Spatial oxygen-flow models for streams of the Heretaunga Plains

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Environmental Science - Hydrology

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Executive summary

Water is taken from streams and aquifers for irrigation, industry and town supply. Hawke's Bay Regional Council manages freshwater resources to protect fish and other stream life that depend on water to survive. Deciding how much water should be allocated, and when takes should be subject to restrictions, requires information on flows required to protect stream ecosystems. For many Heretaunga streams, dissolved oxygen will be exhausted before the streams run dry. Hence this report examines the impact of reduced stream flow on oxygen saturation, focussing on how flow requirements for oxygen vary spatially across the riverscape.

Model development followed ELOHA (Ecological Limits of Hydrologic Alteration), which provides a framework for developing flow-ecology methods that can be applied at a regional extent to assess many streams and rivers simultaneously, within a hydrogeomorphic template. A Generalized Oxygen Model was successfully developed for low-gradient streams of the Heretaunga Plains. The model uses Froude number to predict oxygen, with oxygen measured as daily minimum oxygen saturation at multiple sites on 21 January 2015. Froude number increases with velocity and decreases with depth; so is smaller for slow, deep pools. In terms of flow management, the use of Froude number demonstrates that the same flow will produce less oxygen in streams with a flatter gradient and a larger channel.

The model predictions were tested against a second set of dawn oxygen measurements (total 50 sites sampled across 5 occasions between 2013 and 2015). The validation data produced a similar rate of decline in oxygen saturation with Froude number, and indicated that the Generalized Oxygen Model was predicting annual minima, rather than typical summer conditions. Validity of the Generalized Oxygen Model was also supported by time-series data from Awanui Stream. The accuracy of model predictions is dependent on accurate estimates of Froude number, including the depth and velocity estimates used to calculate Froude number. Other models should be used instead of poor estimates of Froude number, such as the more conservative slope-threshold (2 m/km) for screening streams that are more likely to experience low-oxygen.

In my opinion, the Generalised Oxygen Model is suitable for guiding the selection of minimum flow sites (i.e. monitoring sites for triggering restrictions on water use). A prioritised list of potential monitoring sites is presented for each sub-catchment on the Heretaunga Plains (see Appendix B), which is intended to inform decisions by stakeholders or regulators. Priority was given to sites that better represent the reaches at risk of low oxygen and with the highest water demand. The flexibility of a prioritised list allows sites to be added in future, as water demand increases. That flexibility also allows stakeholders to choose lower priority sites based on other criteria (e.g. higher instream values).

The effect of aquatic plants and riparian shade on the oxygen-flow relationship was also investigated. Riparian shading that reduces solar access to less than 30% of the November-April maximum is expected to reduce aquatic plant growth and improve oxygen supply from the water to fish. Complimentary methods for controlling aquatic plants are also discussed. Other benefits of shading riparian vegetation were not investigated for this report, such as reduced water temperatures in small streams. Decreased water temperatures reduce the oxygen demand for fish survival (requirements for cellular respiration). Hence, both flow management and riparian management can be applied to ensure oxygen supply from the water exceeds oxygen demand for fish survival.

1 Introduction

1.1 Background

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 (HBRC) manages freshwater resources under its Regional Resource Management Plan. Deciding how much water should be allocated, and when takes should be subject to restrictions, requires information on flows required to sustain stream ecosystems.

Stream flow requirements for aquatic ecosystems may depend on various factors, including water temperature, oxygen saturation and water depth (Allen & Hay, 2011). This report examines the impact of reduced stream flow on oxygen saturation, focussing on how flow requirements for oxygen vary spatially across the riverscape.

The term "oxygen" is used throughout this report to refer to O_2 gas dissolved in water, measured as percent saturation. 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). Oxygen diffuses into water from the atmosphere in a process called reaeration. Reducing the flow of water can decrease reaeration in some low-gradient streams.

This study focuses on low-gradient single-thread streams of the Heretaunga Plains. The Heretaunga Plains have a maritime-temperate climate, with about 800 mm of rainfall, and about 2150 sunshine hours per year (Chappell, 2013). The seasonality of rainfall is small compared to the high evaporation rates through summer that increase water demand for irrigation. Most irrigation water is sourced from groundwater. Intensive development of the Heretaunga gravel aquifers 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 aquifers. Artesian pressure produces springs through openings in the confining clays.

In addition to these point-source springs, diffuse springs seep through streambeds along the boundary between the confined and unconfined aquifers. The flow of some streams on the Heretaunga Plains is spring dominated, including the Raupare, Irongate, Mangateretere and Tutaekuri-Waimate Streams (Wilding & Waldron, in prep.). The depletion of stream flows by groundwater use is being investigated by Hawke's Bay Regional Council in a parallel study of the Heretaunga gravel aquifers. Springs arising from limestone in the surrounding hill-country flow into the Awanui Stream. However, the Awanui would not be described as spring-dominated because the limestone springs represent a small proportion of annual flow (all streams are groundwater fed, few are groundwater dominated).

Streams on the Heretaunga Plains are characterized by low-gradient channels that support high abundances of aquatic plants, and these characteristics increase the risk of oxygen stress (Wilding *et al.*, 2012). Invertebrate monitoring indicates that conditions are degraded at many sites in the Karamu catchment (HBRC, 2014). Haidekker (2016) demonstrated that inadequate oxygen, together with elevated temperatures, have constrained macroinvertebrate communities in the Karamu catchment.

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 instream flows as a basis for water allocation and to trigger irrigation restrictions.

A previous report examined the site-specific relationships between oxygen concentration and flow, based on intensive study of three sites in the Karamu catchment: Raupare, Awanui and Irongate (Wilding, 2015).

Setting minimum flows for these three sites will provide a level of protection for aquatic ecosystems at those locations. A question arising is how representative are those three sites of all streams across the Heretaunga Plains? It is not feasible for Hawke's Bay Regional Council to conduct intensive studies of oxygen-flow relationships for every stream reach affected by water takes. It is also not realistic to provide ongoing monitoring and enforcement of minimum flow requirements for every stream reach. A few sites are therefore selected to provide adequate representation of the consequences of water use for instream oxygen saturation.

