESS curve (local regression). As well as interpolating values, this provides a degree of smoothing. The LOESS was performed using R (Version 3.0.2 2013-09-25; package: 'stats'; function "loess" and "scatter.smooth"; smoothing span = 0.18 for Raupare and 0.3 Awanui; degree = 2nd order polynomial). Plant surveys that were affected by poor water clarity (i.e. less than 70% of the bed was visible) were omitted from the smoothing analysis. Poor clarity affected four surveys for Raupare and three surveys for Awanui between June and September 2013.

4.3 Flow Monitoring

Raupare Stream

Flow data for the Raupare Stream was obtained from three sources. The first, and most accurate, source was manual flow measurements, which were completed twice weekly over the period 1 January to 30 April 2013, and once a week, on average, for the rest of the year, with the largest gap of 24 days from 19 July. Manual flow measurements used a Sontek Flowtracker and wading rod, with at least twenty offsets using velocity measured at 60% of depth for 40 second intervals. High precision gaugings were achieved owing to the straight channel, which is 18 m long through an arch culvert immediately upstream, and uniform depths created by a concrete gauging platform. Back to back measurements produced flow estimates within 1.1%, from five paired gaugings during the monitoring period, compared to the National Environmental Monitoring Standard of 8% error (Willsman *et al.*, 2013).

Flow data was also obtained using a bed-mounted velocity meter (up looking acoustic Doppler Sontek IQ Standard) to provide continuous data at 15 minute intervals. This was installed mid-way through the oxygen monitoring period on 23 May 2013. The velocity meter derives channel area using depth measured from a vertical sensor calibrated to stage, together with a surveyed cross-section profile that remained stable over the monitoring period because it is a concrete platform with arch culvert banks. An index-velocity was calculated by averaging velocities across the four sensors. Each sensor measures velocity throughout the depth profile, and the sensors are tilted at 60 degrees, covering a stream width of about 1.5 m mid-channel, when 0.5 m deep. The index velocity was then calibrated (or rated) to cross-section average velocity, as measured by manual gauging, using Equation 4:

$$MeanVelocity = 0.89 \times IndexVelocity + 0.36 \quad \text{(units m/s)} \qquad 4)$$

(50% quantile regression performed using R: quantreg package; n=18; 23 May to 25 September 2013; 94% of data within 8% of measured values).

Note that secondary predictors, such as stage (Levesque & Oberg, 2012), did not improve the index velocity rating. Flow was then derived from estimated mean velocity and channel area using Equation 5:

$$Flow = MeanVelocity \times ChannelArea \qquad 5)$$

Flow information was also obtained from rated stage-to-flow continuous data. Flow data derived from stage-to-flow rating curves were less reliable during times of heavy plant growth and die-back, because water level changes were affected by the volume of obstructing vegetation. For these reasons, manual flow measurements were important to quantify flow dynamics, prior to installing the velocity meter.

Awanui Stream

Flow in the Awanui Stream was monitored using manual flow measurements and stage-flow ratings. Manual flow measurements were completed fortnightly from 1 December 2012 to 30 June 2013, at a maximum interval of fifteen days). Flow was measured monthly on average for the rest of the calendar year, with the largest gap being the fifty-five days from 20 June 2013.

Manual flow measurements used a Sontek Flowtracker and wading rod, with more than twenty offsets where velocity was measured at 60% of total depth for 40 s intervals. Gauging methods were selected with the aim of achieving the National Environmental Monitoring Standard of 8% error (Willsman *et al.*, 2013), though this was difficult at the lowest flows when flow over the concrete flume was less than 8 cm deep (from January to April). Three manual flow measurements were omitted from rating calculations due to low-flow conditions on (13 December 2012, 1 February 2013, and 27February 2013).

This site has a concrete flume constructed for low-flow monitoring, enabling precise flow data to be derived from water level using a rating curve. The flume is less susceptible to backwater effects from weed growth, compared to the Raupare, and hence the stage-to-flow rating remained stable over the monitoring period.

A raised weir board (500 mm high) was removed from the flume to restore fish passage on 16 August 2012, prior to the oxygen monitoring period. This also restored stream-depths for the section upstream of the flume to conditions more typical of the Awanui Stream. The flume did not suffer backwater effects from vegetation during the monitoring period, so the stage to flow rating was unaffected.

Irongate Stream

Rated flows are generally good at this site, despite the growth of aquatic plants, because a weir with a free-falling outlet controls the stage to flow rating. Gaugings were performed during the week before and the week after oxygen logger deployment to confirm the rating for this period.

4.4 Channel Cross-Section Survey

Cross-section surveys were completed in autumn after aquatic plant abundance had stabilised sufficiently for flow to be the primary driver of water level. Reaches were chosen to ensure the control points (stage to flow rating) for the oxygen monitoring site were equivalent to the surveyed cross-sections. The Raupare survey-section was 100 m long and was located immediately downstream of the oxygen and flow monitoring site. Survey sections for the Awanui and Irongate were located upstream of the oxygen probe and flow monitoring site. Ten cross-sections were surveyed at randomly selected locations. Random sites were used instead of stratified habitat-mapping because mesohabitats were not visually distinct. Cross-sections all received the same weighting of 10% each. A wooden peg was installed as a temporary water level reference for each cross-section. Offset, depth and velocity were measured at sufficient cross-section offsets to describe the shape of stream bed and the banks up to 0.5 m above water level.

Calibration measurements of flow and water level were completed on several occasions (Table 4-1). These measurements were used to calibrate rating curves, which predict the change in water level with flow. The rating curves and input data are presented in Appendix A. Pegs installed in the Raupare Stream were damaged prior to the last gauging, which was therefore omitted from rating calibration.

Table 4-1: Cross-section survey information. Details of cross-section surveys completed for the three sites as input to the oxygen models. The flow range used to calibrate the ratings (maximum and minimum) is specified. The rating error is the average percentage error in predicted and measured calibration gaugings as a % of the survey discharge (from Appendix A).

	Raupare	Awanui	Irongate
Survey Date	11 April 2013	26 April 2013	1 May 2013
Location (NZTM)	E1929901, N5609656	E1925643, N5599624	E1926747, N5605028
Number of cross-sections	10 (random placement over 100 m)	10 (random placement over 100 m)	10 (random placement over 100 m)
Cross-section weighting	10% each	10% each	10% each
Calibration gaugings	5 (+1 omitted)	4	3
Flow min L/s	465	56	58
Flow max L/s	586	286	584
Survey flow L/s	473	57	58
Rating error	1.3% to 2.1%	3.4% to 8.5%	0.9% to 5.8%
Comments	Pegs damaged before last gauging, so omitted.		

4.5 SEFA Oxygen-Flow Modelling

The System for Environmental Flow Assessment software (SEFA Version 1.2, Jowett *et al.*, 2014) was used to predict how oxygen concentration changes with flow. This section describes methods used for calibrating the SEFA oxygen models for each site and scenario, plus the settings used for predicting daily minimum oxygen concentrations. For an explanation of how the model works, see Section 2. The SEFA model uses the Delta Method to fit starting values of reaeration, respiration and photosynthesis parameters separately to each day of measured oxygen and temperature data.

The model defaults to a constant value of 2 for the ratio of respiration rates 10 °C apart. With these starting values, manual fine-tuning of the respiration rate, the photosynthesis/respiration ratio and the ratio of respiration rates was made for each day, to produce a better visual fit to observed diurnal oxygen plots. Modified parameters were retained if this produced a lower root mean square error than the starting values. A single set of parameters was then selected to represent each site from this sample of model parameters. The median parameter values typically provided as good or better fit to the calibration data than the best daily values, with exceptions noted in the following text. The median values were also more stable, with manual fine tuning for each day producing relatively small improvements in fit of the median parameters. A reference flow was selected to represent the average depth and velocity associated with these median parameter values. The median flow for the calibration provided a flow estimate that was adequate in most cases, with exceptions noted in the following text.

Model predictions were made for 31 January, to standardise day length across sites and scenarios. The 31st of January was chosen represent a period of high irrigation demand that coincided with low stream flows. Model predictions were made for water temperatures calculated from observed night-time data that represented average temperatures about 31 January. Night temperatures (mean temperature between sunset and sunrise) were used instead of day temperatures because overnight respiration produces oxygen minima. Depths and velocities for the modelled flows were predicted using the SEFA hydraulic model (see Section 4.4 for survey and calibration methods).

Raupare

The change in plant abundance and climate between seasons cannot be represented using a single set of parameters. To address the changes in plant abundance over time, two scenarios were modelled for Raupare Stream.

The **Autumn Scenario** represents moderate plant abundance and low stream flows. The oxygen model was calibrated using oxygen and temperature data for the period 15 March to 15 May (Table 4-2). Stage to flow ratings were derived from flow and stage measurements completed for the SEFA hydraulic model (see Section 4.4). Model predictions were made for the same date (31 January) and temperature (16.2 °C) as the Summer Scenario to enable direct comparison. The overnight temperature of 16.2 °C was calculated as the median of observed overnight means (sunset to sunrise) for 26-Jan to 6-Feb-2013.

The **Summer Scenario** represents maximum plant abundance and low stream flows. The oxygen model was calibrated using oxygen and temperature data for the period 1 January to 25 January 2013, because this was the period of deepest water for a given flow, as observed from gauging data. Depth predictions were then made using a modified version of the autumn hydraulic model, which predicts deeper water for a given flow. A steeper stage-to-flow rating was calculated from continuous velocity-meter data for the period when the stage was highest for a given flow (23 December 2013 to 26 January 2014). The velocity meter data provided a wider flow range compared to spot gaugings.

This summer rating was reproduced in SEFA by changing the flow values for each calibration stage to fit the summer rating. Autumn velocity data were deleted, triggering the SEFA hydraulic model to synthesize cross-section velocity data that achieved continuity of flow and velocity distribution factors. The SEFA model is not sensitive to the precision of point velocities and depths because reach averages are used for both. Model predictions were for 31 January and an overnight temperature of 16.2 °C, which is the median of overnight means for the period 26 January to 6 February-2013.

The reaeration coefficient was fixed as a constant value for the summer and autumn Raupare models, because oxygen predictions a constant value produced a better fit to observed oxygen minima than allowing the reaeration coefficient to vary with flow. In addition, there was no correlation between flow and the daily-series reaeration coefficients estimated for Raupare Stream.

The SEFA oxygen model was used to produce parameter values for each day of measured oxygen data using the Delta Method, as described in Section 2. Manual fine-tuning of parameters had the most pronounced effect on outlier values that were much higher than the median. There were few outliers with values less than the median, producing a lower bound to the parameter distribution.. Median parameters were calculated from the revised set of daily parameters (Table 4-2). The SEFA model requires depth estimates because respiration rates are scaled by the ratio of the depth at reference flow to each predicted flow. The median flow provided a reference flow for the Summer Scenario, which adequately represented flows during the calibration period. But the median autumn flow (467 L/s) could not be used for the Autumn Scenario because it was not typical of flows during the calibration period. Autumn flows exhibited a bimodal distribution, with modes at 400 L/s and 600 L/s. Of the two modes, 400 L/s was adopted as the reference flow because it produced oxygen predictions with a better fit to the observed data.

Awanui

Despite the intention to model two scenarios for the Awanui (summer and autumn), only the Summer Scenario was successfully modelled. Autumn conditions were not modelled because observed daily minimum oxygen dropped to 0 mg/L, producing distorted estimates of the respiration coefficient. The Summer Scenario model was calibrated using temperature and oxygen data that preceded anoxic conditions (29 November 2012 to 10 January 2013, Table 4-2). Within this period, 16 days were excluded because of rapidly varying flows ([daily maximum – daily minimum flow] more than 30% of 3 day minimum flow). The reaeration coefficient was set to vary with flow because this achieved better agreement with the calibration data than having a constant reaeration coefficient. Model predictions were for 31 January, with a high overnight temperature (20.5 °C median 26-Jan to 6-Feb) reflecting the arrival of the warmest water at midnight from somewhere upstream (see Section 5.1 for explanation).

Irongate

Oxygen data were collected from 14 to 22 February 2013, representing extreme low-flows during summer. Calibration of the SEFA oxygen model did not achieve as good a fit to the diurnal oxygen pattern as the other sites. Oxygen concentrations started increasing later in the day, which may be a consequence of riparian shading that reduces morning sunlight. The SEFA model was calibrated using only the parameters for 18 February 2013, which was overcast, after manual fine tuning (Table 4-2). A better fit to the calibration data was achieved by varying the reaeration coefficient with flow, although using a constant reaeration coefficient produced similar predictions. Model predictions were for 31 January using an overnight temperature of 17.2 °C (Table 4-2). This median temperature was calculated using data from 26 January to 5 February 2001 and the same dates in 2002, in the absence of temperature data for January 2013.

Table 4-2: Model parameters to predict change in oxygen with flow. Summary of model parameters from SEFA, after manual fine-tuning.

	Raupare	Raupare	Awanui	Irongate
Scenario	Summer	Autumn	Summer	Summer
Reaeration coefficient at 20°C (/d)	13.7	14.2	6.32	8.27
Respiration rate at 20°C ($g/m^3/d$)	73.1	65.1	54.0	58.5
Photosynthesis rate at 20°C ($g/m^3/d$)	70.4	35.3	25.0	32.8
P/R ratio	0.962	0.542	0.463	0.561
Ratio respiration 10°C apart	2.00	1.95	1.90	2.00
Reference flow (m^3/s)	0.349	0.400	0.071	0.025
Depth at reference flow (m)	0.66	0.50	0.65	0.185
Median of N days	25	62	27	1
Calibration period	1/1 to 25/1/13	15/3 to 15/5/13	29/11/12 to 10/1/13	18/2/13
Prediction date	31/1/13	31/1/13	31/1/13	31/1/13
Prediction temperature (°C)	16.2	16.2	20.5	17.2
Latitude (for day length)	39° 36’ S	39° 36’ S	39° 41’ S	39° 38’ S
Longitude	176° 50’ E	176° 50’ E	176° 47’ E	176° 48’ E
Vary reaeration coefficient with flow?	no	no	yes	yes

4.6 Oxygen-Flow Quantiles

In addition to predicting the change in oxygen with flow using the deterministic SEFA model, a statistical approach using quantile regression was feasible because of the long period of record for both the Raupare Stream (16 November 2012 to 18 September 2013; n = 61) and the Awanui Stream (28 November 2012 to 30 September 2013; n = 240). Flow is an important driver of oxygen concentrations in streams, but flow is not the sole determinant (see Section 2). Consequently, increasing water takes can reduce oxygen concentrations. But limiting water use does not guarantee oxygen targets will be met because other factors can further constrain oxygen (e.g. pollution discharges, increased plant biomass). SEFA provides a deterministic model to describe the oxygen response to flow, assuming other drivers are somewhat static.

Quantile regression provides a complementary approach to account for other drivers of oxygen concentration. Rather than isolating the effect of flow, quantile regression accounts for unknown drivers and their effect on the probability of exceeding a given oxygen concentration. Using the long oxygen record, the flow associated with oxygen exceeding 4 mg/L for 95% of days was calculated, together with a matrix of other oxygen concentrations and flow percentiles.

There were two steps in choosing a mathematical function to describe the relationship between oxygen and flow. The first step was using a LOESS function to determine the shape of the relationship (using R Version 3.0.2 2013-09-25; package: "stats"; function: "loess" and "scatter.smooth"; 2nd order polynomial). The LOESS function (local regression) fits a sequence of regression lines that each describe a subset of data. A single mathematical function was then sought that could approximate the LOESS line. An exponential function provided an adequate fit (Equation 6).

$$MinDO = upperbound - a.EXP(flow \times b) \qquad 6)$$

Quantile regression was used to generate a set of functions (quantile percentages of 5%, 10%, 25%, 50%, 75%, 90% and 95%), and parameters '*a'* and '*b'* were solved using R software (Version 3.0.2 2013-09-25; package: QuantReg; function: "nlrq"), (Koenker *et al.*, 2013). The '*upperbound*' parameter was selected by trial and error to be a constant of 9 mg/L, because the software was unable to solve the upper bound as well as '*a'* and '*b'* (Equation 6). These equations were then rearranged to calculate the flow required to exceed 4, 5 and 6 mg/L oxygen.

For the Raupare Stream, flow values more than 650 L/s were excluded because the function did not fit well at higher flows. Oxygen concentration observed at higher flows were not considered deleterious (about 7 mg/L), hence subsequent analysis did not include higher flows. Oxygen minima were omitted for days when only rated flow values were available for the Raupare. Awanui flow values less than 30 L/s were excluded, below which minimum oxygen concentrations had dropped to 0 mg/L. Again, the exponential function could not represent a flat line of zero values. The Raupare Stream did not drop to such low flows (minimum observed flow 283 L/s). Logarithmic transformation (base *e*) of flow and oxygen data improved the fit of the exponential model for the Awanui Stream.

5 Results

5.1 Observed Oxygen Dynamics

The selected sites were monitored during the 2013 drought, which provided a useful record of oxygen response to extreme low flows. Low oxygen concentrations were observed overnight in the Raupare Stream (Figure 5-1) and the Awanui Stream (Figure 5-2). The Awanui Stream experienced persistent anoxia, with dissolved oxygen dropping below 0.1 mg/L every morning for 77 days between 8 January and 6 April 2013, coinciding with a period of flows less than 50 L/s (Figure 5-2). Daily maximum temperatures in the Awanui peaked in excess of 25 °C for eight days during late December and early January. The daily minimum temperature averaged 18.3 °C during summer and 13.8 °C in autumn, with five minima exceeding 20 °C between late December and mid-February. When flows were low, temperature in the Awanui reached its maximum around midnight each day. This unusually late maxima was probably caused by stream heating some distance upstream of the study site (e.g. Pekapeka swamp, Paritua gravel section), with the increasing time of travel resulting from lower flows.