The aim of this investigation is to inform policy development for instream flow requirements across the Heretaunga Plains. In meeting that aim, the primary objective of this report is to examine how oxygen stress varies across the riverscape. There are many possible applications for an oxygen-flow model. Applications provided in this report focus on informing policy development, including the selection of representative minimum flow sites for streams of the Heretaunga Plains. Other applications for the model are discussed, including better informed limit-setting for oxygen in low-gradient streams. Flow is not the only management variable that can constrain oxygen supply, and hence the effect of riparian shading and aquatic plants on oxygen supply were also investigated to help understand their interactions with flow management.

1.2 Oxygen and Stream Flow

Fish and aquatic 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, it is important to understand the processes that determine how much oxygen is available to stream life.

This report examines only gaseous oxygen that is dissolved in water (dissolved O_2 or DO), rather than dissolved oxygen that is bound to other compounds (e.g. CO_2, NO_3^-, H_2O). 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 at sea level (21% of mean 1013 hPa). But oxygen diffuses through water about 10,000 times slower than through air. This is why water movement and mixing is important for distributing oxygen through the water column (Cox, 2003). The management variables that affect water movement, such as flow, are therefore important for managing oxygen supply.

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 oxygen demand surpasses the increasing oxygen supply (Verberk *et al.*, 2011). The management variables that affect water temperature, such as riparian shading, are therefore important for managing oxygen demand.

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 (Figure 1-1). As a result, streams dominated by aquatic plants and algae can fluctuate from oxygen super-saturation by day (photosynthesis minus respiration) to hypoxic conditions at night (minus respiration).

The diffusion of oxygen from the atmosphere to stream water is termed reaeration (Odum, 1956). The more reaeration, the better the stream's ability to offset oxygen consumed by aquatic plants and sediment microbes. Reaeration is directly relevant to this investigation because reducing the flow of water can decrease reaeration in some low-gradient streams. The ability of a stream to reaerate oxygen from the atmosphere, during periods of oxygen depletion, can be quantified using the reaeration coefficient. The net amount of oxygen that moves from air to water per hour is the reaeration rate. This rate depends both on the reaeration coefficient and the oxygen deficit (deficit relative to the equilibrium saturation). For example, the reaeration coefficient of a stream could remain the same over the period of a week, but the reaeration rate will increase each night in response to the oxygen deficit created by respiring plants. Streams with waterfalls, rapids and riffles have a higher reaeration coefficient than low-gradient streams. For the low-gradient streams, the reaeration coefficient can increase with water velocity (Cox, 2003). Reduced flow can reduce water velocity, as can the growth of aquatic plants that increases channel roughness (Champion & Tanner, 2004; Wilcock *et al.*, 1999).

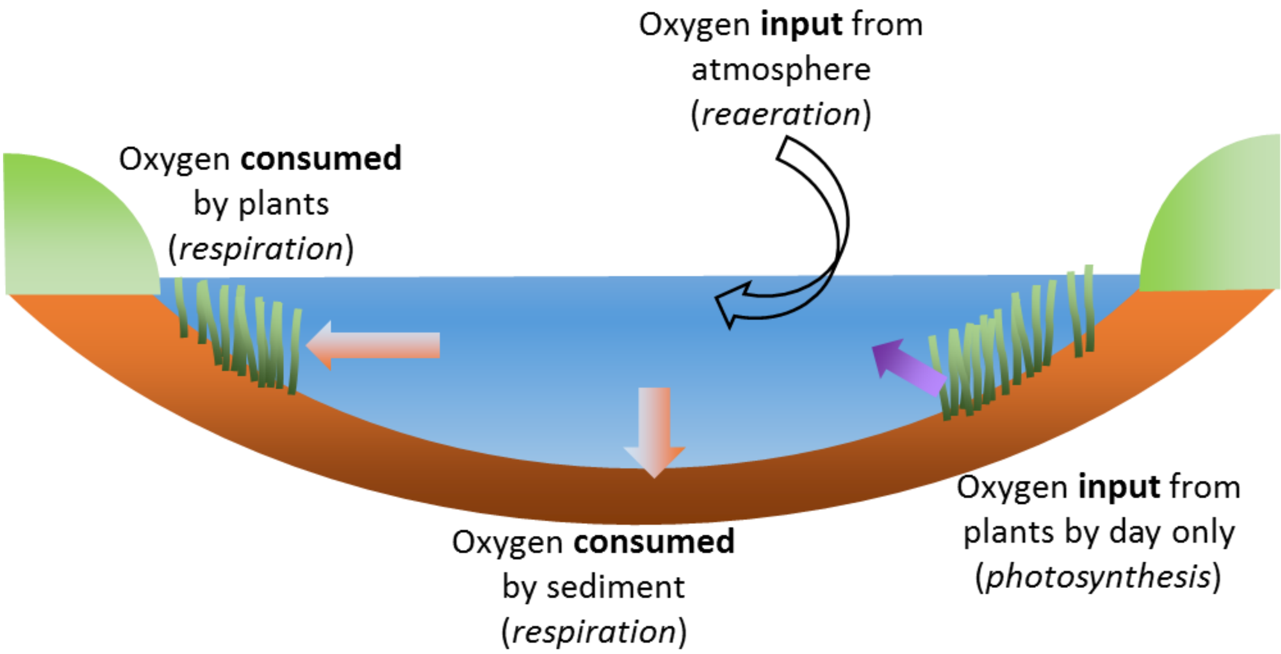

Figure 1-1: Oxygen inputs and outputs for streams. The atmosphere provides the main input of oxygen (termed "reaeration"). At night, oxygen inputs from plant photosynthesis stops, and plants continue to consume oxygen (termed "respiration"). The sediment also consumes oxygen day and night, as microbes break down organic matter (respiration). The balance of inputs and outputs will determine oxygen supply to fish.

Groundwater also affects oxygen saturation in streams of the Heretaunga Plains, both negatively and positively. The effect on oxygen can be negative at the spring source because groundwater often has little or no oxygen (Hall & Tank, 2005). The groundwater input then transitions to a positive effect at some distance downstream of the discharge because of increased flow, which can increase reaeration. That distance downstream, over which the water transitions to a new equilibrium oxygen saturation, 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 within 400 m downstream of anoxic groundwater discharge (Internal Files 1). The beneficial effects of spring inputs also include cooler water temperatures for fish in summer (spring water emerges at 14 °C to 15 °C during summer). Management of groundwater use is therefore an important component of managing stream flows for oxygen.

Riparian shade is a management variable for Hawke's Bay Regional Council, as is flow. There are important links between flow management, riparian management and oxygen for fish. These links are portrayed in

Figure 1-2, which relates those management variables to fish response using the concepts of *oxygen supply* from the water and *oxygen demand* for cellular respiration proposed by Verberk *et al.* (2011). Flow management is the reason for this report, so investigations were focussed on drivers of oxygen supply. Riparian management is not the focus of this report, beyond its effect on oxygen supply. However, riparian shading is important for managing oxygen demand, because demand increases with temperature (Clarke & Fraser, 2004). Climate and riparian shading are expected to be the primary constraints on stream temperature for small, low-gradient streams (Bartholow, 1989; Poole & Berman, 2001). Flow can also affect temperature, but the effect is relatively small in streams that are narrow enough to be shaded by riparian vegetation.

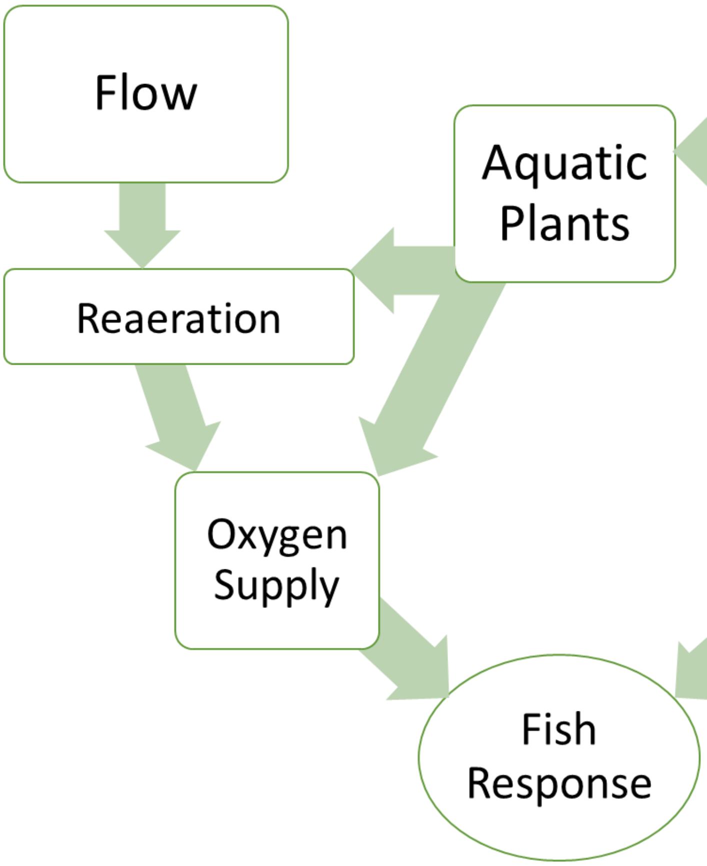

Figure 1-2: Managing oxygen supply to exceed demand. Survival of fish depends on *Oxygen Supply* from the water exceeding *Oxygen Demand* for cellular respiration. Management variables that affect oxygen demand include riparian shading, which decreases temperature and, consequently, demand. Management variables that affect oxygen supply include flow, which affects reaeration. Aquatic plants add complexity to the interaction between riparian management and flow management, by reducing reaeration of oxygen, as well as directly consuming and producing oxygen. While simplified, this diagram demonstrates the importance of both flow management and riparian management in determining the biological response.

This investigation focuses on streams where aquatic plants are significant consumers of oxygen. It is important to note that other drivers can dominate oxygen dynamics in other rivers. Oxygen saturation is affected by chemical and biological oxygen demand. For example, oxygen decreases downstream of point discharges of sewage effluent because of the decomposition of organic waste by bacteria. Some dissolved chemicals also consume oxygen, such as the oxidation of ammonium to nitrate.

Aquatic plants and decomposing plant material are now likely to be the main consumers of oxygen for most streams of the Heretaunga Plains. That was not always the case. At the time of a 1957 oxygen study, the Karamu River was subject to point discharges downstream of Havelock North (MOW, 1957). Oxygen was decreased by bacteria consuming organic pollutants from meatworks, woolscourers (Whakatu and Tomoana), sewage (Havelock North) and a sausage casing factory (Mangateretere). At that time, point discharges were a more critical management variable for oxygen supply (compared to flow).

1.3 Study Design - Developing Regional Methods for Oxygen

Selecting the scale of Investigation

Conventionally, the relationship between oxygen and flow has been investigated using site-specific process models (e.g. SEFA, night-time reaeration) (Chapra & DiToro, 1991; Jowett *et al.*, 2014). Those process models are intensive, requiring oxygen monitoring data for each site to estimate photosynthesis, reaeration and respiration, together with hydraulic modelling. The cost of such process models has limited their application to just three stream reaches (Wilding, 2015), out of the hundreds of reaches on the Heretaunga Plains.

With thousands of water takes spread across the Heretaunga Plains (HBRC, 2014), intensive studies for each individual take are not practical. Hawke's Bay Regional Council manages the use of water throughout the Hawke's Bay region, and this management is not confined to one stream, one species or one diversion. Therefore, flow-ecology methods need to be appropriate for the larger scale of flow management (Figure 1-3). ELOHA (Ecological Limits of Hydrologic Alteration) provides a framework for developing flow-ecology methods that can be applied at a regional extent to assess many streams and rivers simultaneously (Poff *et al.*, 2010). For example, the ELOHA framework was implemented at the catchment scale in Colorado to assist the state government planning for increasing water demand (Sanderson *et al.*, 2011). To inform flow management across the Heretaunga Plains, method development for this report followed the ELOHA framework. Flow-ecology methods developed at that scale can be termed "regional flow-ecology methods" (Wilding, 2012). The scale of a study can be defined in terms of the *extent* and the *grain* (Guisan & Thuiller, 2005; Wiens, 1989). This study extends across the Heretaunga Plains, which defines the study extent. Within the plains, the stream reach is an appropriate sample unit and hence defines the grain (a reach is typically delimited by tributaries, as detailed in Section 2.1). That larger scale of investigation is in contrast to conventional process models, where a channel cross-section is the grain for a reach extent (Wilding, 2015).