The Raupare Stream remained above 4 mg/L for all but five days in 2013, with the lowest oxygen (3.7 mg/L) coinciding with the lowest flow (283 L/s on 3 Feb 2013), (Figure 5-1). Water temperatures did not exceed 25 °C in the Raupare, but there were nine days over 23 °C (Figure 5-1). The daily minimum temperature remained cool, peaking at 16.1 °C and averaging 14.5 °C on summer mornings.

Maximum oxygen exceeded 150% saturation both in the Awanui (21 days >150%, mostly in December) and in the Raupare (61 days >150%, mostly from December to January). The accuracy of measurements that are more than 100% cannot be confirmed because there is not a super-saturated calibration solution (Wilcock *et al.*, 2013). It is still sufficient to conclude that dissolved oxygen concentrations exceeded 100% for extended periods, because 100% is a calibration point (Figure 5-1, Figure 5-2).

Eight days of data were collected for the Irongate Stream during the lowest flows experienced since records began in 1978. Flows continued to recede after the monitoring period. Dissolved oxygen concentrations were low, with a minimum of 2.6 mg/L on 22 February 2013 when flow was 21 L/s. The Irongate did not experience anoxia despite flows being as low as the Awanui. Water temperatures were high during the monitoring period, exceeding 25 °C on four out of eight days. The average maximum temperature was 24.6 °C; with an average minimum of 15.5 °C (14 to 22 February 2013). Continuous monitoring data from 2000-2003 confirms that temperatures have exceeded 25 °C previously, typically for three days each year.

These monitoring results confirm that dissolved oxygen is potentially a critical issue for aquatic ecosystems in these streams. Dissolved oxygen provides both a direct measure of a vital resource, and can also be used to calculate rates of ecosystem metabolism, which is a functional indicator of stream health (Clapcott *et al.*, 2010; Young *et al.*, 2008). The high photosynthesis and respiration rates (Table 4-2) place the Awanui and Raupare in the class of “poor ecosystem health”, and Irongate as “satisfactory” to “poor”, using the Ecosystem Metabolism classes from Young *et al.* (2008). Using the risk classification from Wilcock *et al.* (1998), the three Karamu sites fall in the “moderate risk” class for oxygen deficit.

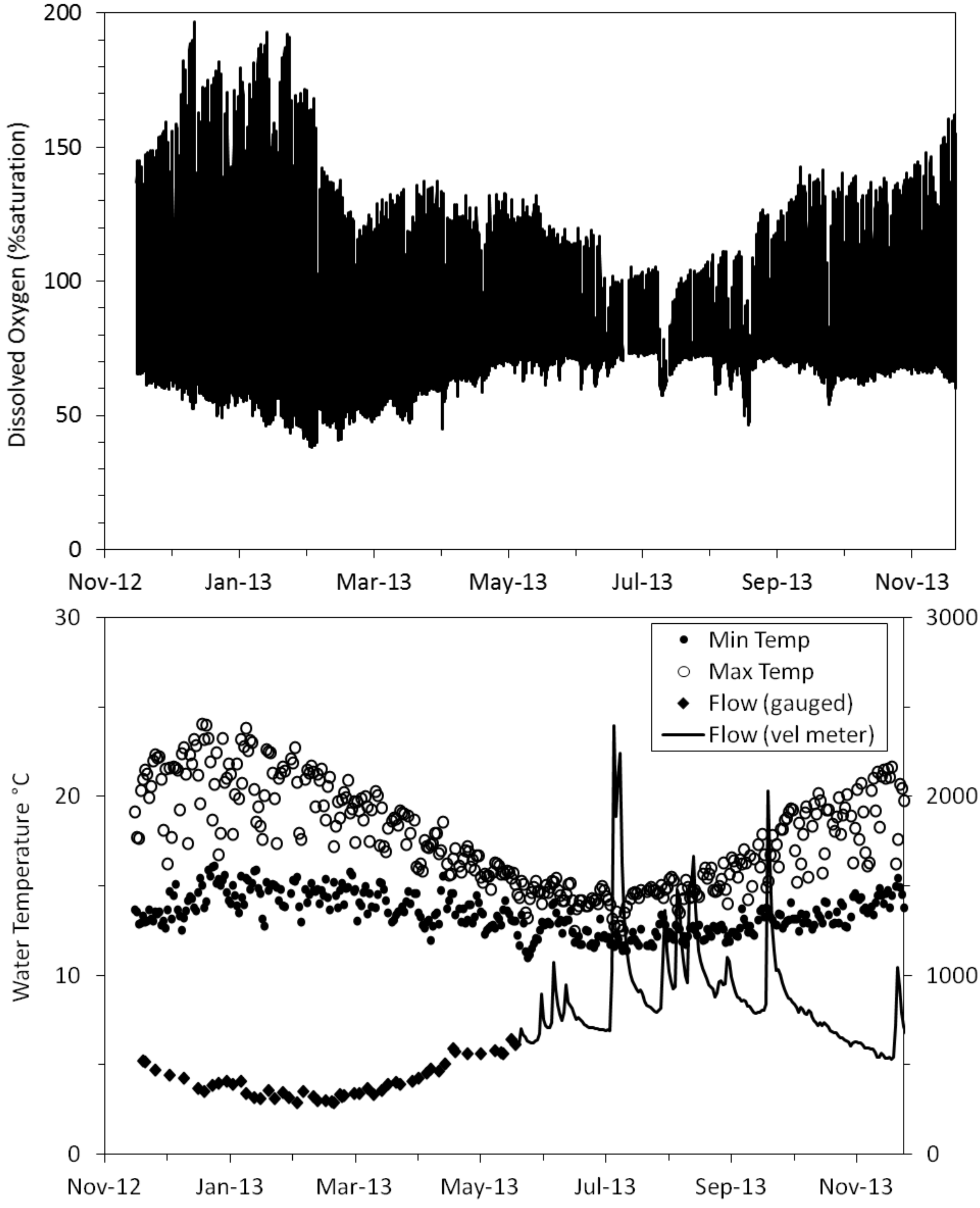

Figure 5-1: Raupare Stream annual time-series of oxygen, temperature and flow. Dissolved oxygen saturation was corrected for atmospheric pressure. Water temperatures are plotted as daily maxima (circles) and daily minima (dots), with flow from gauging data (diamonds) prior to installation of the velocity meter for continuous data (solid line).

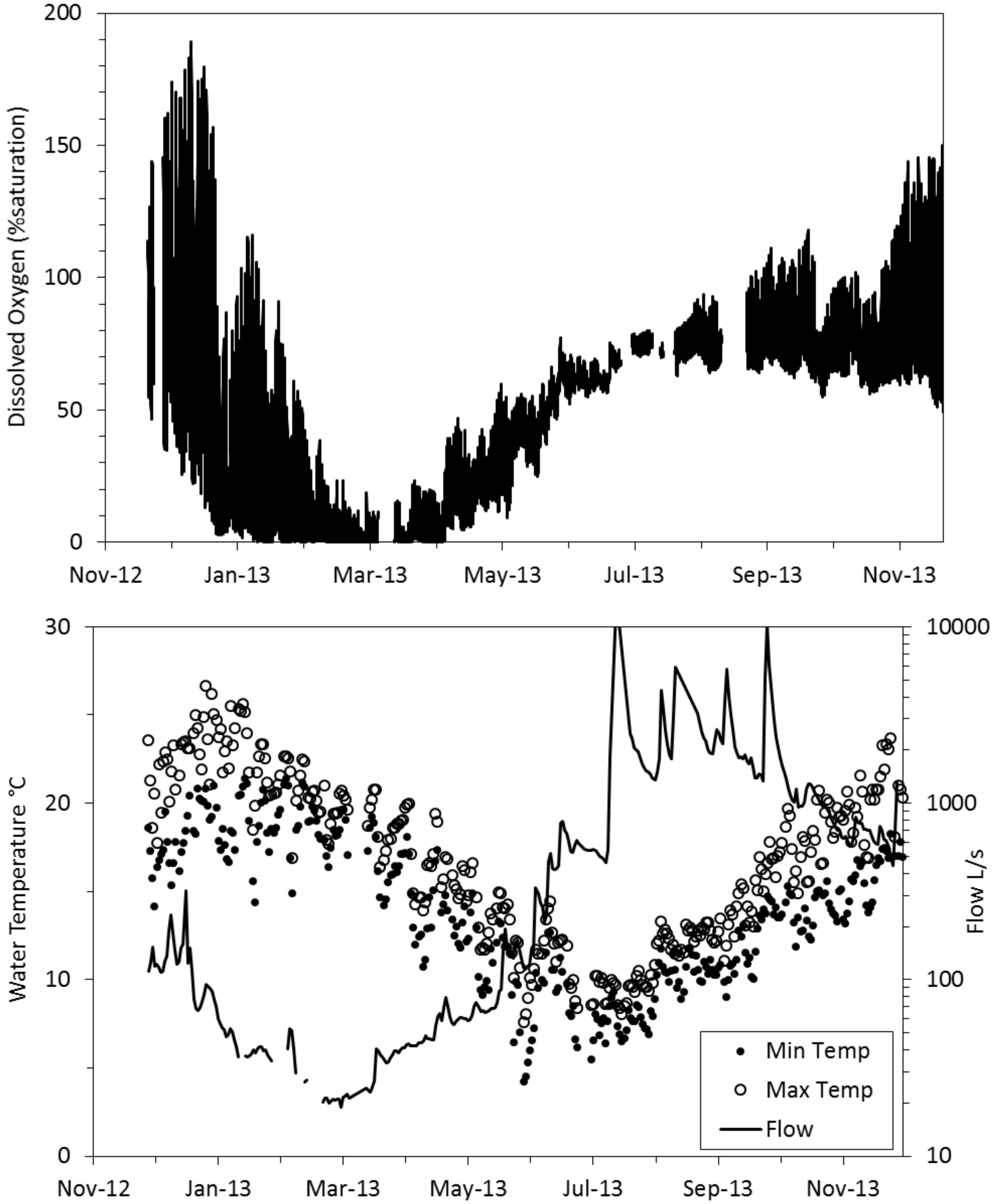

Figure 5-2: Awanui Stream annual time-series of oxygen, temperature and flow. Dissolved oxygen saturation was corrected for atmospheric pressure. Water temperatures are plotted as daily maxima (circles) and daily minima (dots), with flow (solid line) plotted on a log scale. Flow data were rated from stage records.

5.2 Aquatic Plant dynamics

The change in aquatic plant cover over time was assessed for the Raupare and Awanui using the four structural categories of submerged plants, surface-reaching plants, emergent plants and no plants.

Raupare

Of the four categories monitored, emergent plants (green line) produced the most pronounced change over time for Raupare Stream, followed by no-plants (purple line), (Figure 5-3). Submerged aquatic plants retained extensive cover year-round, including *Elodea canadensis* and *Potamogeton crispus*. The interpolation line (LOESS) in Figure 5-4 indicates increasing cover of emergent plants in November and December, followed by a stable period in January, before cover declined in February and March. The change in emergent plant cover over time was similar in form to the change in daily maximum oxygen concentration (Figure 5-4). Plant material emerging above the water's surface may not contribute oxygen to the stream, but it does provide a measurable proxy for photosynthetic activity by submerged plants. The seasonal rise and fall in maximum dissolved oxygen concentrations appears to precede the rise and fall of emergent plants by a week or two. Daily minimum dissolved oxygen concentrations show less similarity to plant dynamics than maximum oxygen.

Awanui

The abundance of aquatic plants was more seasonal in the Awanui Stream, compared to the Raupare, transitioning from submerged plants to surface-reaching plants as plant height and low water-velocities allowed (Figure 5-5). Submerged species included *Ceratophyllum demersum*, *Stuckenia pectinata*, *Elodea canadensis* and *Potamogeton crispus*. In contrast to the Raupare, emergent plants (mostly *Glyceria maxima*) maintained a stable cover year-round. The LOESS interpolation line (Figure 5-6) describes surface-reaching plants increasing for a longer period from November through February, compared to Raupare, with emergent plant growth from November through December. Cover of surface-reaching plants then declined from March through May.

The long period with almost complete plant cover (approaching 0% bare in Figure 5-5) coincided with the period of anoxic daily minima from late December to 6 April (Figure 5-6). The daily maximum oxygen concentrations declined rapidly after 18 December 2012, despite peak day length being experienced during this period. The declining maximum oxygen saturation indicates declining net plant productivity from late December through to the end of March, perhaps because plants were becoming resource-limited (e.g. light, carbon dioxide) as the stream became smothered in surface-reaching and emergent plants (see site photograph, Figure 3-3). If plants were not achieving a net productivity at solar noon (i.e. daily maximum photosynthesis was less than respiration), the transition of aquatic plants from submerged to surface-reaching may reflect declining flow, rather than growth. Water velocity was slow, with reach velocities less than 0.04 m/s (mean 0.017 m/s) predicted by the SEFA hydraulic model during this period (for plant survey dates from 19 December 2012 to 8 April 2013). Further evidence for this velocity control includes the lowest flows (2 March 2013) coinciding with the maximum cover of surface-reaching plants (6 March 2013). When flow increased again, surface-reaching plants decreased in cover and maximum dissolved oxygen concentrations increased.

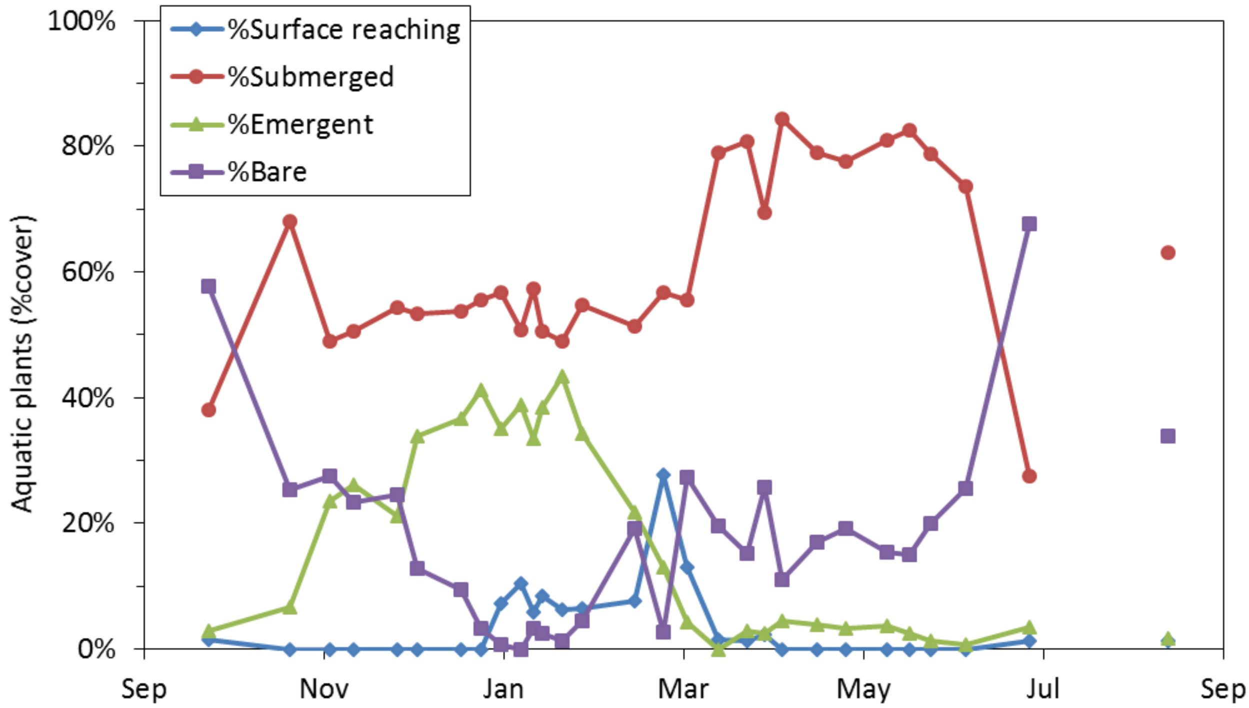

Figure 5-3: Change over time in the cover of aquatic plants for Raupare Stream. The change in proportional cover of four categories of aquatic plants (Sept. 2012 to Sept. 2013).

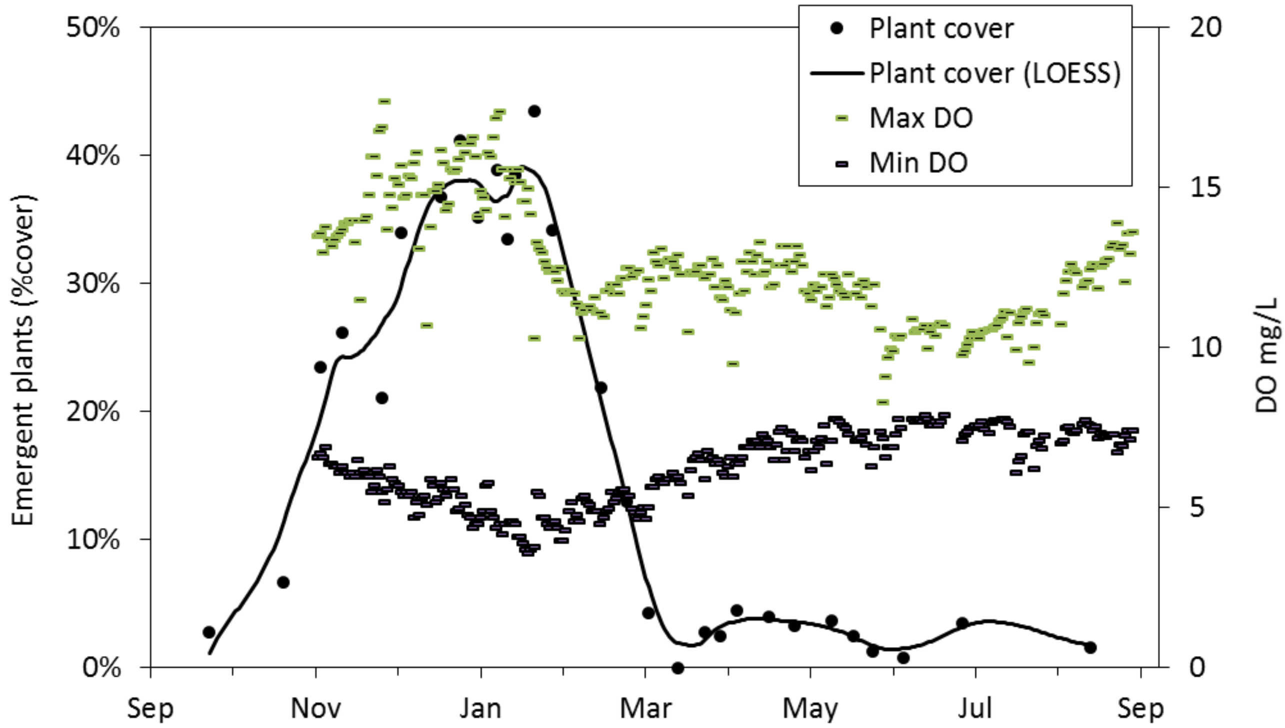

Figure 5-4: Change over time in the cover of emergent plants for Raupare Stream. The proportional cover of emergent aquatic plants (September 2012 to September 2013), with a continuous record (black line) interpolated using local regression (LOESS). Daily minimum and maximum dissolved oxygen (DO) concentrations are also plotted.

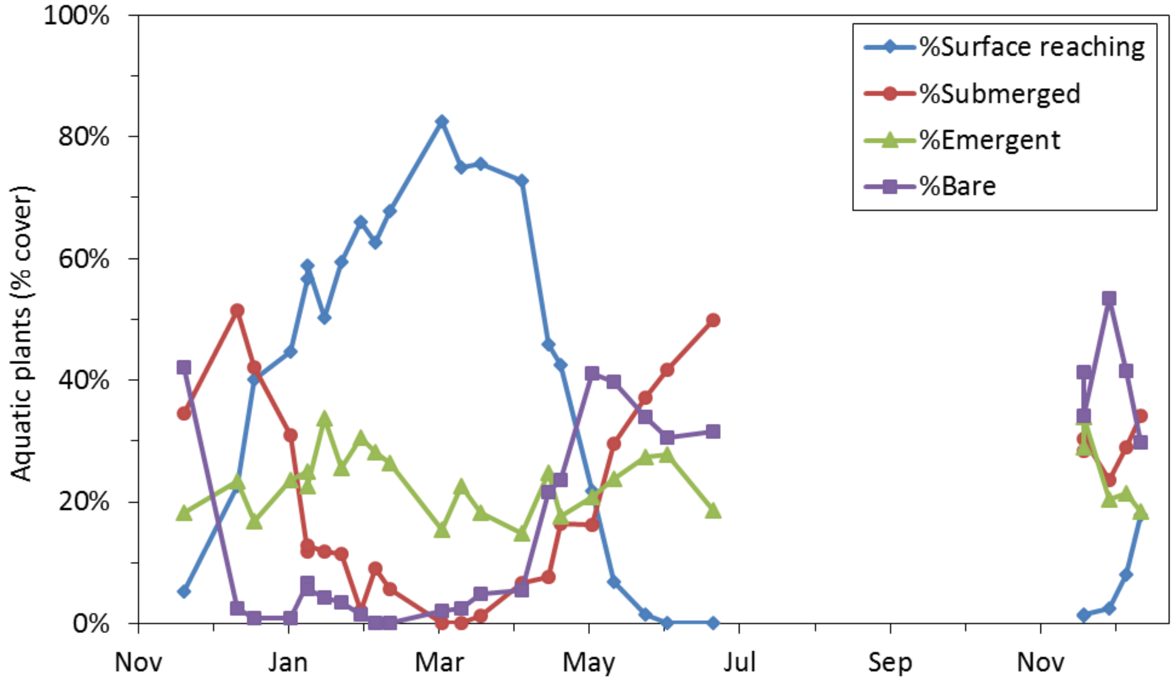

Figure 5-5: Change over time in the cover of aquatic plants for Awanui Stream. The change in proportional cover of four categories of aquatic plants (November 2012 to December 2013), excluding data when visibility was poor (less than 70% of bed visible).

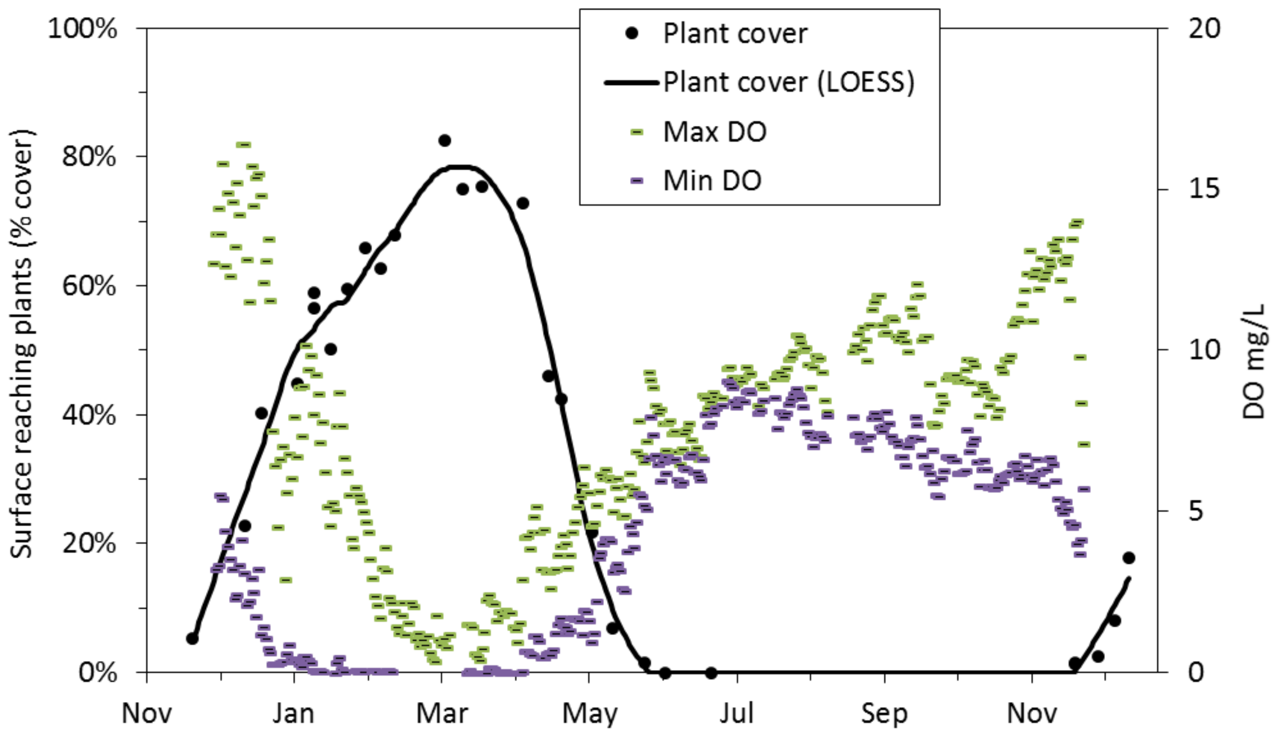

Figure 5-6: Change over time in the cover of surface-reaching plants for Awanui Stream. The proportional cover of surface-reaching aquatic plants (black dots) was interpolated using local regression (LOESS black line). Daily minimum and maximum dissolved oxygen (DO) concentrations are also plotted. Data period is November 2012 to December 2013.

5.3 SEFA Oxygen-Flow Modelling

The SEFA model predicts how dissolved oxygen changes with flow for a given scenario of climate, plant abundance, stream shading and channel hydraulics. Climatic conditions are specified using the location and prediction date (for sunrise/sunset) and prediction temperature. Channel shape is described by the cross-section survey, and the hydraulic model was used to predict changes in depth with flow. For an explanation of how the model works, see Section 2. Calibration of the model to observed dissolved oxygen data reflects existing plant abundance and shading. The calibration of these model parameters and settings used for predictions are described in the methods (Section 4.5). This section examines outputs from the calibrated dissolved oxygen models.

Raupare

The SEFA oxygen model predicted that daily minimum concentrations of dissolved oxygen would decline at flows less than 600 L/s, dropping to 4 mg/L at 240 L/s (Figure 5-7). These predictions were generated using autumn oxygen data and autumn stage-to-flow ratings. This also provides a good fit to the observed oxygen-flow data, which are measured minimum oxygen concentrations on the day of flow gaugings.

The Autumn Scenario model represents moderate plant abundance (dashed line in Figure 5-7) compared to the Summer Scenario, which was developed to represent high plant abundance (solid line in Figure 5-7). The Summer Scenario model was calibrated using summer oxygen data, together with a summer hydraulic model that predicts a steeper increase in depth with flow. This model predicted that oxygen would not increase as steeply with flow, as it does in the Autumn Scenario (Figure 5-7).

Predicted flows to maintain various oxygen concentrations are summarised in Table 5-1. The two modelling scenarios differ in shape, but predict equivalent oxygen concentrations at the existing minimum flow (4.6 mg/L at 300 L/s).

Awanui

The SEFA model predicted a steep decline in dissolved oxygen concentration at flows less than 300 L/s (Figure 5-8), using a Summer Scenario for Awanui Stream. This is in general agreement with the observed dissolved oxygen data (Figure 5-8). Large seasonal changes in temperature exacerbated the deviation between predicted and observed oxygen for flows more than 200 L/s, which arrived during winter. For example, Summer-Scenario predictions were made for 20.5 °C, compared to winter temperatures of around 10 °C (Figure 5-2). Predicted flow requirements for dissolved oxygen in the Awanui (Table 5-2) were similar to those for the Raupare (Table 5-1), despite the Awanui having lower summer flows (see Table 3-1). However, the observed dissolved oxygen concentrations in the Awanui were more variable for a given flow, compared to the Raupare Stream (compare to Figure 5-7). Upstream conditions in the Awanui are less uniform than in the Raupare, with the Awanui site located 400 m downstream of the confluence of three diverse tributaries (Figure 3-1).

Modelling an Autumn Scenario was not possible for the Awanui Stream because extended anoxic periods (i.e. 0 mg/L oxygen) during autumn 2013 concealed the rate of change of oxygen concentrations needed to calibrate the model.

Irongate

For the Irongate Stream, the SEFA oxygen model predicted that dissolved oxygen would decrease more rapidly at flows less than 80 L/s (Figure 5-9), with 33 L/s required for oxygen concentrations to exceed 4 mg/L (Table 5-3).

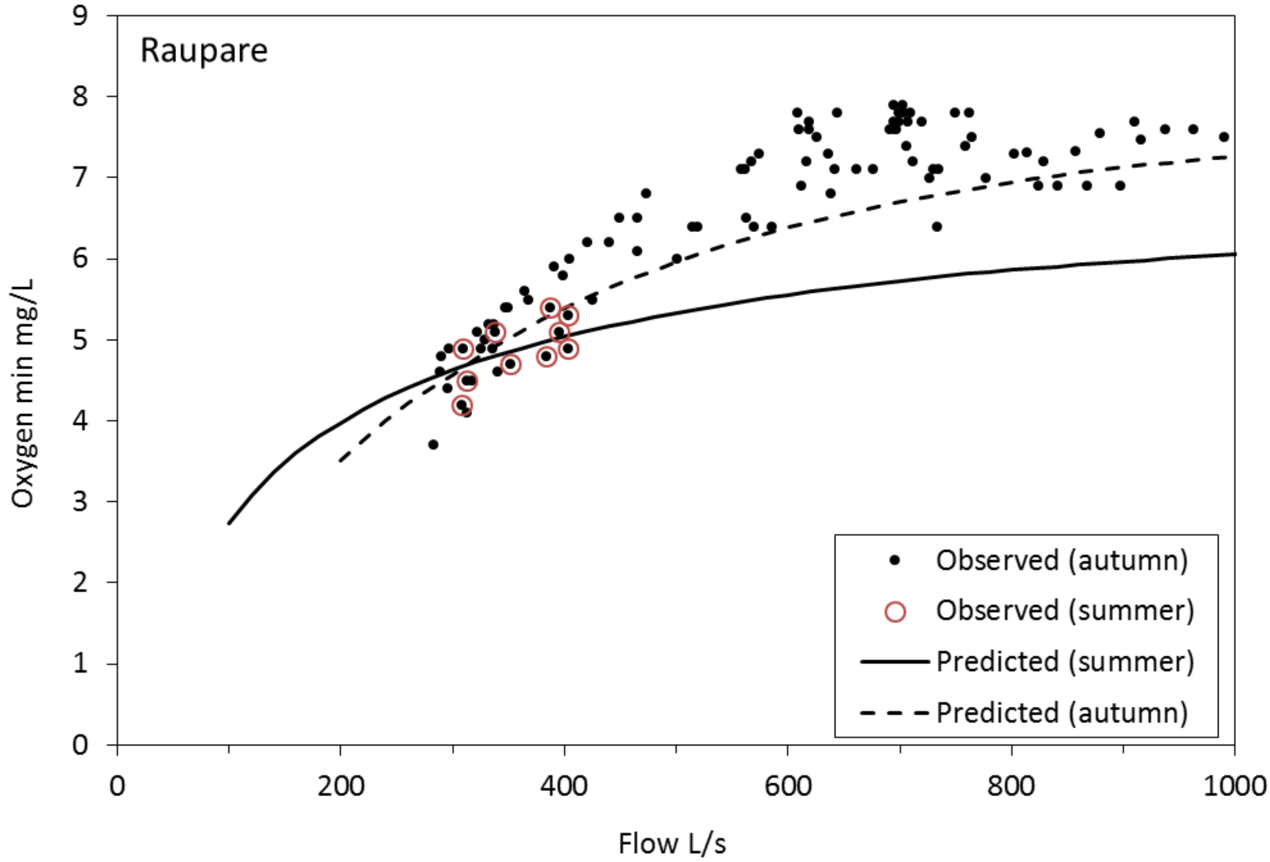

Figure 5-7: SEFA predicted oxygen-flow relationship for the Raupare Stream. Predictions from the SEFA model are plotted from an Autumn Scenario of plant growth (dashed line), plus a Summer Scenario (solid line). The observed daily minimum oxygen concentration and flow data are also plotted as points (from 20 November 2012 to 10 September 2013), with summer observations distinguished by red circles (24 December 2012 to 25 January 2013). High flows are not displayed (13 data points >1000 L/s).

Table 5-1: Flow requirements to achieve oxygen concentrations in the Raupare Stream. Daily minimum dissolved oxygen concentrations are specified in the left column. Flow requirements are presented for two SEFA model scenarios (summer and autumn), which correspond to the two lines plotted in Figure 5-7. Flows were rounded to two significant digits. * denotes predicted flows that are extrapolated well beyond the observed flow range. Predicted dissolved oxygen concentrations at the existing minimum flow (300 L/s) are also presented.

Min oxygen (mg/L)	Flow L/s Summer Scenario	Flow L/s Autumn Scenario
3	*110	*160
4	*200	240
5	390	350
6	-	510
4.6		300
4.6	300	

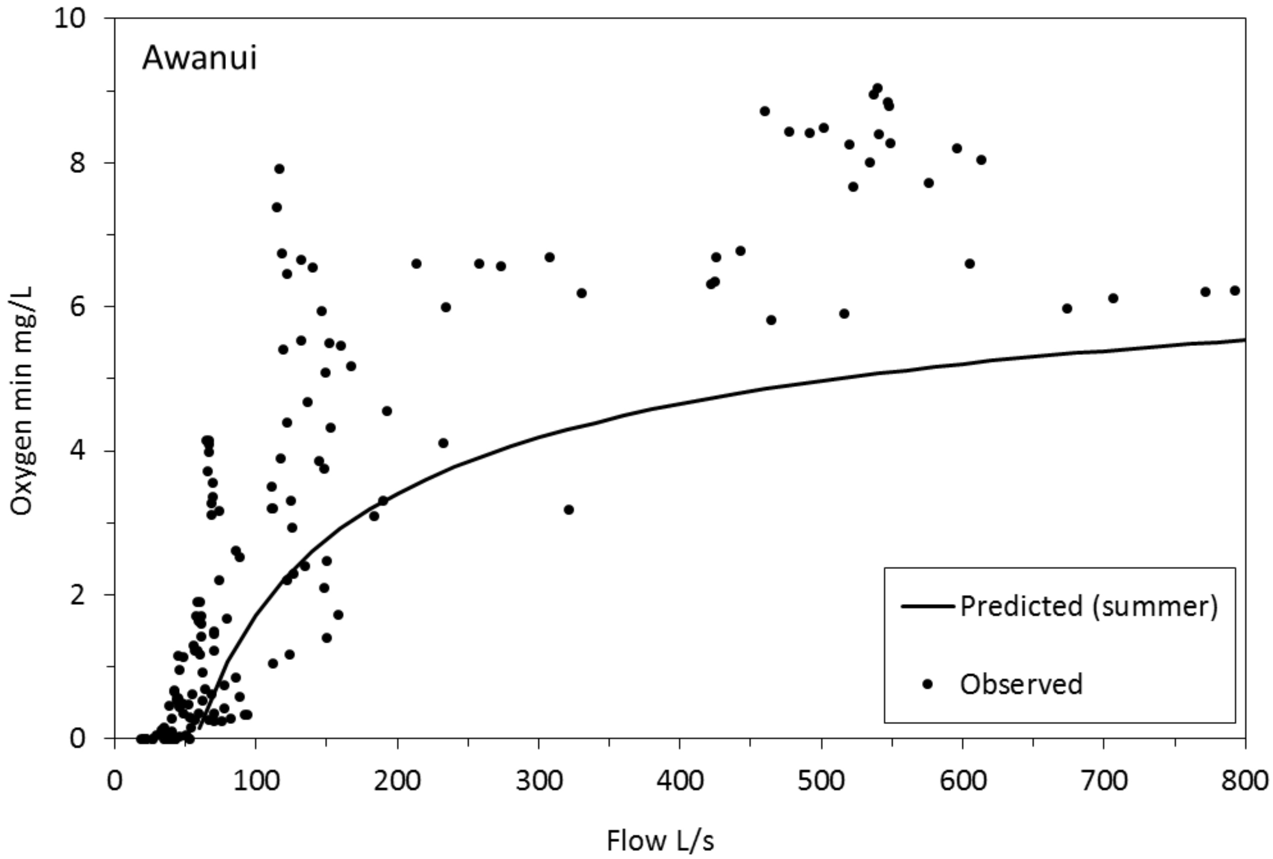

Figure 5-8: SEFA predicted oxygen-flow relationship for the Awanui Stream at Flume. The predicted response of dissolved oxygen to flow is plotted from the SEFA model under a Summer Scenario of plant growth (black line). The measured daily minimum oxygen concentration and flow data are also plotted as points (from 28 November 2012 to 30 September 2013).