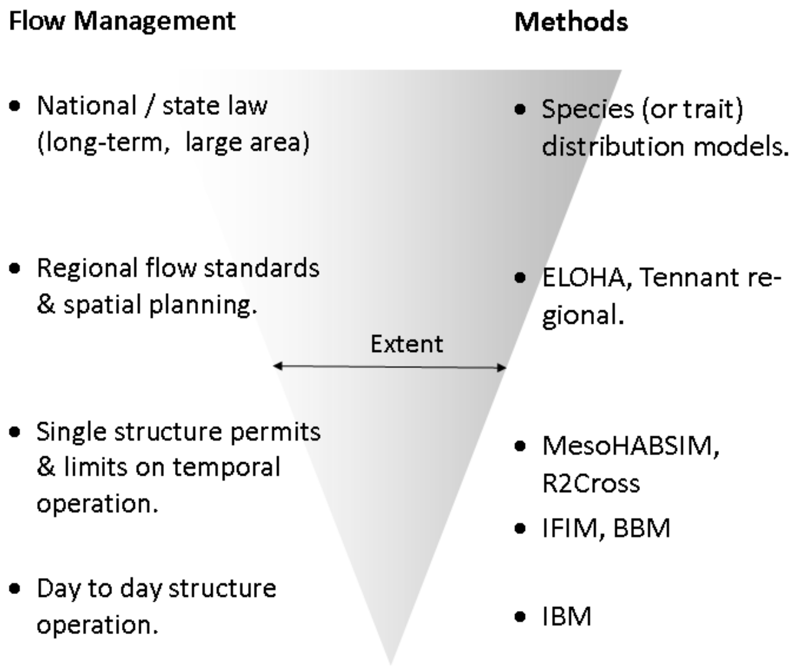

Figure 1-3: Matching the scale of flow-ecology investigations to the scale of water management. From Wilding (2012), this places flow-ecology methods and flow-management within a hierarchical framework. On the management side, this portrays the laws that constrain local decisions on individual structures, and so on. The methods used should reflect the scale of management under consideration. For example, prescribed operational limits for a single dam can be informed by more precise flow-ecology methods, such as IFIM. Because of the limited spatial extent of such precise methods, ELOHA (Poff *et al.*, 2010) is the better option for spatial planning (e.g., where to monitor minimum flows).

The Hydrogeomorphic Template

In addition to covering more reaches, ELOHA provides a vehicle for incorporating prior knowledge and hydrogeomorphic processes into flow management (Wilding, 2012). ELOHA users are directed to classify areas with a common hydrogeomorphic setting (e.g. single thread low-gradient streams) in order to define reaches that experience similar physical processes (e.g. low-energy deposition of fine sediments). Quantitative recognition of the broader environmental setting is essential for larger study areas, compared to site-specific studies that typically do not traverse changes in stream type (e.g. SEFA, RHYHABSIM).

The Heretaunga Plains has formed a diverse range of habitats, as a function of gravel deposition by rivers interwoven with fine sediment deposition during maritime intrusions (Dravid & Brown, 1997; Hauer *et al.*, 2016). Defining the hydrogeomorphic setting for oxygen response to flow started with dividing streams into two classes: gravel-bank rivers and low-gradient streams. The large gravel-bank rivers that traverse the Heretaunga Plains have steeper slopes, mountainous headwaters and dynamic wetted width (e.g. Ngaruroro River, Tutaekuri River). The gravel-bank rivers were classified primarily to exclude waterways that have a lower risk of oxygen suppression as a consequence of inherent physical processes (e.g. flow regime, sediment regime). This study focuses instead on the low-gradient stream class, which includes single-channel streams that originate on the plains or adjacent hill-country. Within the low-gradient stream class, there is variability in the flow regime and channel form (e.g. spring-dominated; limestone hill-country).

Rather than rely exclusively on stream type classification, the hydrogeomorphic variability within the low-gradient stream class was incorporated into the flow-ecology relationships using continuous attributes, as advocated by Wiens (2002). This required identification of continuous hydrogeomorphic attributes (i.e. aspects of flow and channel form) to measure for development of the oxygen-flow models for low-gradient streams.

Selecting Predictor Variables

Prior knowledge was used to inform the selection of hydrogeomorphic metrics for the flow-ecology methods (Wilding, 2012). In the context of this report, that prior knowledge included regional methods for oxygen that were developed for the Coromandel Peninsula (Wilding *et al.*, 2012). The Coromandel study indicated that low-gradient streams required more flow to generate adequate oxygen (Wilding *et al.*, 2012). Streams with slower, deeper water typically receive less reaeration of oxygen from the atmosphere (Cox, 2003; Jowett, 2012). Channel metrics that have been used to predict the reaeration coefficient include reach-average water velocity, depth and slope (Cox, 2003; Jowett, 2012). The speed and depth of water are affected by flow, and flow is the management variable of interest for this project. Therefore, models that have been developed for predicting reaeration coefficients provide a good starting point for an oxygen-flow model.

Development of the regional oxygen-flow model based on physical attributes like reach slope, velocity and depth commenced with a pilot study using results from the intensive process models (SEFA) developed for three Heretaunga streams (Raupare, Awanui, Irongate) (Wilding, 2015). The oxygen predicted by the SEFA process model was plotted against reaeration coefficients predicted by a subset of models from Table 4 in Cox (2003), (O'Connor and Dobbins 1956; Isaacs & Gaudy 1968; Melching and Flores 1999; Thyssen et al. 1987). In their original form, the selected reaeration models performed poorly in terms of their correlation between sites for diel minimum oxygen saturation (best correlation from Thyssen reaeration coefficient, worst using O'Connor and Dobbins). This is not surprising, because reaeration models typically perform poorly when applied to stream types that differ from those where each model was developed (Cox, 2003; Melching & Flores, 1999). Additionally, the model parameters for predicting oxygen will be different to the parameters for predicting the reaeration coefficient. So, rather than adapt existing reaeration models, hydraulic metrics were evaluated in a pilot study (flow, unit stream power, Froude number).

The best results were achieved using Froude number, in so much as the minimum oxygen saturation at a given Froude number was similar for Raupare, Awanui and Irongate streams. The equation for calculating Froude number is similar in form to most reaeration models: Froude number increases with velocity and decreases with depth. Froude number is also dimensionless (no units), which potentially improves the spatial generalisation by reducing the effect of stream size.

Development of a hydrogeomorphic template for the Heretaunga Plains focussed on estimating reach slope, mean depth and mean velocity; either directly or using precursors (Figure 1-4). These variables may then be used to estimate Froude number. Compared to prior studies, finer resolution of channel metrics was made possible by the availability of high-resolution elevation data from terrain maps based on LiDAR (**Li**ght **D**etection **A**nd **R**anging) data. The approach used in calculating Froude number is summarised in the flow diagram (Figure 1-4), with methods detailed in the next section (Section 2).

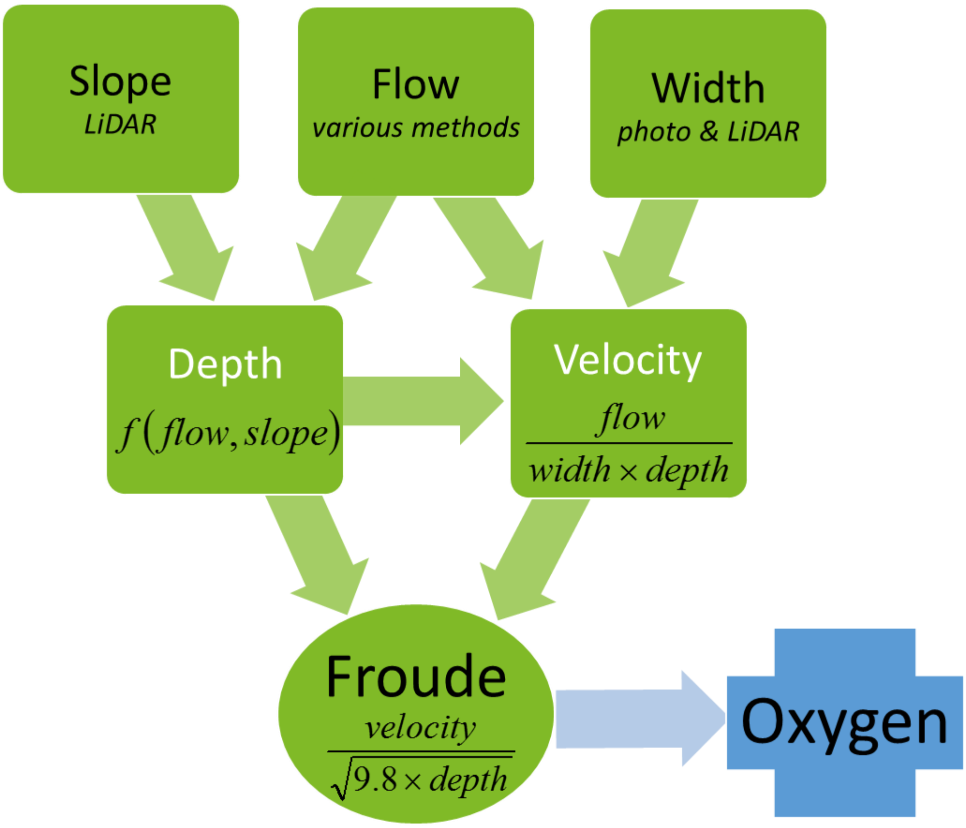

Figure 1-4: Constructing the oxygen model using Froude number. An outline of the methods used to develop an oxygen-flow model, focussing on the hydrogeomorphic attributes (slope, flow, width) used to calculate Froude number for each stream reach. Detailed methods are provided in Section 2.

A Response Variable to Match

This investigation focused on the response of oxygen to flow, within a hydrogeomorphic template. Like the hydrogeomorphic predictors, the scale of that oxygen response variable also needs to align with the scale of flow management (Heretaunga Plains extent, reach grain). Oxygen saturation at one point in a stream is consequence of oxygen drivers upstream of the measuring point (Chapra & DiToro, 1991), provided the measurement probe is placed in flowing water rather than a still backwater. Measuring oxygen at one point can therefore be compatible with reach-average measures used for slope and width, in terms of grain size.

Because oxygen saturation varies over time, the timing and duration of the oxygen measurement is critical (i.e. the temporal grain). The diel pattern of dawn minima and afternoon maxima (from photosynthesis) needs to be accounted for when making spatial comparisons between streams of the Heretaunga Plains. There is also a seasonal pattern in oxygen saturation, typically with less oxygen during summer (at dawn) in response to lower flows and more aquatic plants than during winter (Wilding, 2015). Ideally, this temporal variation would be accounted for using long-term monitoring of oxygen at every study site. However, the cost of establishing and maintaining monitoring sites would limit site replication. For example, only two long-term oxygen sites are maintained on the Heretaunga Plains (Raupare and Awanui streams).

Spatial coverage can be extended using point-in-time measurements of multiple sites, if the sites are subject to equivalent conditions. Dawn measurements during an extended low-flow period in mid summer were targeted in pursuit of equivalent conditions between sites. A time of low-oxygen was targeted both as the period of concern and as the period that distinguishes sites, because all streams are likely to experience 100% oxygen saturation at some point during the year. In developing a regional scale model, concurrent dawn measurements better isolate spatial drivers of oxygen by sampling at a time of day when all sites should be close to their diel minimum oxygen saturation. Validation measurements on other dates provided a valuable test of how sensitive the spatial pattern was to the time of year for those measurements.

How oxygen is measured is also an important consideration for study design. Oxygen probes measure oxygen saturation and then use measured temperature to derive oxygen concentration (YSI, 2009). This report is intended to inform flow management and hence focuses exclusively on oxygen supply (Figure 1-2). The oxygen supply to organisms does not decrease at higher temperatures (Verberk *et al.*, 2011), so oxygen supply is better represented by oxygen saturation, compared to oxygen concentration that decreases with temperature (at equilibrium). Note, the use of oxygen saturation is a departure from conventional oxygen-flow studies that typically measure oxygen as a concentration (Cox, 2003).