Table 5-2: Flow requirements to achieve oxygen concentrations in the Awanui Stream. Daily minimum dissolved oxygen concentrations are specified in the left column. Flow requirements are presented from SEFA modelling of a Summer Scenario (corresponding to the line in Figure 5-8). Flows were rounded to two significant digits. Predicted dissolved oxygen concentrations did not reach 6 mg/L, despite modelling up to 800 L/s. The predicted dissolved oxygen concentration at the existing minimum flow (120 L/s) is also presented.

Min oxygen (mg/L)	Flow L/s Summer Scenario
2	110
3	170
4	270
5	510
6	-
2.2	120

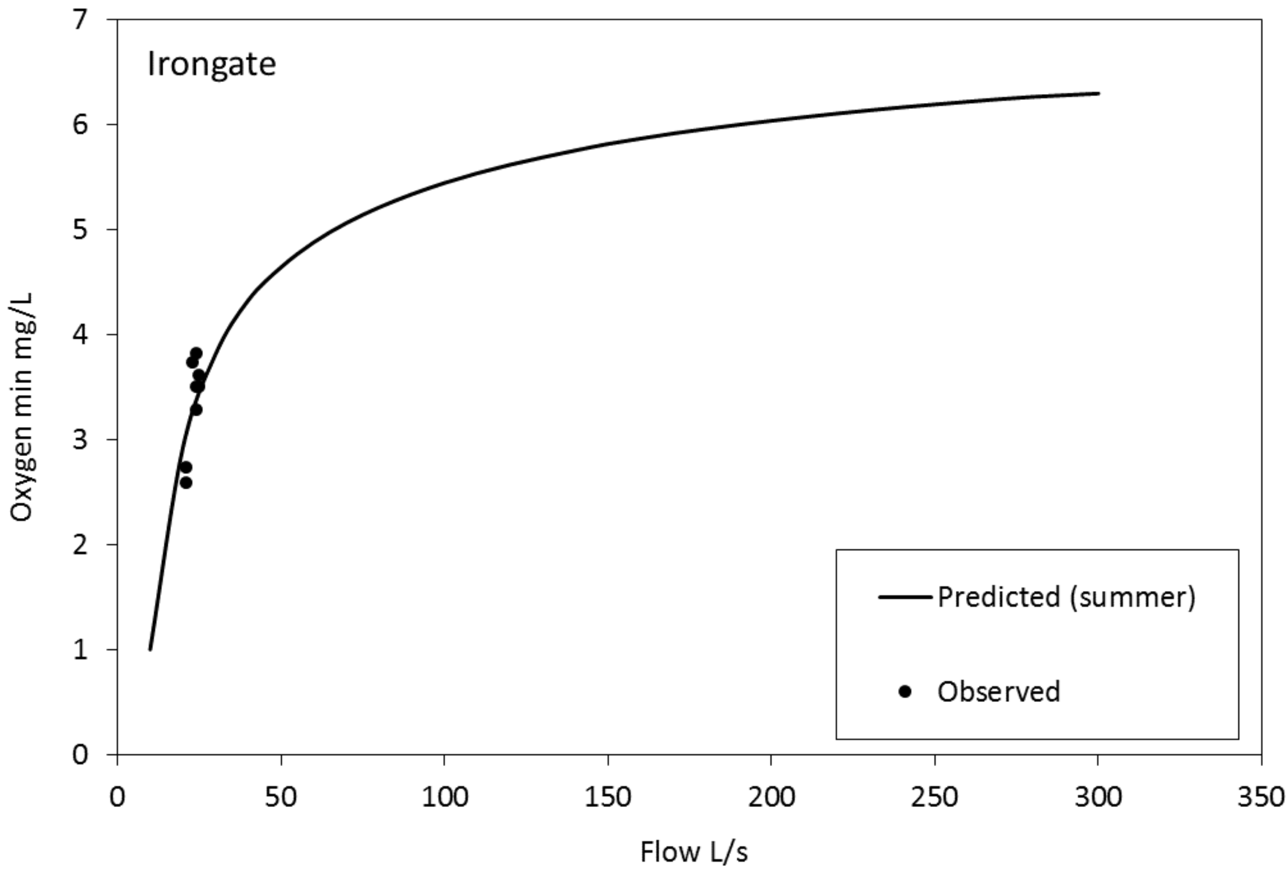

Figure 5-9: SEFA predicted oxygen-flow relationship for the Irongate Stream. Predictions from the SEFA model for daily minimum dissolved oxygen concentration are plotted as a black line. The measured dissolved oxygen and flow data are plotted as points (from 15 to 22 February 2013).

Table 5-3: Flow requirements to achieve oxygen concentrations in the Irongate Stream. Daily minimum dissolved oxygen concentrations are specified in the left column. Flow requirements are presented from SEFA modelling of a Summer Scenario (corresponding to the line plotted in Figure 5-9). Flows were rounded to two significant digits. The predicted dissolved oxygen concentration at the existing minimum flow (100 L/s) is also presented.

Min oxygen (mg/L)	Flow L/s Summer Scenario
2	14
3	21
4	33
5	67
6	190
5.4	100

5.4 Oxygen-Flow Quantiles

The long period of record for the Raupare and Awanui Streams (from November 2012 to September 2013) can be used to examine the observed relationship between dissolved oxygen and flow. Rather than isolating the effect of flow, quantile regression accounts for unknown drivers and their effect on the probability of exceeding a given oxygen concentration.

Quantile regression was used to generate a set of functions (quantile percentages of 5%, 10%, 25%, 50%, 75%, 90% and 95%). These equations were then rearranged to calculate the flow required to exceed 4, 5 and 6 mg/L oxygen for the Raupare (Table 5-4; Figure 5-10) and Awanui (Table 5-5; Figure 5-11). For example, an oxygen concentration of 4 mg/L for Raupare Stream was exceeded 50% of days at a flow of 261 L/s (Table 5-4). Adopting a higher flow would increase the number of days that flow exceeded 4 mg/L.

The quantile regression results were compared to the SEFA predictions for the change in daily minimum oxygen with flow. For the Raupare's Autumn Scenario, oxygen-flow predictions from SEFA are most similar to the quantile regression 75% exceedance overall (most similar to 50% at lower flows; most similar to 90% at higher flows). For the Awanui Stream, SEFA predictions from the Summer Scenario are again most similar to the quantile regression 75% exceedance overall (Table 5-5). Note that, unlike pollutants, it is desirable to exceed dissolved oxygen limits because oxygen is a vital resource for aquatic life.

Comparing the Awanui and Raupare, there were more data pairs available for the Awanui Stream (n = 240 for Awanui; n = 61 for Raupare) because flow estimates derived from rated stage were acceptable for use, compared to the Raupare, where manual gaugings were used prior to velocity-meter installation. The Awanui Stream also experienced a wider range of flows over the monitoring period, and a wider range of oxygen concentrations (from 0 to 9 mg/L for the Awanui and from 3.6 to 7.9 mg/L for the Raupare). The oxygen-flow response was also more variable for the Awanui.

Table 5-4: Flow that exceeded oxygen concentrations for the Raupare Stream. A range of exceedances was estimated (from 5% to 95%) to represent the proportion of days when dissolved oxygen exceeded 4, 5 and 6 mg/L. Flows were estimated by performing quantile regression on observed oxygen-flow data (flow less than 650 L/s; excluding flow from rated stage), as plotted in Figure 5-10 (fitted to 61 observations). Coefficients and statistics for model fit are also presented for the equation MinDO = 9 - a * exp(FlowLS * b). For comparison, flow requirements predicted using SEFA are reproduced in the bottom rows (Summer Scenario and Autumn Scenario; from Table 5-1).

Exceedance	Oxygen (mg/L)	Estimated flow (L/s)	Coefficients:	Value	Std. Error	t value	Pr(>|t|)
5%	4	241	a	11.779	0.748	15.8	<0.0001
	5	303	b	-0.00356	0.00017	-20.5	<0.0001
	6	384					
10%	4	253	a	12.452	0.753	16.5	<0.0001
	5	315	b	-0.00361	0.00016	-23.3	<0.0001
	6	394					
25%	4	250	a	11.452	0.792	14.5	<0.0001
	5	317	b	-0.00332	0.00019	-18.0	<0.0001
	6	403					
50%	4	261	a	11.601	1.523	7.6	<0.0001
	5	330	b	-0.00323	0.00037	-8.7	<0.0001
	6	419					
75%	4	292	a	10.988	1.160	9.5	<0.0001
	5	374	b	-0.00270	0.00026	-10.3	<0.0001
	6	481					
90%	4	304	a	10.563	0.706	15.0	<0.0001
	5	395	b	-0.00246	0.00017	-14.8	<0.0001
	6	512					
95%	4	308	a	10.310	0.534	19.3	<0.0001
	5	403	b	-0.00235	0.00013	-18.5	<0.0001
	6	525					
Summer	4	200					
(SEFA)	5	390					
	6	-					
Autumn	4	240					
(SEFA)	5	350					
	6	510					

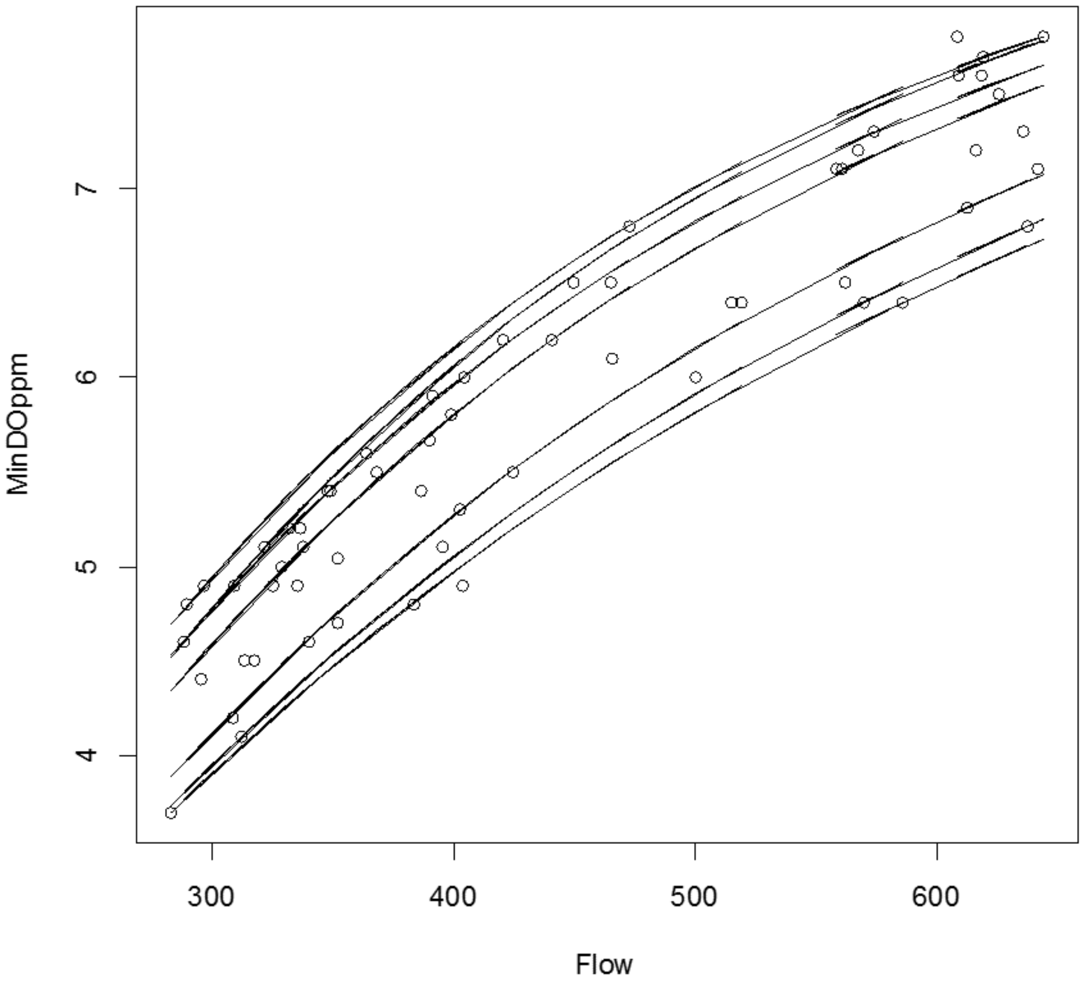

Figure 5-10: Quantiles describing the oxygen-flow relationship for Raupare Stream. The plotted lines were fitted to observed data, and then used to derive the flow requirements listed in Table 5-4. Measured oxygen (daily minimum dissolved oxygen concentration (mg/L), and flow (L/s) values are plotted as points (from 16 November 2012 to 18 September 2013). Exponential functions were fitted to flows of less than 650 L/s, and repeated for a series of quantiles (5%, 10%, 25%, 50% 75%, 90, 95%).

Table 5-5: Flow that exceeded oxygen concentrations for Awanui Stream. A range of exceedances were estimated from 5% to 95% to represent the proportion of days when dissolved oxygen exceeded 4, 5 and 6 mg/L. Flows were estimated by performing quantile regression on observed dissolved oxygen-flow data, for flows exceeding 30 L/s, as plotted in Figure 5-11 (fitted to 240 observations). Coefficients and statistics for the model fit are also presented for the equation LN(MinDO+1) ~ 9 - a * exp(LN(Flow) * b). For comparison, flow requirements predicted using SEFA are reproduced in the bottom rows (Summer Scenario and Autumn Scenario; from Table 5-2).

Exceedance	Oxygen (mg/L)	Estimated flow (L/s)	Coefficients:	Value	Std. Error	t value	Pr(>|t|)
5%	4	67	a	982.177	544.54	1.80	0.0726
	5	80	b	-1.728	0.149	-11.61	<0.0001
	6	98					
10%	4	77	a	455.676	233.92	1.95	0.0526
	5	94	b	-1.495	0.139	-10.78	<0.0001
	6	120					
25%	4	103	a	128.664	38.69	3.33	0.0010
	5	135	b	-1.127	0.080	-14.03	<0.0001
	6	186					
50%	4	159	a	46.3913	9.28	5.00	<0.0001
	5	229	b	-0.830	0.054	-15.39	<0.0001
	6	353					
75%	4	287	a	22.236	1.53	14.55	<0.0001
	5	472	b	-0.613	0.019	-32.82	<0.0001
	6	848					
90%	4	508	a	15.543	2.77	5.61	<0.0001
	5	936	b	-0.499	0.044	-11.32	<0.0001
	6	1921					
95%	4	739	a	13.743	3.33	4.13	0.0001
	5	1452	b	-0.452	0.057	-7.89	<0.0001
	6	3213					
Summer (SEFA)	4	270					
	5	510					
	6	-					

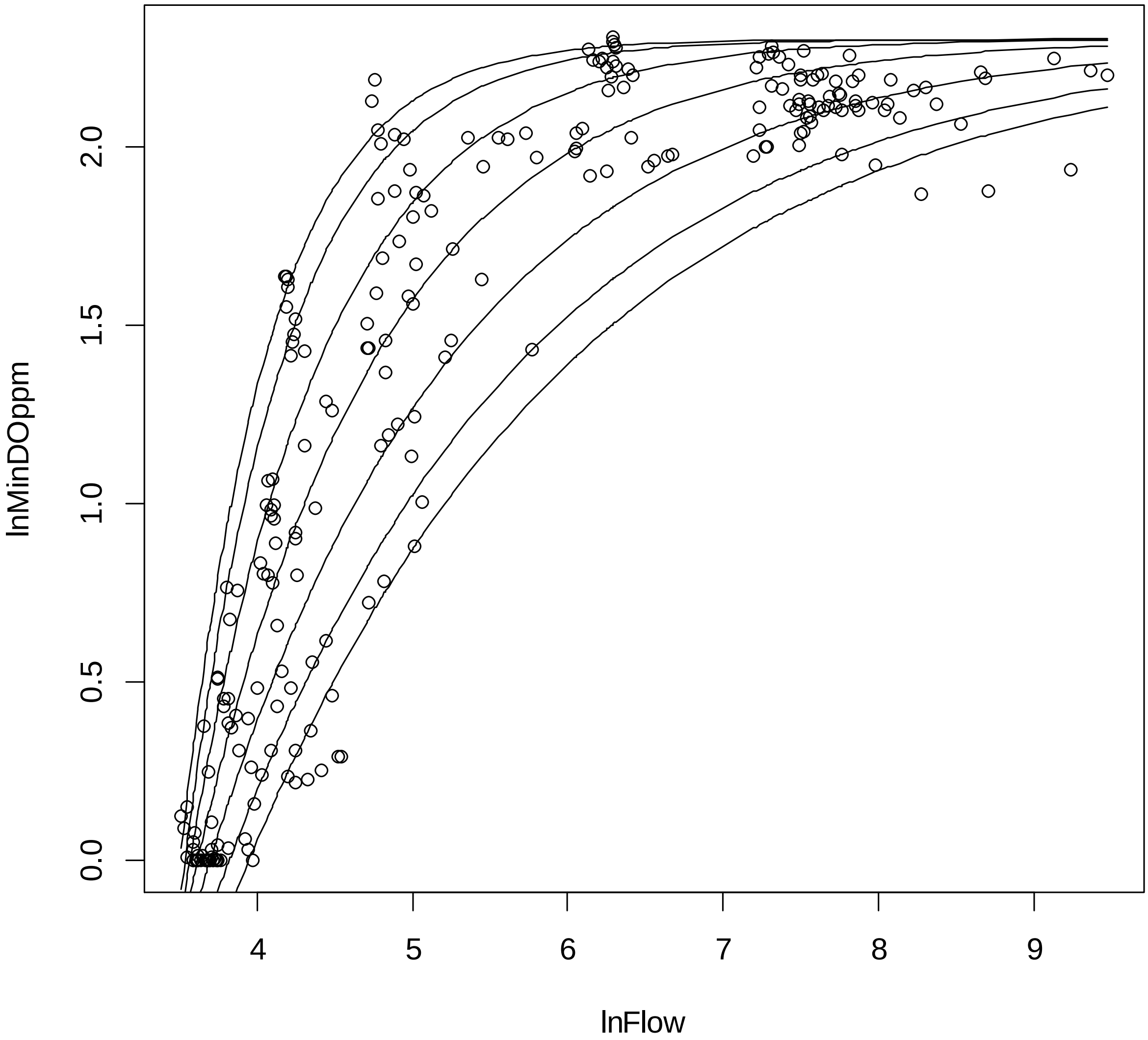

Figure 5-11: Quantiles describing the oxygen-flow relationship for Awanui Stream. The plotted lines were fitted to observed data, and then used to derive the flow requirements listed in Table 5-5. Measured oxygen ("lnMinDOppm" = log-transformed daily minimum dissolved oxygen concentration mg/L + 1) and flow (log transformed flow in L/s) data from 28 November 2012 to 30 September 2013. Exponential functions were fitted to points with a flow more than 30 L/s for a series of quantiles (5%, 10%, 25%, 50% 75%, 90, 95%).

5.5 Validation of Oxygen-Flow Predictions

The oxygen-flow models were calibrated using data for 2012-2013. This section compares the predictions of those models to data collected the following year (2013-2014) to validate model predictions intended for application to a population of future years. The SEFA model predicts how dissolved oxygen changes with flow for a given scenario of climate, plant abundance, stream shading and channel morphology. Validation success reflects not just performance of the SEFA model, but also how representative the calibration conditions are of changes in climate, plant abundance and channel hydraulics. This validation does not address how well each study site represents the broader stream network, which is to be investigated in subsequent reports.

Validation analysis focused on the Raupare and Awanui streams, with fewer data available for the Irongate Stream. Only data that met the highest NEMS quality code - QC600 were used for validation for the Raupare and Awanui streams. No spot measurements were available to establish the quality standard of the Irongate validation data collected in 2003, which predated the NEMS standards. Days were excluded with rapidly changing flow, defined as where daily maximum flow less daily minimum flow was more than 30% of the three day minimum flow. Validation data are presented in units of percent saturation, to distinguish model uncertainty from seasonal temperature changes, because lower temperatures increase the saturation concentrations.

Raupare

Three models were examined for the Raupare Stream, including both the summer and autumn SEFA scenarios, and the quantile regression 75% exceedance. The upper bound of the 2014 data is consistent with the SEFA Autumn Scenario and the quantile regression model (upper plot, Figure 5-12). However, there was more variability in the dissolved oxygen response to flow during 2014. The lower dissolved oxygen concentrations coincided with higher water levels (23 December 2013 to 26 January 2014). Increasing aquatic plants produced an increase in water level, despite the decline in flow. The Summer Scenario was intended to represent such conditions, and provides a better fit to the summer data (lower plot, Figure 5-12). A bloom of filamentous algae was also noted during site visits in late December through to mid-January 2014. For example, 0.5 m filaments smothered the velocity meter sensors on 4 January 2014.

Awanui

Two models were tested for the Awanui Stream, including the SEFA Summer Scenario and the quantile regression at 75% exceedance. The 2014 validation data confirm that dissolved oxygen declines steeply at flows less than 300 L/s (Figure 5-13). The increased flows experienced during the 2014 summer produced less scatter over the flow range of steeply declining dissolved oxygen (300 to 50 L/s), compared to the extreme low flows of 2013 that dropped below this range.

It took more flow to provide dissolved oxygen saturation levels of more than 10% in 2014 than in 2013. In 2014 flows around 135 L/s were required to provide saturation of this level, but flows of 95 L/s provided the same dissolved oxygen saturation levels in 2013. However, it is clear that oxygen stress can be severe at flows less than 150 L/s. Both the SEFA model and quantile regression (75% exceedance) provide an adequate representation of the validation data, including the flows at which dissolved oxygen starts declining toward zero.

Irongate

Predictions from the SEFA model were tested for the Irongate Stream (Figure 5-14). In the absence of long-term deployment data, two data sources were available for comparison. Dissolved oxygen was monitored using a Greenspan logger during spring of 2003 (29 August to 24 November 2003). The 2003 oxygen data could not be filtered using National Environmental Monitoring Standards because quality control data were not available (i.e. no spot measurements or calibration records). The flow data were filtered to exclude days with rapidly changing flows (rapid if daily maximum flow minus daily minimum flow was more than 30% of three day minimum flow).

The 2003 validation data are generally consistent with predictions from the SEFA oxygen model, which describes the lower bound of the data at a time when plant biomass was probably low. In addition, one dissolved oxygen measurement was available at dawn (6:45 am 25 February 2014), representing the daily minimum. This summer measurement is also consistent with predictions from the SEFA model (red triangle in Figure 5-14), confirming that the model successfully identified the flow at which dissolved oxygen starts declining to zero.

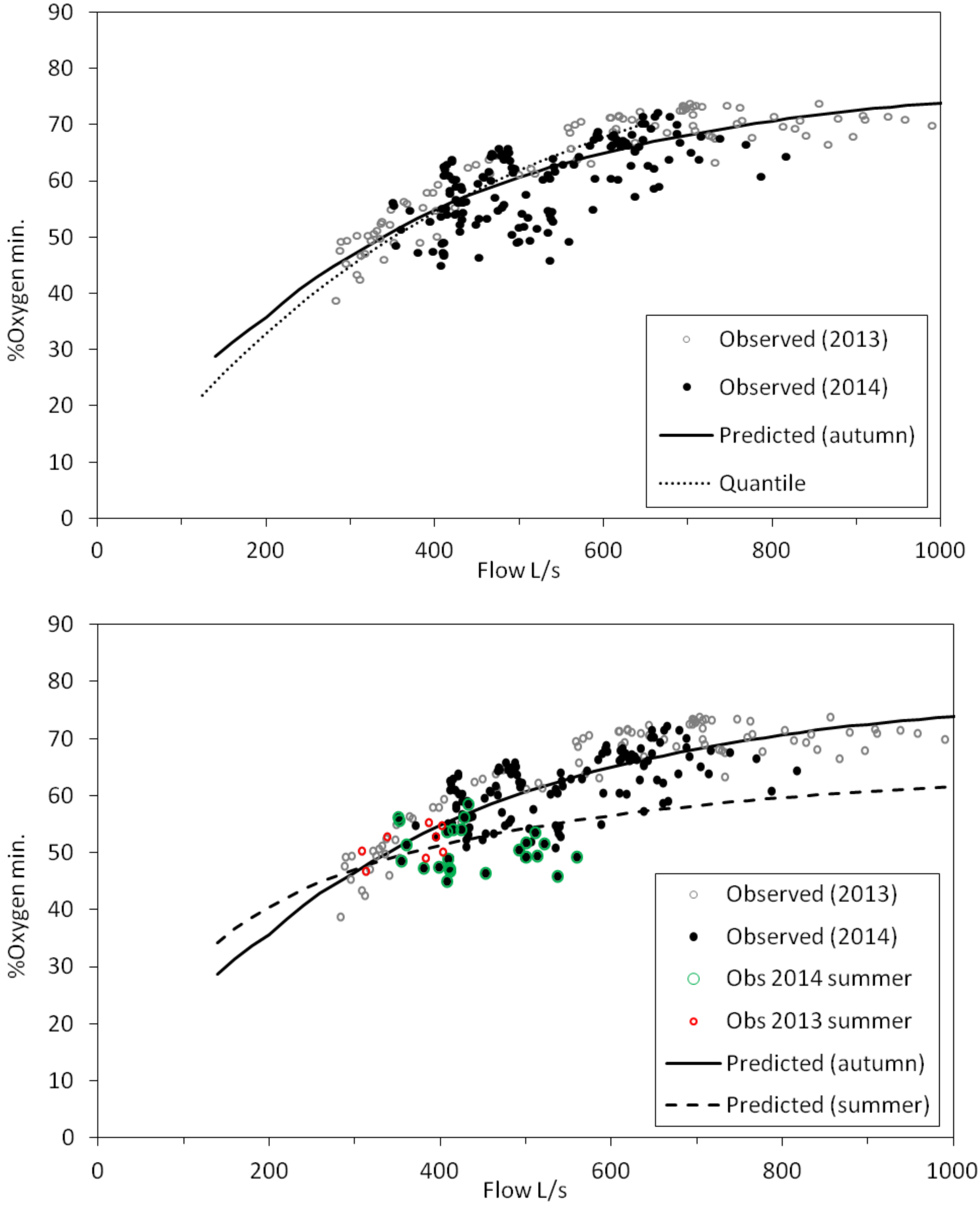

Figure 5-12: Validating oxygen predictions for Raupare Stream using 2014 data. The response of daily minimum dissolved oxygen saturation to flow, predicted from the SEFA model (Autumn Scenario solid line) and from quantile regression (dotted line, 75% exceedance) are compared to validation data (black dots "Observed 2014") not used to calibrate the models for the period November 2013 to May 2014. The original calibration data from 2013 are also displayed (grey circles). The lower plot adds the Summer Scenario (dashed line), with summer data are highlighted using green circles for 2014 (23 Dec. 2013 to 26 Jan. 2014) and red circles for 2013 (24 Dec. 2012 to 25 Jan. 2013).

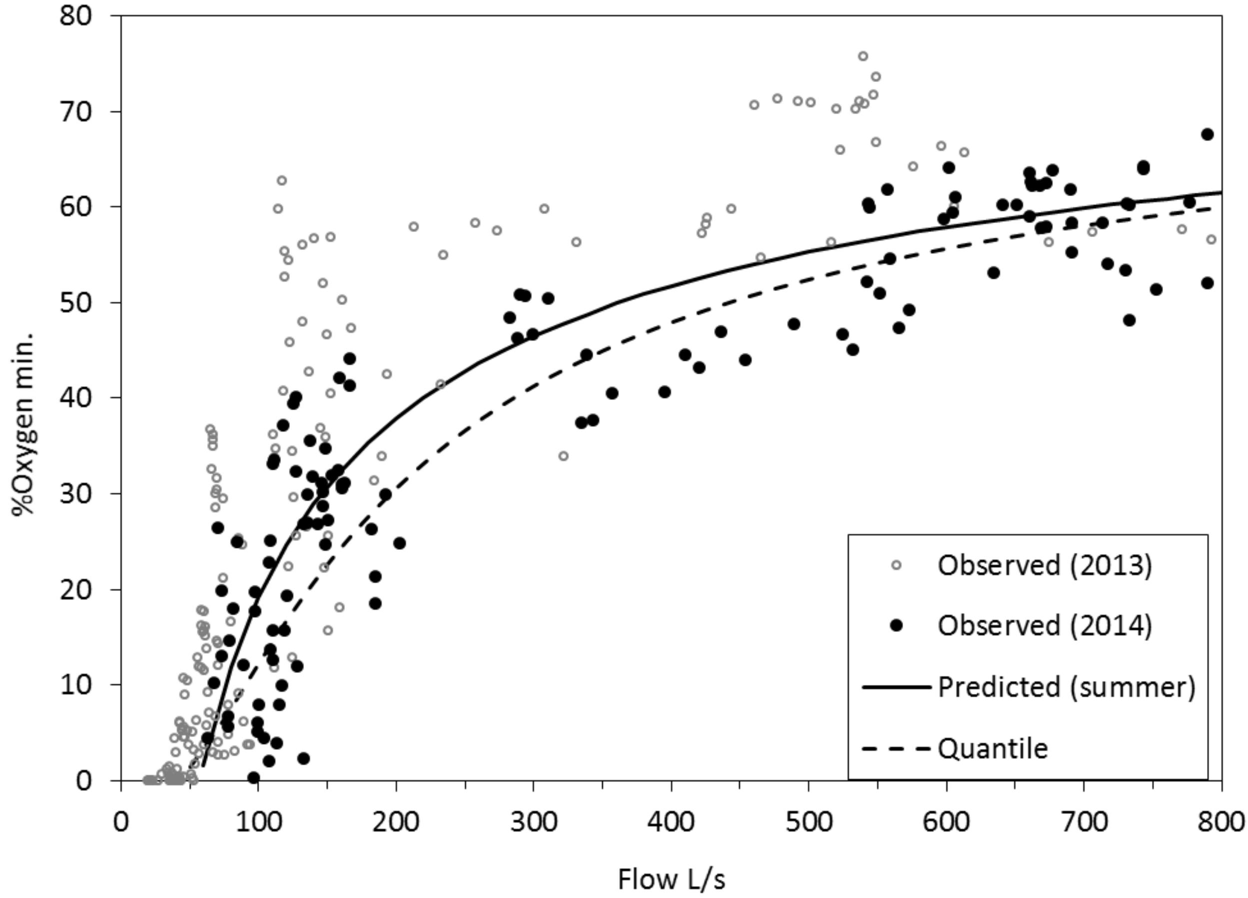

Figure 5-13: Validating model predictions for Awanui Stream using 2014 oxygen data. The response of daily minimum dissolved oxygen saturation to flow predicted from the SEFA model (solid line) and from quantile regression (dashed line, 75% exceedance) are compared to validation data (black dots "Observed 2014") not used to calibrate the models for the period November 2013 to May 2014. The original calibration data from 2013 are also displayed (grey circles).

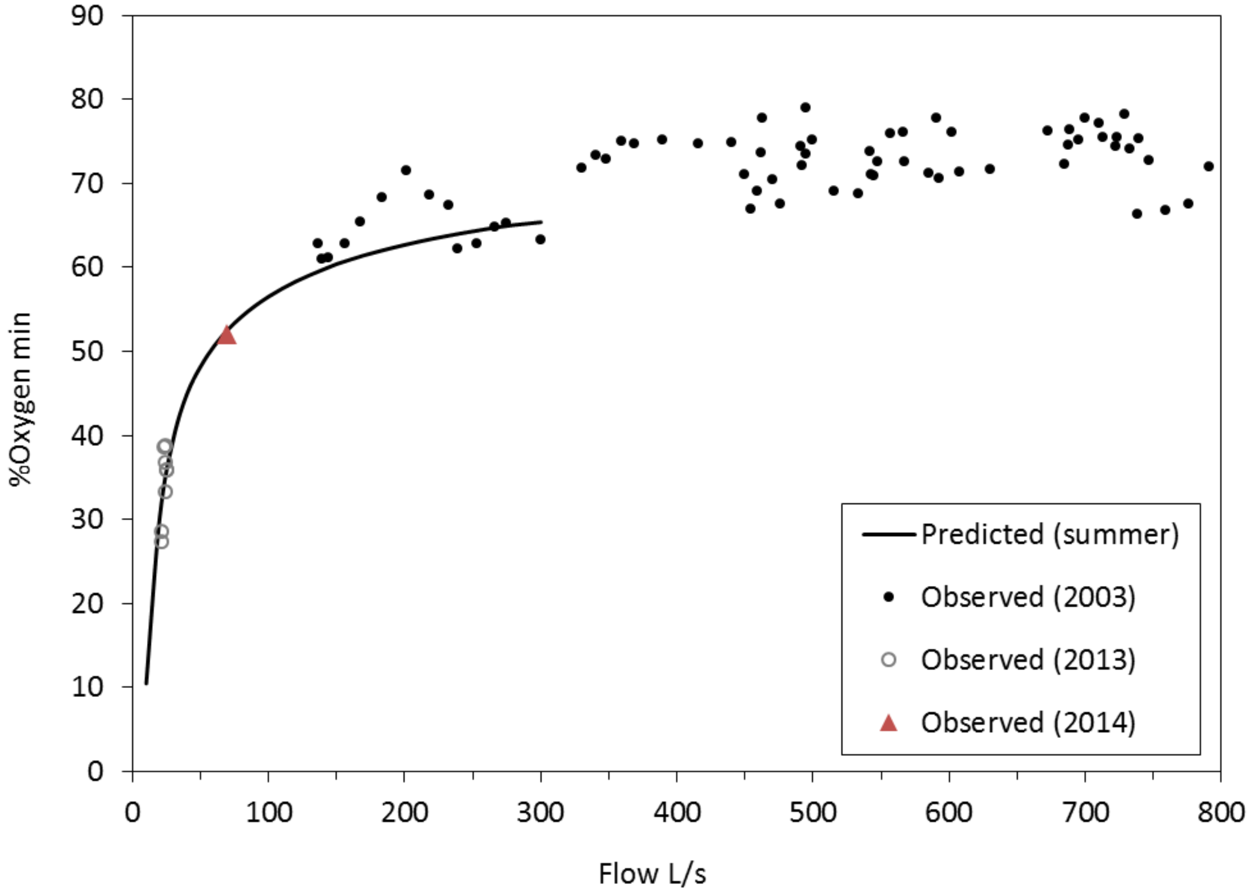

Figure 5-14: Validating model predictions for Irongate Stream using 2003 oxygen data. The response of daily minimum dissolved oxygen saturation to flow predicted from the SEFA Summer Scenario model (dashed line) is compared to validation data not used to calibrate the models (29 August to 24 November 2003). A spot measurement at dawn (25 February 2014 06:45 am) is also displayed as a red triangle. The original calibration data from 2013 are displayed as grey circles.