Interactions with Aquatic Plants and Riparian Vegetation

The relationship between oxygen and flow is the focus of this report. However, the management of flow should not be considered in isolation of other management variables that affect oxygen supply. Aquatic plants play an important role in oxygen dynamics, as oxygen producers, as oxygen consumers, and as modifiers of water depth and velocity (Champion & Tanner, 2004; Madsen *et al.*, 2001; Wilcock *et al.*, 1999). The growth of aquatic plants is managed in streams of the Heretaunga Plains: i) directly, using weed cutter boats, boom mowers and herbicide application and ii) indirectly via riparian management.

The growth of aquatic plants is fuelled by sunlight, which can be reduced by shade from trees growing alongside the stream. For this investigation, solar access was expected to constrain plant growth only at times and places where other factors are suitable for plant growth. Those other factors affecting plant growth include water velocity, substrate type and flood regime (Riis & Biggs, 2003). The effect of riparian shading on the abundance of aquatic plants was investigated. In selecting the sampling grain for this component, each plant was expected to respond to overhead shade more than reach-average shade. Therefore, channel cross-sections were selected as the grain of plant abundance surveys, and solar access was measured at the same cross-section.

The abundance of aquatic plants varies over time, and temporal monitoring of Raupare and Awanui streams demonstrated a seasonal pattern of more abundant plants in summer and less in winter (Wilding, 2015). The spring and summer growth can be interrupted by flood disturbance events (Riis & Biggs, 2003), biomass collapse and weed control programs. (e.g. weed cutting, herbicide application). All sites could not be measured on the same day because the plant surveys take too long. Repeat surveys proved necessary because of the seasonal dynamics of aquatic plants. Trees offering shade are relatively static within a growing season. However, the amount of sunlight reaching the stream is dynamic at any given location; changing with the time-of-day and day-of-year as the position of the sun in the sky changes. Aquatic plant growth is expected to integrate *solar access* over the growing season (rather than *solar radiation* at the time of the site visit). Therefore, solar access was estimated over the entire growing season for each cross-section (see section 2.9).

2 Methods

2.1 Mapping of the Heretaunga stream network

The blue lines for the stream network (Figure 2-1) were adapted from the "Heretaunga drains" GIS layer created by the Engineering team at Hawke's Bay Regional Council. The council's stream network was used as a starting point because it is more accurate than both the NZMS 260 topomaps and the stream network developed for the REC (River Environment Classification), (Snelder *et al.*, 2004). Hawke's Bay Regional Council has maintained and, in some cases, designed the stream network for flood control and drainage. The most relevant reach number from the REC network was added as a mapping attribute to improve cross-compatibility with the Heretaunga stream network.

The council's GIS drains layer was pruned to omit ephemeral water courses because flow requirements for ephemeral waterways are outside the scope of this investigation. This pruning relied on site surveys, Google street view and aerial photographs (in order of accuracy). The intention was to identify reaches with surface water present during the 2013 summer drought and retain only those reaches for analysis.

Polylines were edited to lie within channels, as depicted by the LiDAR terrain map (Turton, 2005; Turton & Hyam, 2003). In some cases, recent aerial photographs indicated that the stream path had changed since 2003, when the LiDAR data were captured (e.g. Irongate through SH50a expressway). In these cases, the old stream bed was used because this matched the LiDAR data that would be used to extract elevation for estimating slope. Several iterations of stream alignment were required to ensure that polylines did not deviate from the LiDAR channel (i.e. the channel as represented by LiDAR terrain map).

The stream reach is the smallest unit of the network, and was typically delineated at inflowing tributaries (total 336 reaches, median length 1.0 km). Each reach was delineated to represent a relatively uniform environment, which required some additional reach splits, including notable changes in slope (e.g. Awanui flume reach, Irongate Railway Rd, Ongaru, Karamu Clive reach), (Internal Files 2).

A groundwater model is being developed in a parallel investigation by Hawke's Bay Regional Council. It is complimentary to the oxygen study because a better understanding of surface water-groundwater interactions will improve understanding of the effects of groundwater use on stream ecosystems. Hence, the stream network considered in this investigation was extended to the boundary of the Heretaunga groundwater model (black outline in Figure 2-1). In some cases, this required extending the stream network beyond the LiDAR data extent (e.g. Ngaruroro upstream of Crownethorpe, Paritua upstream of Valley Rd), with reach delineations added at the LiDAR boundary to simplify data processing.

The location of springs and flow losses to groundwater were investigated both for this oxygen investigation and for the groundwater model. Various methods were used to quantify losses and gains from groundwater (e.g. concurrent gaugings, longitudinal electrical conductivity profiles), and those methods will be documented in a separate report on Heretaunga hydrology (Wilding & Waldron, in prep.). Gains and losses from groundwater necessitated additional reach divisions. For example, the Paritua Stream was split using the transition from losing-to-groundwater to gaining-from-groundwater, which was identified from concurrent flow gauging investigations (Wilding & Waldron, in prep.). Diffuse springs in the Karamu Stream were identified from longitudinal electrical conductivity surveys (Wilding & Waldron, in prep.). The Karamu gaining reaches were split at tributary confluences, as these provided a discrete delineation of incremental gains from groundwater. Reaches in the Ngaruroro, Tukituki and Tutaekuri rivers were delineated by a flow loss to groundwater that was identified from concurrent gauging data (Wilding & Waldron, in prep.).