6 Discussion

The Awanui Stream dropped below 1 mg/L dissolved oxygen during the 2013 drought, with 77 days of overnight anoxia measured during summer and autumn. These low dissolved oxygen concentrations created stressful conditions for biota in the Awanui Stream, as confirmed by previous studies that reported very low macroinvertebrate community scores for the main stem (HBRC, 2014). For example, the Awanui Stream at Crystal Road had an MCI score of 42. The three tributaries feeding the lower Awanui, which are the Karewarewa, Poukawa, and upper Awanui, had scores of 33, 44 and 32 respectively (HBRC, 2014). Those invertebrate samples were collected in 2010 indicating the effect was not limited to the 2013 drought.

Lower diversity of native fishes was observed in the Awanui, compared to the Raupare (Table 3-2), which is also consistent with oxygen stress. Porter and Cairns (1990) reported several fish kills in the Awanui, and attributed this to deoxygenation caused by low flows and high temperatures (Appendix B).

The Raupare Stream exceeded 4 mg/L of oxygen for all but 5 days in 2013. The Raupare Stream also recorded better macroinvertebrate scores (MCI scores around 70) than the Awanui (HBRC, 2014). Neither the oxygen concentrations nor MCI scores for the Raupare represent good water quality, but they are better than the Awanui and arguably indicative of the benefits of more flow.

The potential for reduced flows to exacerbate oxygen stress for the Awanui, Raupare and Irongate Streams, was confirmed using both observed oxygen-flow relationships and SEFA model predictions. Oxygen is therefore a critical issue if managing flows of these streams to safeguard their life-supporting capacity. The flows predicted to achieve alternative oxygen limits are presented in this report for each site (Table 5-1, Table 5-2 and Table 5-3). These predictions were confirmed, using validation data, for the Awanui and Irongate. Validation data for the Raupare demonstrated the potential for reduced oxygen concentrations, for a given flow, when plants are more abundant. Lower oxygen concentrations coincided with a bloom of filamentous algae (epiphyton) in late December to early January 2014. Algae were observed the previous year, but were not as prolific.

Flow recommendations to achieve nominated oxygen targets are based on predictions from the SEFA model. The SEFA model is based on the physical processes that directly link oxygen and flow, for a given scenario of climate, plant abundance, riparian shade and channel form. The SEFA approach is reasonable because the predictions are intended to support decisions on managing in-stream flows, not precisely predict the oxygen concentrations on any given day (i.e. under all possible scenarios).

Stakeholders need to be aware that flow is not the only factor constraining dissolved oxygen, when considering oxygen-flow model predictions. The real-world changes in plant abundance, and other drivers, increase scatter about the observed relationship between dissolved oxygen and flow. Even if those other drivers remained constant, some uncertainty would remain in predictions from the SEFA oxygen-flow model because stream processes are, in reality, more complex than the model. For example, a single reaeration coefficient is used to represent spatially variable upstream conditions. To better understand model uncertainty, a cross-check of the oxygen model parameters (reaeration coefficient, respiration, and photosynthesis) was calculated using the Metabolism Calculator (Wilcock *et al.*, 2011; Young *et al.*, 2006). The two models use different methods to estimate reaeration: The Metabolism Calculator uses the rate of oxygen decline after dusk, known as night-time regression. By contrast, SEFA Delta Method uses the lag between oxygen maximum and solar noon. For the Raupare and Awanui, similar reaeration coefficients were estimated using SEFA and the Metabolism Calculator. But, for the Irongate, there was a notable difference in reaeration coefficients between the two models, with the SEFA model producing 8.3 /day, while the Metabolism Calculator used 10.9 /day for the 18 February 2014. Riparian shading could have delayed solar-noon for the Irongate compared to that estimated by SEFA using latitude, longitude and date. This delay produces an under-estimate of reaeration because the time lag to maximum oxygen is overestimated. Despite the difference in the reaeration coefficients between the two models, the final oxygen-flow predictions were equivalent for both (predicted oxygen within 0.05 mg/L for 95% of flow increments). Oxygen-flow predictions for the Irongate were robust over a wide range of reaeration coefficients (5 to 14 /day), provided each coefficient was used with the respiration and photosynthesis parameters fitted to the same day's data. The combination of parameter values was therefore more important than the absolute value of individual parameters for Irongate oxygen-flow predictions, as demonstrated by the close agreement with validation data.

Groundwater enters a stream with little or no oxygen. For example, groundwater emerges with 0 mg/L oxygen near the coast (Bore No. 15918) and 4 mg/L closer to the recharge area (Bore No. 8521). The effect on in-stream oxygen can be negative at the spring source, transitioning to a positive oxygen effect at some distance downstream where the stream achieves a new oxygen equilibrium that reflects the increase in stream flow. Prior to reaching a new equilibrium, the groundwater inflows can affect estimates of respiration that are produced using SEFA and the Metabolism Calculator (Hall & Tank, 2005). It is still unknown what, if any, effect this has on oxygen-flow relationships. This is less likely to be a source of error for the Raupare and Awanui, because groundwater inflows were located more than 1 km upstream of the monitoring sites. Studies by Hawke's Bay Regional Council in the Harakeke Stream revealed a net oxygen benefit just 0.4 km downstream from an anoxic groundwater discharge (see **File Note**). The Irongate monitoring site may receive direct groundwater inflows, with gaugings (2 December 2014) revealing a flow increase that extends downstream of the monitoring site. But the agreement between model predictions and observed oxygen data reduce the potential for groundwater inflows to have introduced error to the oxygen-flow predictions, despite the uncertain respiration parameters.

Quantile regression can also be used to understand the variability in dissolved oxygen concentrations associated with each flow option. For example, predictions from the SEFA model were similar to the 75% exceedance from quantile regression (Section 5.5), indicating that 75% of sampled days exceeded the predicted dissolved oxygen concentration at a nominated flow. Note, that 75% of sampled days is not equivalent to 75% of days in the year. Choosing a greater exceedance value (e.g. 95%) would increase water restrictions for resource consent holders. Instead of relying solely on water restrictions to avoid oxygen stress, safeguarding the life supporting capacity of these streams will require more balanced management of the critical factors affecting stream health, including riparian shade, point discharges and flow. Management actions that are undertaken when minimum flows are breached, such as irrigation bans or stepped reductions, will change the consequences of a minimum flow decision for resulting oxygen concentrations, and therefore also needs consideration when choosing an oxygen limit.

A benefit of using SEFA model predictions is the feasibility of applying this method across multiple sites, by contrast with quantile regression methods, which are applicable only to sites with long-term dissolved oxygen records, such as the Raupare and Awanui. Of the two SEFA scenarios presented for the Raupare Stream, the Autumn Scenario represented prevailing conditions better than the Summer Scenario. The Summer Scenario describes a short period from early December to mid-January when extreme low flows are less likely to occur, reducing the chance of conflict between in-stream and out-of-stream use. The Autumn Scenario predicted that less flow is required to achieve 5 mg/L dissolved oxygen than the Summer Scenario, but the two scenarios were consistent in their prediction of dissolved oxygen concentrations at the existing minimum flow, of 4.6 mg/L at 300 L/s. Only one scenario was possible for the other sites. The SEFA model predicts the minimum flows required to achieve a given oxygen limit. This information can be used by stakeholders to choose the oxygen limits and minimum flows to recommend to council for adoption in plans and policies. The following is intended to assist stakeholders in making that choice.

Stream flow can be managed to balance the water use (e.g. irrigation, municipal supply) with the risk of impacts on aquatic life.

Understanding the consequences of oxygen suppression for aquatic ecosystems is largely reliant on scientific research into the oxygen tolerances of fish and invertebrates (Dean & Richardson, 1999; Landman *et al.*, 2005; Urbina *et al.*, 2012). These studies determined the lowest continuous oxygen concentration that can be tolerated before death results (e.g. 48h LC_{50} - the concentration lethal to 50% of organisms after 48 hours continual exposure). Common smelt and rainbow trout were less tolerant of low dissolved oxygen, experiencing mortalities at 3 mg/L, but eels and common bully can survive concentrations as low as 1 mg/L (Dean & Richardson, 1999; Landman *et al.*, 2005). Inanga were the *most* tolerant species tested, according to Dean and Richardson (1999), but were the *least* tolerant species tested by Landman *et al.* (2005). Inanga are more dependent on access to the water surface to survive periods of low oxygen (Urbina & Glover, 2012; Urbina *et al.*, 2012). Conventional laboratory experiments have used exposure to fixed dissolved oxygen concentrations, with few studies using the diurnally-fluctuating oxygen concentrations, which are characteristic of plant-dominated streams (Coiro *et al.*, 2000; Li & Brouwer, 2013; Neilan & Rose, 2014). Dissolved oxygen guidelines are conventionally specified as a concentration (e.g. mg/L, g/m^3). The biological relevance of this unit of measure (concentration) has come under question, with Verberk *et al.* (2011) demonstrating that rates of oxygen diffusion increase with temperature.

Recommended oxygen limits are conventionally set to be more protective (i.e. more oxygen) than the lethal limit because of the sub-lethal effects on populations (Davies-Colley *et al.*, 2013; Franklin, 2013). A technical report for New Zealand's National Objectives Framework recommended minimum dissolved oxygen concentrations to *"protect the value Ecosystem Health and indigenous species"* (Davies-Colley *et al.*, 2013). The limits are expressed as seven-day means, seven-day mean minima or one-day minima. Of these options, the seven-day mean minima are probably comparable to the minimum dissolved oxygen concentrations predicted using SEFA. The recommended limits range from 8 mg/L, which is the lower threshold for Band A (near pristine rivers), to 5 mg/L, which is the lower threshold for Band C (moderate stress to aquatic organisms). The National Policy Statement has adopted 5 mg/L as a "*National Bottom Line*", but only "*below point discharges*" (Appendix 2 in MfE, 2014). I interpret "*below point discharges*" to mean that dissolved oxygen should not drop below 5 mg/L as a consequence of a point discharge. The National Bottom Line for dissolved oxygen is therefore not a statutory limit for the Karamu study sites because low oxygen concentrations are more a consequence of aquatic plants and low flows than point discharges. Stakeholders therefore have the opportunity to select a dissolved oxygen limit for these streams, which could be 5 mg/L or some other value.

The Awanui Stream is unlikely to meet any dissolved oxygen limits year-round, at least in the near future. An alternative to setting oxygen limits is to allow abstraction, provided this does not reduce oxygen more than 10% relative to a natural condition (Franklin, 2013), and provided lethal limits are not exceeded (USEPA, 1986). Daily mean concentrations that are persistently less than 3 mg/L are expected to have lethal effects and eventually alter fish communities (Franklin, 2013). Mitigation options should be considered for this catchment, including examples such as riparian shading to reduce the abundance of aquatic plants. Reducing aquatic plants is more desirable than complete removal because low abundances of aquatic plants provide beneficial habitat (Champion & Tanner, 2004).

Given that more conservative dissolved oxygen limits are unlikely to be achieved in streams such as the Awanui and Raupare, effects-based monitoring of fish and invertebrates should form part of the ongoing water management. Monitoring the health of inanga in the Awanui and Raupare is recommended. Inanga are more abundant and widespread in these streams than common smelt, and they support a valued whitebait fishery. The apparent preference that inanga have for smaller streams, in contrast to the predominance of common smelt in larger rivers, was reported in previous studies (compare Figure 10 and

16 in Leathwick *et al.*, 2008). It is possible that smelt are less common than inanga in the Karamu tributaries as a consequence of dissolved oxygen stress. But it is also possible that these streams are simply too small for smelt to be abundant. For example, common smelt were more abundant than inanga in large rivers with low dissolved oxygen such as the Tarawera River, which dropped below 3 mg/L (Park & Wilding, 1998). Common smelt were also more abundant than inanga in large rivers with high temperatures, such as the lower Waikato River where the temperatures can exceed 23 °C (Wilding *et al.*, 2006). Common smelt may be more abundant in the mainstem of the Karamu/Clive River because it is larger, but measuring their abundance will be difficult because few fishing methods are suited to deep streams with high plant abundance.

Inanga are more dependent on access to the water surface than common smelt, in order to survive periods of low dissolved oxygen (Landman *et al.*, 2005; Urbina *et al.*, 2012). Past research indicates that fish stop feeding when low dissolved oxygen forces surface breathing (Kramer, 1987; Neilan & Rose, 2014), and that inanga are less likely than smelt to move in search of more oxygen (Richardson *et al.*, 2001). So the condition of inanga might be more responsive to oxygen stress than the condition of smelt. Other species are probably less suited for monitoring:

- because of their ability to tolerate low oxygen concentrations (e.g. longfin and shortfin eels, common bully, koura)
- because they are less-valued introduced species (e.g. goldfish, *Gambusia*)
- because they are not common enough to provide a robust sample (e.g. torrentfish, patiki, rainbow trout)

Yelloweye mullet are abundant in the Raupare, although little is known of their dissolved oxygen tolerance.

The condition factor provides a measure of how skinny a fish is, by standardising weight for length (Wilding *et al.*, 2006). Unlike other fish health measures, such as liver somatic index, condition factor is a potentially non-lethal measure for inanga. Another benefit of the using the condition factor is that it does not depend on achieving comparable abundance estimates between sites, which is more difficult to achieve in streams with high plant abundance. The study sites provide an informative contrast between low dissolved oxygen in the Raupare and long-duration anoxia in the Awanui. Given the many possible confounding effects (e.g. floods, fish movement between streams), monitoring cannot demonstrate an absence of impacts on fish health from low dissolved oxygen. What the monitoring can reveal is the severity of oxygen suppression needed to produce a measurable impact on fish health (Coiro *et al.*, 2000; Li & Brouwer, 2013).

Monitoring aquatic plant dynamics assists in understanding dissolved oxygen suppression. For the Raupare, daily maximum oxygen concentrations increased with plant abundance while daily minimum dissolved oxygen decreased with flow (Section 5.2). For the Awanui Stream, daily minimum oxygen concentrations dropped to zero as aquatic plant abundance increased to the point where surface-reaching and emergent plants smothered most of the stream (more than 75% cover). But that smothering appears to be, in part, a consequence of flow being low enough to allow submerged plants to reach the surface (Franklin *et al.*, 2008; Wilcock *et al.*, 1999), with average water velocities less than 0.04 m/s during the period of smothering. Plant growth was probably inhibited in this situation, as shown by declining daily-maximum oxygen concentrations. Low velocities can allow epiphytic algae to proliferate to the point of shading out aquatic plants and reducing gas exchange (Franklin *et al.*, 2008). A scenario of reduced gas exchange may explain why a better model fit was achieved for Awanui Stream by decreasing the reaeration coefficient with flow. Decomposition of smothered plants would compound the reduction in reaeration. Blackened, decomposing plants, including *Elodea* and *Ceratophyllum*, were observed beneath a surface layer of live plants, including *Ceratophyllum* and filamentous algae, in the Awanui Stream (February 2014).

7 Conclusions

Examining the relationship between dissolved oxygen and flow was made possible by the severe drought conditions of 2013. Flows in the Ngaruroro River were the lowest recorded since 1983, and the Ministry of Primary industries declared drought across Hawke's Bay and the entire North Island (Porteous & Mullan, 2013). Recent advances in dissolved oxygen sensors (fluorescent D-Opto) have extended oxygen monitoring durations from weeks to years. Oxygen data from the Awanui demonstrate the value of long-term records in documenting the duration of anoxia. Clapcott and Young (2009) emphasised the need for long-term monitoring to improve estimates of respiration and photosynthesis. Advances in oxygen modelling software (SEFA) enabled better use of this long-term data. The National Environmental Monitoring Standards (Wilcock *et al.*, 2013) were important for establishing best practices for maintaining equipment and data. Most critical to pursuing those high standards was the dedication of HBRC field technicians to an unprecedented maintenance schedule, including weekly oxygen checks and gauging up to twice weekly.

This report examined flow requirements for dissolved oxygen at several specific sites. The sites provide a contrast between streams draining limestone hill-country and streams that are spring-fed from the Heretaunga gravel aquifer. The degree to which the sites in this report represent the broader Karamu catchment will be investigated in a subsequent report on spatial patterns of dissolved oxygen concentrations.

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Appendix A Stage-flow ratings for Hydraulic model

Raupare Stream at Ormond Road

SEFA version 1.2 25/08/2014
File: M:\E_Science\Projects\311 SW R&I Hydro\600_Karamu\01 IFIM\Analysis\oxygen\Raupare analysis\Raupare autumn rating.rhbx
Raupare Ormond Road surveyed 11/4/2012 calibration 15/4, 18/4, 22/4, 29/4, 6/5, 16/5
File creator: tkwilding - Hawkes Bay Regional Council
Imported from file: M:\E_Science\Projects\311 SW R&I Hydro\600_Karamu\01 IFIM\Data\RHYHABSIM surveys\Processed RHYHABSIM files\Raupare.rhb
Reach length: 100.000 m
Single channel reach with 10 cross-sections
Representative reach slope: 0.0009
Representative reach

Survey details
The reach was surveyed at a flow of 0.473 m^3/s
The average characteristics were:

Width (m)	Depth (m)	Velocity (m/s)	R	B	C	G	F	S	M	V
4.74	0.557	0.144	0.00	0.00	0.00	0.06	0.85	0.00	32.66	66.42

Cross-section details

Section	Name	Distance m	Weight	Habitat type	XStart	YStart	XEnd	YEnd	Channel	Comment
1	**8m downstream of gat**	8.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
2	**18m E1929909 N560965**	18.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
3	**21m not GPSed**	21.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
4	**30m E1929921 N560965**	30.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
5	**49m E1929938 N560964**	49.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
6	**60m E1929949 N560963**	60.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
7	**61m E1929950 N560964**	61.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
8	**75m E1929962 N560963**	75.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
9	**94m**	94.000	0.1000		0.00	0.00	0.00	0.00	Single	

	E1929978 N560962								channel	
10	**100m downstream of g**	100.000	0.1000		0.00	0.00	0.00	0.00	Single channel	

Rating curves

	Section	Selected rating	Exponent	Constant	Zero	R2	Mean error in Q %
1	**8m downstream of gat**	SZF rating	1.644	0.970	-0.850	0.957	1.651
2	**18m E1929909 N560965**	SZF rating	1.609	0.963	-1.050	0.956	1.814
3	**21m not GPSed**	SZF rating	1.705	0.899	-0.930	0.957	1.630
4	**30m E1929921 N560965**	SZF rating	1.726	0.909	-0.922	0.952	1.811
5	**49m E1929938 N560964**	SZF rating	1.768	0.921	-0.818	0.974	1.532
6	**60m E1929949 N560963**	SZF rating	1.815	0.844	-1.028	0.961	1.587
7	**61m E1929950 N560964**	SZF rating	2.070	0.900	-1.040	0.969	1.320
8	**75m E1929962 N560963**	SZF rating	2.004	0.889	-1.005	0.971	1.598
9	**94m E1929978 N560962**	SZF rating	1.847	0.821	-1.040	0.958	1.772
10	**100m downstream of g**	SZF rating	2.021	0.833	-1.046	0.916	2.107

Levels and calibration flows Autumn Scenario

	Section	Minimum level (m)	Stage at zero flow (m)	Survey		Calibration 1		Calibration 2		Calibration 3		Calibration 4		Calibration 5	
				flow (m^3/s)	stage (m)	flow (m^3/s)	stage (m)	flow (m^3/s)	stage (m)	flow (m^3/s)	stage (m)	flow (m^3/s)	stage (m)	flow (m^3/s)	stage (m)
1	**8m downstream of gat**	-1.144	-0.850	0.473	-0.204	0.465	-0.198	0.500	-0.167	0.586	-0.114	0.558	-0.146	0.562	-0.130
2	**18m E1929909 N560965**	-1.417	-1.050	0.473	-0.407	0.465	-0.402	0.500	-0.367	0.586	-0.320	0.558	-0.345	0.562	-0.330
3	**21m not GPSed**	-1.084	-0.930	0.473	-0.244	0.465	-0.240	0.500	-0.202	0.586	-0.156	0.558	-0.180	0.562	-0.170
4	**30m E1929921 N560965**	-1.147	-0.922	0.473	-0.237	0.465	-0.230	0.500	-0.198	0.586	-0.148	0.558	-0.178	0.562	-0.162
5	**49m E1929938 N560964**	-1.082	-0.818	0.473	-0.132	0.465	-0.126	0.500	-0.098	0.586	-0.047	0.558	-0.070	0.562	-0.058
6	**60m E1929949 N560963**	-1.071	-1.028	0.473	-0.301	0.465	-0.294	0.500	-0.262	0.586	-0.211	0.558	-0.239	0.562	-0.228
7	**61m E1929950 N560964**	-1.187	-1.040	0.473	-0.307	0.465	-0.308	0.500	-0.275	0.586	-0.228	0.558	-0.254	0.562	-0.240
8	**75m E1929962 N560963**	-1.175	-1.005	0.473	-0.275	0.465	-0.270	0.500	-0.243	0.586	-0.196	0.558	-0.218	0.562	-0.205

9	**94m E1929978 N560962**	-1.158	-1.040	0.473	-0.298	0.465	-0.290	0.500	-0.260	0.586	-0.204	0.558	-0.235	0.562	-0.230
10	**100m downstream of g**	-1.230	-1.046	0.473	-0.290	0.465	-0.290	0.500	-0.249	0.586	-0.200	0.558	-0.230	0.562	-0.236

Levels and calibration flows Summer Scenario

	Section	Minimum level (m)	Stage at zero flow (m)	Survey		Calibration 1		Calibration 2		Calibration 3		Calibration 4		Calibration 5	
				flow (m^3/s)	stage (m)	flow (m^3/s)	stage (m)	flow (m^3/s)	stage (m)	flow (m^3/s)	stage (m)	flow (m^3/s)	stage (m)	flow (m^3/s)	stage (m)
1	**8m E1929901 N5609656**	-1.144	-0.850	0.199	-0.204	0.209	-0.198	0.245	-0.167	0.314	-0.114	0.278	-0.146	0.292	-0.130
2	**18m E1929909 N560965**	-1.417	-1.050	0.199	-0.407	0.209	-0.402	0.245	-0.367	0.314	-0.320	0.278	-0.345	0.292	-0.330
3	**21m not GPSed**	-1.084	-0.930	0.199	-0.244	0.209	-0.240	0.245	-0.202	0.314	-0.156	0.278	-0.180	0.292	-0.170
4	**30m E1929921 N560965**	-1.147	-0.922	0.199	-0.237	0.209	-0.230	0.245	-0.198	0.314	-0.148	0.278	-0.178	0.292	-0.162
5	**49m E1929938 N560964**	-1.082	-0.818	0.199	-0.132	0.209	-0.126	0.245	-0.098	0.314	-0.047	0.278	-0.070	0.292	-0.058
6	**60m E1929949 N560963**	-1.071	-1.028	0.199	-0.301	0.209	-0.294	0.245	-0.262	0.314	-0.211	0.278	-0.239	0.292	-0.228
7	**61m E1929950 N560964**	-1.187	-1.040	0.199	-0.307	0.209	-0.308	0.245	-0.275	0.314	-0.228	0.278	-0.254	0.292	-0.240
8	**75m E1929962 N560963**	-1.175	-1.005	0.199	-0.275	0.209	-0.270	0.245	-0.243	0.314	-0.196	0.278	-0.218	0.292	-0.205
9	**94m E1929978 N560962**	-1.158	-1.040	0.199	-0.298	0.209	-0.290	0.245	-0.260	0.314	-0.204	0.278	-0.235	0.292	-0.230
10	**100m E1929983 N56096**	-1.230	-1.046	0.199	-0.290	0.209	-0.290	0.245	-0.249	0.314	-0.200	0.278	-0.230	0.292	-0.236

Oxygen Model parameters for Summer Scenario:

Description	Reaeration coefficient 20C (/d)	Respiration rate 20C (mg/L/d)	P/R ratio	Ratio respiration 10C apart	Reference Flow (m3/s)	RMS error (C) over 31 days
Median of calculated daily values	12.994	74.161	0.922	1.809	0.345	0.898
Mean of calculated daily values	14.196	80.815	0.921	1.758	0.349	0.941
1/01/2013	8.199	58.43	0.888	2	0.394	1.354
2/01/2013	14.379	74.668	1.032	2	0.386	1.142
3/01/2013	12.625	75.183	0.793	2	0.379	1.149

4/01/2013	19.561	105.404	0.869	2	0.387	1.140
5/01/2013	13.917	73.136	0.968	2	0.385	0.952
6/01/2013	12.672	70.023	0.966	2	0.386	0.950
7/01/2013	13.715	75.667	0.922	1.669	0.399	0.951
8/01/2013	14.592	77.765	0.988	1.809	0.38	1.062
9/01/2013	13.717	70.732	1.023	1.619	0.363	1.130
10/01/2013	12.1	60.967	1.036	1.525	0.356	1.123
11/01/2013	11.629	66.242	0.982	2	0.356	0.994
12/01/2013	11.787	67.498	0.99	1.755	0.335	1.051
13/01/2013	15.829	87.795	0.946	1.603	0.328	1.043
14/01/2013	17.46	111.833	0.842	2	0.32	1.143
15/01/2013	16.182	102.478	0.721	2	0.327	1.525
16/01/2013	11.641	66.894	0.919	2	0.334	0.899
17/01/2013	32.002	201.394	0.754	2	0.327	1.761
18/01/2013	14.495	79.206	0.864	2	0.337	1.000
19/01/2013	13.459	61.296	1.068	1.379	0.349	1.180
20/01/2013	13.201	70.505	0.962	1.523	0.351	0.965
21/01/2013	12.604	65.894	1.011	1.449	0.345	1.095
22/01/2013	12.007	68.432	1.023	1.634	0.332	1.219
23/01/2013	15.356	82.037	1.019	1.405	0.322	1.269
24/01/2013	23.989	136.769	0.828	1.507	0.316	1.383
25/01/2013	5.894	47.068	0.785	2	0.328	2.012
26/01/2013	12.819	76.735	0.931	2	0.335	0.917
27/01/2013	12.645	67.451	0.921	1.283	0.346	0.913
28/01/2013	12.965	79.435	0.901	2	0.347	0.921
29/01/2013	12.994	74.161	0.872	1.494	0.329	0.919
30/01/2013	12.933	78.061	0.857	1.494	0.319	0.972
31/01/2013	12.714	72.092	0.879	1.362	0.315	0.913
median 1/1 to 25/1 inclusive	13.715	73.136	0.962	2	0.349	

Oxygen Model parameters for Autumn Scenario:

Description	Reaeration coefficient 20C (/d)	Respiration rate 20C (mg/L/d)	P/R ratio	Ratio respiration 10C apart	Reference Flow (m3/s)	RMS error (C) over 62 days		depth m
Median of calculated daily values	14.165	65.078	0.542	1.953	0.467	**0.721**	35.27	0.55
Mean of calculated daily values	15.643	71.701	0.534	1.916	0.479	0.725		0.56
15/03/2013	12.7	74	0.557	1.878	0.332	1.140		0.45
16/03/2013	12.5	73	0.565	1.916	0.332	1.126		0.45
17/03/2013	23.4	135	0.41	2	0.341	1.282		0.46
18/03/2013	15.0	77	0.455	1.485	0.347	1.194		0.46

19/03/2013	20.0	121	0.471	2	0.355	1.254		0.47
20/03/2013	10.2	68	0.542	2	0.398	1.328		0.50
21/03/2013	10.5	61	0.546	2	0.391	0.993		0.50
22/03/2013	10.7	63	0.607	2.112	0.382	1.071		0.49
23/03/2013	11.9	61	0.61	1.938	0.386	0.952		0.49
24/03/2013	12.7	64	0.587	1.893	0.391	0.882		0.50
25/03/2013	14.6	69	0.642	1.809	0.395	1.053		0.50
26/03/2013	12.5	66	0.556	2	0.395	0.828		0.50
27/03/2013	13.0	64	0.604	1.893	0.388	0.901		0.49
28/03/2013	12.1	57	0.618	1.747	0.383	0.942		0.49
29/03/2013	14.0	67	0.601	1.846	0.385	0.882		0.49
30/03/2013	9.8	52	0.601	2	0.392	0.949		0.50
31/03/2013	13.9	67	0.619	1.864	0.393	0.946		0.50
1/04/2013	12.8	64	0.573	2	0.39	0.807		0.49
2/04/2013	13.1	61	0.575	1.619	0.399	0.846		0.50
3/04/2013	13.8	79	0.538	1.956	0.407	0.994		0.51
4/04/2013	7.5	43	0.448	1.901	0.415	1.310		0.51
5/04/2013	20.0	99	0.523	2.025	0.426	0.802		0.52
6/04/2013	11.9	60	0.538	1.898	0.443	0.769		0.53
7/04/2013	19.0	93	0.533	2.025	0.44	0.791		0.53
8/04/2013	11.4	56	0.574	1.907	0.438	0.803		0.53
9/04/2013	31.9	54	0.566	0.398	0.457	1.062		0.55
10/04/2013	11.4	59	0.564	1.926	0.469	0.803		0.55
11/04/2013	14.8	71	0.508	1.921	0.457	0.720		0.55
12/04/2013	16.9	76	0.52	1.884	0.454	0.725		0.54
13/04/2013	17.5	79	0.569	1.941	0.456	0.806		0.54
14/04/2013	13.5	63.0	0.499	1.95	0.459	**0.718**		0.55
15/04/2013	18.0	81	0.542	1.902	0.464	0.767		0.55
16/04/2013	19.0	91	0.441	2.005	0.481	0.839		0.56
17/04/2013	9.0	48	0.478	2	0.508	0.888		0.58
18/04/2013	25.8	126	0.485	2	0.505	0.904		0.58
19/04/2013	23.5	108	0.467	2	0.513	0.861		0.59
20/04/2013	24.7	109	0.39	1.926	0.52	1.038		0.59
21/04/2013	9.7	51	0.313	2	0.6	1.443		0.65
22/04/2013	14.9	70	0.424	2	0.589	0.874		0.64
23/04/2013	15.4	70	0.456	1.96	0.577	0.801		0.63
24/04/2013	20.3	89	0.532	1.921	0.565	0.857		0.62
25/04/2013	30.8	122	0.443	1.874	0.56	1.041		0.62
26/04/2013	22.7	92	0.505	1.941	0.561	0.916		0.62
27/04/2013	14.3	61	0.605	2	0.553	0.896		0.61
28/04/2013	12.2	51	0.577	1.995	0.552	0.844		0.61
29/04/2013	15.7	62	0.539	1.985	0.548	0.875		0.61
30/04/2013	27.4	105	0.576	1.97	0.543	1.073		0.61
1/05/2013	13.6	53	0.648	1.97	0.549	1.037		0.61
2/05/2013	13.3	52	0.543	1.921	0.547	0.862		0.61
3/05/2013	15.8	63	0.525	1.99	0.542	0.862		0.61
4/05/2013	12.8	52	0.591	2	0.548	0.892		0.61

5/05/2013	15.4	67	0.477	2.071	0.56	0.813	0.62
6/05/2013	22.2	98	0.445	2.102	0.567	0.924	0.62
7/05/2013	15.0	64	0.535	2.113	0.571	0.835	0.63
8/05/2013	11.7	47	0.556	1.941	0.58	0.863	0.63
9/05/2013	13.2	56	0.599	2.04	0.586	0.892	0.64
10/05/2013	14.9	63	0.509	1.771	0.584	0.762	0.64
11/05/2013	15.9	67	0.57	2.06	0.578	0.877	0.63
12/05/2013	11.9	47	0.56	1.901	0.578	0.876	0.63
13/05/2013	11.8	48	0.522	1.755	0.578	0.790	0.63
14/05/2013	18.6	75	0.533	1.98	0.586	0.903	0.64
15/05/2013	15.6	62	0.598	1.941	0.584	0.949	0.64

Awanui Stream at Flume

SEFA version 1.2 25/08/2014

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Awanui at Flume surveyed 26/4/2012 calibration 7/5, 16/5, 29/5, 7/6

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Reach length: 108.500 m

Single channel reach with 10 cross-sections

Habitat mapped reach with weights summing to 100.000%

Survey details

The reach was surveyed at a flow of 0.057 m³/s

The average characteristics were:

Width (m)	Depth (m)	Velocity (m/s)	R	B	C	G	F	S	M	V
5.21	0.642	0.022	0.00	1.47	0.00	0.09	0.00	0.62	44.16	53.65

Cross-section details

Section	Name	Distance m	Weight	Habitat type	XStart	YStart	XEnd	YEnd	Channel	Comment
1	0m upstream of tower	0.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
2	9m E1925636 N5599618	9.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
3	19m E1925627 N559961	19.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
4	30m E1925615 N559960	30.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
5	31m E1929938	31.000	0.1000		0.00	0.00	0.00	0.00	Single channel	

	N560964									
6	32m E1925615 N559960	32.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
7	57m E1925595 N559959	57.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
8	89m E1925567 N559958	89.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
9	92m E1925564 N559957	92.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
10	100m upstream of to	100.000	0.1000		0.00	0.00	0.00	0.00	Single channel	

Rating curves

	Section	Selected rating	Exponent	Constant	Zero	R2	Mean error in Q %
1	0m upstream of tower	SZF rating	1.582	4.725	-0.823	0.997	2.815
2	9m E1925636 N5599618	SZF rating	1.562	4.462	-0.703	0.996	5.742
3	19m E1925627 N559961	SZF rating	1.672	5.459	-0.373	0.997	4.735
4	30m E1925615 N559960	SZF rating	1.687	5.029	-0.414	0.995	5.680
5	31m E1929938 N560964	SZF rating	1.765	5.745	-0.442	0.995	4.060
6	32m E1925615 N559960	SZF rating	1.685	4.883	-0.436	0.993	6.025
7	57m E1925595 N559959	SZF rating	1.998	7.623	-0.544	0.989	5.236
8	89m E1925567 N559958	SZF rating	2.298	10.753	-0.468	0.994	4.409
9	92m E1925564 N559957	SZF rating	2.388	11.765	-0.319	0.990	6.367
10	100m upstream of to	SZF rating	2.338	10.517	-0.531	0.987	6.127