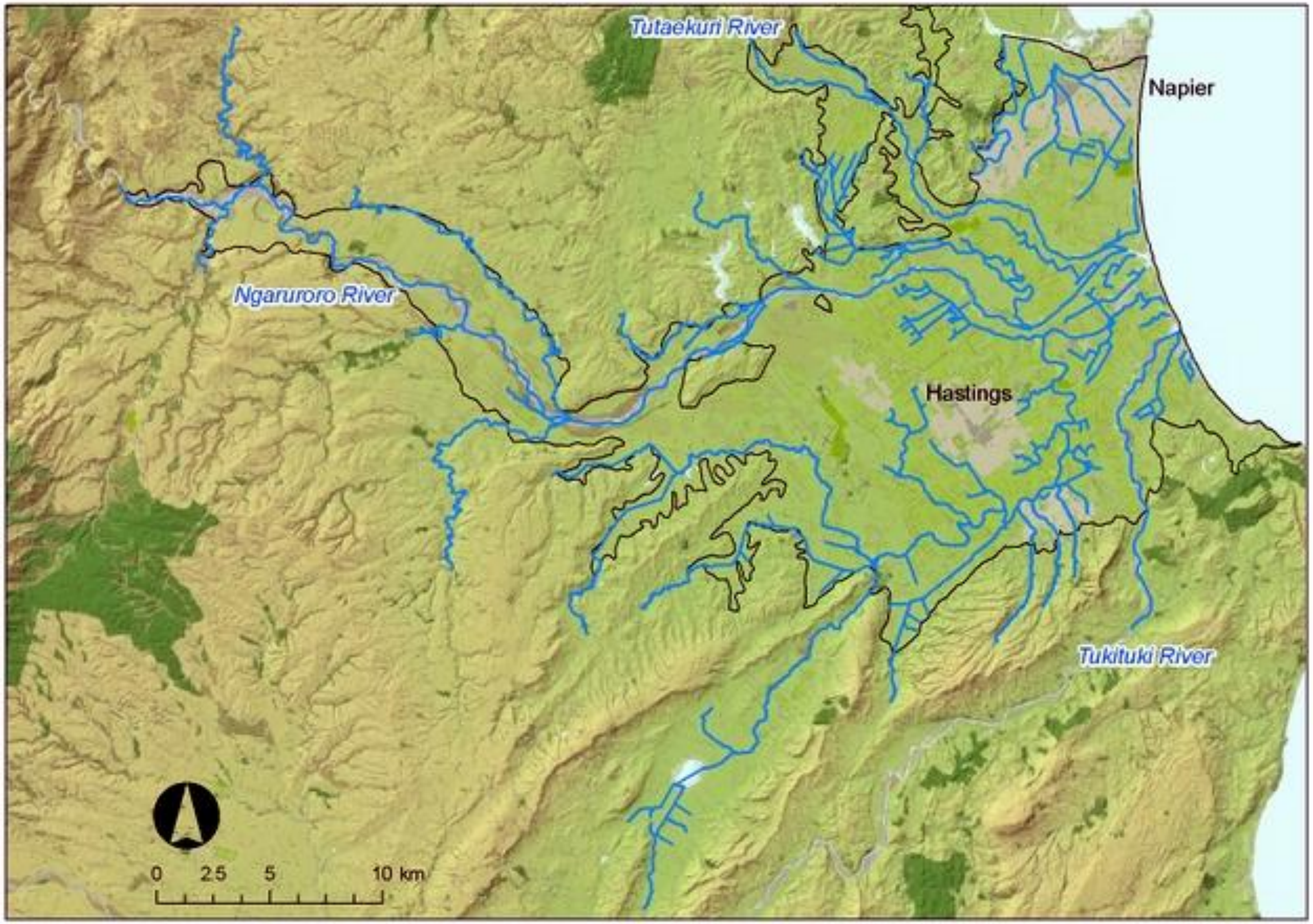

Figure 2-1: Streams map. Blue lines depict the streams mapped for this report. This mapping exercise was mostly limited to the groundwater model domain (black outline).

Muddy Creek has a pump station that can divert its flow into the Karamu Stream. That pump station was historically operated as a permanent diversion to Karamu Stream (at E1935626 N5609773). Craig Goodier (Hawke's Bay Regional Council) confirmed that the pump station operation has changed so that baseflows now follow their more natural course down the lower Muddy Creek to the south end of Waitangi Estuary. Note that the pump station will operate again in future at times when there is a risk of flooding in the Clive area.

Estuarine areas with significant intertidal zones were excluded from the network. However, the network does include freshwater tidal reaches, along with salt-wedge tidal reaches that were delineated by Wade (2013). Freshwater tidal reaches were approximated by an elevation of about 0.8m (mean high-tide elevation), or the nearest natural boundary (e.g. riffle, change in slope, width, etc.). Stream reaches in the Napier area were split at floodgates and pump stations, because these were assumed to be important delimiters of tidal effect.

The Heretaunga stream network was created using ArcMap Version 10.2.2, with polylines and attributes stored as a feature class within a Geodatabase. Stream reaches were individually inspected to ensure all polylines flowed downstream. To check that reaches were connecting correctly, the following ArcMap topology rules were applied:

- Must not have dangles
- Must not overlap
- Must not self-overlap
- Must not self-intersect
- Must be single-part

Additional working notes for implementing the topology rules are contained in Appendix A.

The revised network provides the most accurate representation to date. However, the network was created primarily for the purpose of supporting instream flow investigations and this does not guarantee it will be fit for all purposes. It would certainly be unsuitable for ephemeral stream investigations. The mapped stream network is also a static representation of the network, compared to the actual stream network that lengthens during wet periods.

2.2 Estimating Flow

The previous report for this investigation focussed on changes in flow over time and the effect on oxygen at a site (Wilding, 2015). The present report is focussed on variation of oxygen between sites, rather than at a site, and requires static estimates of flow for each reach. The MALF (mean annual 7-day low flow) provides a measure of the lowest flow during a typical summer, to facilitate comparisons between sites of predicted oxygen saturation at a time when adverse impacts are more likely to arise (see Section 2.6). The MALF is also the conventional statistic used for minimum flow limits and water allocation methods in New Zealand (Beca, 2008; Jowett, 1992; Wilding, 2003). The MALF was estimated for 176 reaches, out of the 336 total mapped reaches (MALF calculations: Internal Files 3). Various methods were used for estimating MALF in the following order of preference:

(1) From continuous flow monitoring data, including stage to flow ratings and velocity meter records (Raupare only). Monitoring data were used for 13% of the 176 reaches, with synthetic continuous data used to extend the length of record for two of the monitoring sites (Raupare at Ormond Rd, Tutaekuri-Waimate at Goods Bridge). Flow statistics derived from the monitoring data by Waldron and Kozyniak (in prep.) were used in the first instance, if available for a given site.