Levels and calibration flows

	Section	Minimum level (m)	Stage at zero flow (m)	Survey		Calibration 1		Calibration 2		Calibration 3		Calibration 4	
				flow (m^3/s)	stage (m)	flow (m^3/s)	stage (m)	flow (m^3/s)	stage (m)	flow (m^3/s)	stage (m)	flow (m^3/s)	stage (m)
1	**0m upstream of tower**	-1.462	-0.823	0.057	-0.762	0.074	-0.746	0.069	-0.754	0.127	-0.723	0.286	-0.654
2	**9m E1925636 N5599618**	-1.672	-0.703	0.057	-0.642	0.074	-0.624	0.069	-0.630	0.127	-0.600	0.286	-0.536
3	**19m E1925627 N559961**	-1.258	-0.373	0.057	-0.308	0.074	-0.292	0.069	-0.296	0.127	-0.269	0.286	-0.204
4	**30m E1925615 N559960**	-1.324	-0.414	0.057	-0.344	0.074	-0.324	0.069	-0.332	0.127	-0.301	0.286	-0.236
5	**31m E1929938 N560964**	-1.369	-0.442	0.057	-0.369	0.074	-0.350	0.069	-0.360	0.127	-0.326	0.286	-0.263

6	**32m E1925615 N559960**	-1.285	-0.436	0.057	-0.365	0.074	-0.344	0.069	-0.353	0.127	-0.322	0.286	-0.255
7	**57m E1925595 N559959**	-1.298	-0.544	0.057	-0.458	0.074	-0.438	0.069	-0.450	0.127	-0.420	0.286	-0.350
8	**89m E1925567 N559958**	-1.396	-0.468	0.057	-0.366	0.074	-0.350	0.069	-0.359	0.127	-0.328	0.286	-0.259
9	**92m E1925564 N559957**	-1.172	-0.319	0.057	-0.212	0.074	-0.198	0.069	-0.209	0.127	-0.176	0.286	-0.103
10	**100m upstream of to**	-1.464	-0.531	0.057	-0.424	0.074	-0.404	0.069	-0.417	0.127	-0.386	0.286	-0.315

Oxygen Model parameters for Summer Scenario:

Description	Reaeration coefficient 20C (/d)	Respiration rate 20C (mg/L/d)	P/R ratio	Ratio respiration 10C apart	Reference Flow (m3/s)	RMS error (C) over 43 days
Median of calculated daily values	5.46	48.573	0.59	1.791	0.096	2.309
Mean of calculated daily values	6.132	52.194	0.628	1.745	0.106	2.410
29/11/2012	3.526	30.969	0.902	0.989	0.133	3.806
30/11/2012	4.122	25.722	0.951	1.562	0.145	4.178
1/12/2012	3.793	33.855	0.988	1.895	0.12	4.674
2/12/2012	9.787	58.014	0.515	2	0.121	2.475
3/12/2012	5.104	40.092	0.886	1.805	0.119	3.868
4/12/2012	7.584	50.783	0.678	1.805	0.106	2.769
5/12/2012	5.1	40.637	0.868	1.582	0.119	3.726
6/12/2012	7.204	52.059	0.72	2	0.129	2.902
7/12/2012	4.255	39.116	0.893	1.791	0.14	3.940
8/12/2012	5.809	46.219	0.839	1.805	0.211	3.800
9/12/2012	5.18	40.646	0.986	1.715	0.225	5.083
10/12/2012	3.702	37.644	0.959	1.572	0.173	4.685
11/12/2012	9.901	77.98	0.654	2	0.135	2.989
12/12/2012	3.065	36.877	0.726	2	0.120	2.695
13/12/2012	3.94	41.59	0.907	1.702	0.139	4.257
14/12/2012	5.162	43.16	0.849	1.232	0.147	3.644
15/12/2012	5.257	47.336	0.867	1.016	0.236	4.257
16/12/2012	6.183	41.539	0.946	1.381	0.247	4.585
17/12/2012	4.638	44.323	0.824	1.975	0.121	3.482
18/12/2012	5.709	45.629	0.684	1.886	0.146	2.551
19/12/2012	6.32	50.699	0.695	1.71	0.102	2.709
20/12/2012	5.147	49.004	0.739	2.172	0.072	2.914
21/12/2012	7.233	64.696	0.59	1.536	0.067	2.463
22/12/2012	11.797	93.959	0.373	2	0.067	2.796
23/12/2012	9.31	74.334	0.305	2.286	0.071	3.109

24/12/2012	8.471	72.95	0.223	1.525		0.077	3.924
25/12/2012	6.146	54.037	0.372	1.778		0.084	3.009
26/12/2012	8.617	73.948	0.372	1.26		0.096	3.008
27/12/2012	9.731	76.414	0.105	1.544		0.091	4.850
28/12/2012	6.318	57.115	0.463	1.593		0.088	2.549
29/12/2012	9.303	77.881	0.34	1.345		0.083	3.054
30/12/2012	4.238	35.632	0.386	2		0.076	2.968
31/12/2012	6.478	52.445	0.429	2.32		0.068	2.539
1/01/2013	3.985	39.776	0.418	2		0.058	2.832
2/01/2013	8.012	72.523	0.447	1.463		0.056	2.506
3/01/2013	10.153	90.484	0.344	0.967		0.053	2.885
4/01/2013	6.964	64.843	0.459	1.479		0.051	2.459
5/01/2013	5.46	54.521	0.557	1.938		0.047	2.350
6/01/2013	4.666	48.573	0.548	2.344		0.049	2.310
7/01/2013	5.178	49.651	0.556	1.681		0.053	2.338
8/01/2013	4.75	45.425	0.463	2.052		0.049	2.483
9/01/2013	3.384	39.406	0.589	2.121		0.045	2.346
10/01/2013	2.995	31.847	0.589	2.189		0.04	2.537
median excl rapid flow fluct	6.318	54.037	0.463	1.895		0.071	27

Irongate Stream at Clark's weir

SEFA version 1.2 25/08/2014
File: M:\E_Science\Projects\311 SW R&I Hydro\600_Karamu\01 IFIM\Analysis\oxygen\Irongate analysis\Irongate.rhbx
Irongate at Clarks Weir surveyed 1/5/2013 by Thomas Wilding and Stacey Fraser, calibration 7/5, 31/5, 17/7. XS distances are upstream of recorder tower.
File creator: tkwilding - Hawkes Bay Regional Council
Imported from file: C:\Users\thomas\Documents\Temp\Irongate.rhb
Imported from file: Irongate
Reach length: 88.500 m
Single channel reach with 10 cross-sections
Habitat mapped reach with weights summing to 100.000%

Survey details
The reach was surveyed at a flow of 0.058 m^3/s
The average characteristics were:

Width (m)	Depth (m)	Velocity (m/s)	R	B	C	G	F	S	M	V
3.92	0.206	0.053	0.00	0.00	1.43	3.26	0.00	0.00	63.14	32.17

Cross-section details

Section	Name	Distance m	Weight	Habitat type	XStart	YStart	XEnd	YEnd	Channel	Comment
1	6A E1926747 N5605028	6.000	0.1000		0.00	0.00	0.00	0.00	Single channel	

2	8B E1926749 N5605029	8.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
3	25C E1926732 N560504	25.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
4	27D E1926744 N560504	27.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
5	29E E1926745 N560504	29.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
6	34F E1926739 N560505	34.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
7	39G E1926740 N560505	39.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
8	63H E1926739 N560508	63.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
9	68I E1926740 N560508	68.000	0.1000		0.00	0.00	0.00	0.00	Single channel	
10	85J E1926739 N560510	85.000	0.1000		0.00	0.00	0.00	0.00	Single channel	

Rating curves

	Section	Selected rating	Exponent	Constant	Zero	R2	Mean error in Q %
1	6A E1926747 N5605028	SZF rating	1.593	4.314	-0.639	1.000	1.921
2	8B E1926749 N5605029	SZF rating	1.603	4.433	-0.678	0.999	4.338
3	25C E1926732 N560504	SZF rating	1.597	4.065	-0.502	1.000	1.057
4	27D E1926744 N560504	SZF rating	1.600	4.003	-0.521	1.000	1.916
5	29E E1926745 N560504	SZF rating	1.634	4.379	-0.516	1.000	2.673
6	34F E1926739 N560505	SZF rating	1.584	3.672	-0.471	0.999	2.654
7	39G E1926740 N560505	SZF rating	1.531	3.071	-0.549	0.998	5.529
8	63H E1926739 N560508	SZF rating	1.639	3.187	-0.460	0.998	4.609
9	68I E1926740 N560508	SZF rating	1.679	3.314	-0.468	0.999	3.697
10	85J E1926739 N560510	SZF rating	1.788	3.386	-0.533	0.999	4.135

Levels and calibration flows

	Section	Minimum level (m)	Stage at zero flow (m)	Survey	Calibration 1	Calibration 2	Calibration 3

				flow (m³/s)	stage (m)	flow (m³/s)	stage (m)	flow (m³/s)	stage (m)	flow (m³/s)	stage (m)
1	6A E1926747 N5605028	-0.972	-0.639	0.058	-0.572	0.080	-0.556	0.130	-0.531	0.584	-0.352
2	8B E1926749 N5605029	-0.991	-0.678	0.058	-0.611	0.080	-0.602	0.130	-0.570	0.584	-0.391
3	25C E1926732 N560504	-0.762	-0.502	0.058	-0.432	0.080	-0.416	0.130	-0.388	0.584	-0.204
4	27D E1926744 N560504	-0.720	-0.521	0.058	-0.450	0.080	-0.436	0.130	-0.406	0.584	-0.218
5	29E E1926745 N560504	-0.715	-0.516	0.058	-0.445	0.080	-0.432	0.130	-0.403	0.584	-0.221
6	34F E1926739 N560505	-0.708	-0.471	0.058	-0.398	0.080	-0.382	0.130	-0.344	0.584	-0.163
7	39G E1926740 N560505	-0.754	-0.549	0.058	-0.474	0.080	-0.454	0.130	-0.412	0.584	-0.222
8	63H E1926739 N560508	-0.733	-0.460	0.058	-0.373	0.080	-0.352	0.130	-0.309	0.584	-0.114
9	68I E1926740 N560508	-0.778	-0.468	0.058	-0.378	0.080	-0.356	0.130	-0.317	0.584	-0.119
10	85J E1926739 N560510	-0.840	-0.533	0.058	-0.430	0.080	-0.406	0.130	-0.365	0.584	-0.166

Oxygen Model parameters for Summer Scenario:

Description	Reaeration coefficient 20C (/d)	Respiration rate 20C (mg/L/d)	P/R ratio	Ratio respiration 10C apart	Reference Flow (m3/s)	RMS error (C) over 8 days
Median of calculated daily values	3.516	35.793	0.542	3.889	0.024	1.807
Mean of calculated daily values	4.28	39.256	0.544	6.713	0.023	1.413
15/02/2013	4.609	43.254	0.589	4.911	0.024	1.321
16/02/2013	2.205	29.016	0.55	22.762	0.024	2.224
17/02/2013	8.174	62.062	0.467	2	0.024	1.527
18/02/2013	8.274	58.471	0.561	2	0.025	1.323
19/02/2013	2.424	31.712	0.535	9.098	0.025	2.555
20/02/2013	4.834	39.874	0.526	2.868	0.023	1.382
21/02/2013	2.225	27.697	0.519	8.064	0.021	2.495
22/02/2013	1.492	21.963	0.604	2	0.021	3.024

Appendix B Minimum flow report 1990

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AGENDA ITEM

HAWKE'S BAY REGIONAL COUNCIL

PLANNING AND POLICY STANDING COMMITTEE

11 JULY 1990

SUBJECT : MINIMUM LOW FLOWS : KARAMU STREAM CATCHMENT

INTRODUCTION:

Water rights holders taking surface water from a stream are granted the right subject to a special condition to abstract water until the stream reaches a certain flow at which time the right holder is required to cease abstraction. This flow at which all abstractions must cease is termed the minimum low flow.

The aim of setting minimum low flows on streams is to protect the instream values and is used in managing the allocation of the water resource between instream users and consumptive users.

Water rights from the Karamu catchment are reviewed every 10 years and all expire in 1990 or 1991. Horticultural development on the Heretaunga Plains has increased over the last 10 years and the potential exists for further development. This has resulted in pressure on the surface water resource and the minimum low flows are an attempt to protect this resource and allocate it fairly.

EXISTING MINIMUM LOW FLOW SITES IN THE KARAMU CATCHMENT

SITE	MINIMUM LOW FLOW l/s	SITE NO.
Karamu Stream at Floodgates	1100	23138
Mangateretere at Napier Road	100	1023112
Louisa Stream at School Road	30	1123110
Irongate Stream at Clark's Weir	100	23169
Awanui Stream at Crystal Road	120	23137

THE KARAMU STREAM SYSTEM AND INSTREAM USERS:

The Karamu Stream drains the southern Heretaunga Plains and flows into the Clive River (see map).

The Karamu river system supports an important fishery and plays an important role in the migratory pathway of many species including whitebait, eels and trout as well as providing access to the suitable spawning and rearing streams such as the Mangateretere and Karewarewa.

All tributaries of the Karamu have been investigated with the Hawke's Bay Acclimatisation Society, and the relative importance of each tributary confirmed.

THE KARAMU STREAM

The Karamu Stream provides access to the suitable spawning and rearing streams such as Mangateretere for trout populations. The instream values of the Karamu Stream itself decline over the summer months due to de-oxygenation. This occurs due to a number of factors including intense weed growth, and high temperature. Maintaining a reasonable flow over the drier summer months can help in alleviating the deterioration in water quality caused by the deoxygenation of the stream.

The existing minimum low flow of 1100 l/s as measured at site 23138 is satisfactory in maintaining the present values of the stream; however, the measuring site is not satisfactory due to dense weed growths. This creates problems in obtaining accurate low flow measurements. Unfortunately, any modifications to this site would require substantial expenditure; however, it is important that this be considered.

THE MANGATERETERE STREAM:

The Mangateretere Stream drains through a predominantly pip and stone fruit developed area. This stream is of very high value providing habitat under low flow conditions that is lost in many of the other streams. The Mangateretere is a spring fed stream thereby maintaining low temperatures and a reasonable flow in times of very hot and dry conditions. Fish species present in this stream include common smelt, eels, common bullies and rainbow trout. It provides good spawning habitat for Rainbow trout.

Over recent years habitat has been lost with the loss of gravels perhaps due to constant mechanical clearance causing an increase in the silt load of the stream. Due to this gradual decline in habitat, the increasing use of the surface water and the high instream values of this stream a minimum low flow of 130 l/s (as measured at site No.1023112) would be more acceptable to maintain the existing values.

THE LOUISA STREAM

The Louisa Stream is protected by an existing minimum low flow figure of 30 l/s measured at School Road (Site No.1123110). Fish populations found in this stream include inanga (whitebait), eels, common smelt, and common carp. To protect this fishery it would be more satisfactory to set the minimum low flow of 30 l/s at Te Aute Road (Site No.1023110)

THE AWANUI STREAM

The Awanui Stream supports fish populations of inanga (whitebait), eels, common smelt, and common carp.

The water quality of the Upper Awanui Stream deteriorates over the summer months with deoxygenation occurring due to high water temperatures and low flows. This has resulted in a number of fish kills being observed in the past.

The existing minimum low flow of 120 l/s measured at Crystal Road (Site No.23137) is satisfactory in protecting the downstream values; however, to protect the water quality of the Upper Awanui Stream an additional minimum low flow of 35 l/s should be measured at Site No.23136 (PakiPaki culvert).

THE IRONGATE STREAM

The Irongate Stream flows through predominantly pasture, pip and stone fruit orchards and the Omahu Road industrial area. The stream supports populations of common smelt, inanga (whitebait), eels, common carp, and Rainbow trout. During recent years there has been an apparent decline in water clarity during low flow periods. Stock access and industrial development have resulted in downstream siltation problems contributing to the loss of good quality habitat and trout spawning substrate. To maintain the existing values a minimum flow of 100 l/s measured at Clerk's Weir (Site No.23169) would be more practical. However, the siltaton problem needs to be investigated to determine whether measures should be taken to prevent further reduction in in-stream ecology.

THE KAREWAREWA STREAM

The Karewarewa Stream provides good habitat for inanga (whitebait), smelt, eels, and common carp and also provides spawning substrate for trout during Winter. There is presently no existing minimum low flow on this stream and the upper section dries partially or completely must summers. To protect this habitat and attempt to maintain a reasonable flow during low flow periods it would be appropriate to establish a minimum low flow of 75 l/s as measured at Turamoe Road (Site No.1023150).

THE HEREHERE AND MANGARAU STREAMS

The Herehere and Mangarau Streams both have concrete drainage structures that provide major fish barriers to the upper waters. Sections below these barriers provide good habitat for inanga, common smelt and eels with good rainbow trout spawning areas in the Mangarau below the Te Aute Road section. However, natural flows are very low (<15 l/s) and it is not practical to enforce blanket restrictions on these streams.

THE TE WAIKAHA STREAM

The Te Waikaha Stream does not have an existing minimum low flow; however, this stream provides a base flow to the Louisa Stream and supports populations of inanga, eels, common smelt and common carp. It would be appropriate to restrict abstraction in this stream when the flow measured at Mutiny Road records 25 l/s.

OTHER STREAMS AND DRAINS

Other streams in the Karamu System include :-

Southland Drain, Awahau, Ruahapia, Karituwhenua and Te Kahika Streams.

These resources have minimal in-stream values and no specific minimum low flows are necessary in these cases.

RECOMMENDATION:

That it be recommended to the Regional Council that :

i. Water Rights to take from streams within the Karamu Stream Catchment be subject to a special condition requiring taking to cease in order to maintain the following minimum low flows.

Stream	Site No.	Flow l/s
Karamu	23138	1100
Mangateretere	1023112	130
Louisa	103110	30
Awanui	23137	120
Awanui	23136	35
Karewarewa	1023148	75
Irongate	23169	100
Te Waikaha	1023107	25

ii. Provision be made within special conditions on those rights subject to a minimum of 1100 l/s on the Karamu Stream (Site No.23138), to have the site of the minimum flow measurement re-located during the term of the right.

S. E. Porter,
ECOLOGIST

I. H. Cairns,
DIRECTOR: RESOURCE MANAGEMENT