(2) Correlation of flows from a site with sufficient gaugings, concurrent with a donor site that has adequate continuous monitoring data. A linear regression equation was then used to transform the donor site MALF (used for 14% of the 176 reaches). These correlations were typically based on more than the ten pairs of gaugings, as recommended by Henderson *et al.* (2003). Six sites had less than ten pairs, however the correlations were considered adequate for spatial risk mapping.

(3) Flow mass balance. For example, the sum of two known tributaries to derive flow downstream of the confluence (17% of the 176 reaches).

(4) Mean annual lowest gauged flow, for sites with many gaugings and no continuous monitoring site that was adequately correlated (4% of the 176 reaches).

(5) Paired gaugings – a single concurrent gauging for two sites close by and measured low flows (e.g. located upstream of the donor site), (14% of the 176 reaches).

(6) MALF estimates from Booker (2015) implemented using the REC network. These estimates were only applied to streams lacking significant trans-basin groundwater inputs because the calculation is based on the surface catchment only. These estimates were primarily used for streams with limestone hill-country sources. If used, the raw value was multiplied by 0.69 to better approximate sites with a measured MALF (e.g. Louisa at Te Aute Rd, Paritua at Valley Rd), (36% of the 176 reaches).

Estimates for the Ruahapia Stream were calculated after omitting pre-1987 data. Historical discharges (e.g. groundwater for cool-store heat-exchangers from Watties and ENZA) may have contributed to the much higher flow measurements between 1969 and 1986 (about 100 L/s, compared to 25 L/s after 2008). For the Mangateretere Stream (Napier Rd), the stage to flow ratings were re-processed for four periods (2005, 2006, 2007 and 2013) to improve the flow record before calculating MALF. Useful estimates of MALF could not be estimated for all reaches on the Heretaunga Plains. For the large gravel rivers, MALF was only calculated for select reaches where RHYHABSIM hydraulic models were also available (MALF calculations: Internal Files 3).

Rules were required when assigning the MALF from a monitoring site to a stream reach. Several options exist for losing and gaining reaches. There would be some advantage in assigning flow at the midpoint of the reach, rather than at the end. For example, the midpoint flow would better represent the typical conditions for that reach. However, that would fail to achieve a logical flow balance from inflowing tributaries and would fail to portray the entire loss or gain over a given reach, and hence the decision to nominate the downstream end of the reach as the measurement point. The following rules were used when assigning MALF estimates from a monitoring site to a stream reach:

(1) Flow recorder MALF should match the reach MALF for the same reach.

(2) Component tributaries should sum to equal the reach downstream of the confluence.

(3) An increase or decrease in flow should be apparent from sequential reach values (i.e. should not be equal between reaches where there is a substantial flow change).

(4) For reaches with a gradual gain or loss (within reach), the stated reach flow should represent the downstream end of the reach.

Where the flow recorder was located part way along a gaining or losing reach (e.g. Ngaruroro at Fernhill), it was necessary to split the reach at the monitoring location to achieve compliance with all four rules.

In addition to estimating MALF, the flow was also estimated on the day of the dawn oxygen surveys at each survey site (oxygen surveys described in Section 2.5). Some oxygen sites were also flow monitoring sites; however, most were not. Hence a mix of methods was needed to estimate flow for each site on the oxygen survey dates, similar to the mix of six methods used for estimating MALF (described above). For example, the linear regression equation used for estimating MALF at Irongate Stream at Railway Rd from MALF at nearby flow monitoring site (Irongate at Clarke's weir) was also used for estimating flow on 21 January 2015 at Railway Rd.

In addition to the six methods, manual flow gaugings were also used for dawn oxygen sites and were typically measured within two days of the oxygen measurement. The two-day window was acceptable because it was a period of stable flow. The only exception to the two-day window was Ongaru Stream, where streamflow was gauged 5 days later. Adequate estimates of flow could not be calculated for two tributaries of Lake Poukawa, because each tributary spuriously appeared to have more flow than the monitoring site on the lake outlet. Hence, these tributaries were omitted from the oxygen-flow analysis.

Flows were also estimated for the validation surveys of dawn-oxygen, which were completed on different dates (described in Section 2.7). Manual flow gaugings were used for 33% of the flow estimates. For the remainder, continuous flow monitoring data were used for 16% of the flow estimates, correlated flows were used for 25%, and flow mass-balance for 14% (flow calculations: Internal Files 4).

2.3 Measuring Reach Slope

Streams with flatter slopes require more flow to meet oxygen limits, as indicated by prior knowledge from other regions (Wilding *et al.*, 2012). An emphasis was therefore placed on accurately estimating the reach slope using LiDAR elevation data (Turton, 2005; Turton & Hyam, 2003). That emphasis included constructing a stream network to align with the LiDAR channels (Section 2.1).

The LiDAR data enabled accurate slope estimates for this low-gradient stream network. Hence LiDAR was used instead of pre-existing estimates of channel slope offered by the REC network, which were based on a 10m digital elevation model. The 10m elevation data can be precise for steeper streams that rise 10m over a single reach. But most Heretaunga streams are not steep. For example, the Karamu River crosses the first 10m contour at more than 20km from the coast, which would necessitate a 20km interpolation to estimate slope for each reach. In contrast, the LiDAR data provided elevation estimates with sub-metre accuracy at a 3 m spatial resolution (elevation standard deviation 0.112 m from 258 test points on open, clear ground on the Heretaunga Plains), (Turton, 2005; Turton & Hyam, 2003).

A detailed description of how reach slope was calculated from the LiDAR terrain map is provided in Appendix A ("Reach Slope" sub-section). Note the noise in the LiDAR elevation profile for Poukawa Stream (Figure 2-2), with elevation spikes in the order of 1 m above stream elevation. Such scatter can be produced by bridges, culverts and trees over the stream. These spikes can also be an artefact of describing the surface using triangulated facets, which can erroneously cross the stream. Manual checking of every reach profile was needed to ensure this noise did not affect estimates of reach slope.

Because the LiDAR laser scan is reflected by water, this calculation provided a measure of water surface slope, rather than the stream-bed slope. The reach slope measured from LiDAR data was also static (i.e. unchanging), representing slope at the time of the LiDAR survey (approximately median flow conditions for Heretaunga Plains 26/6/2003 to 2/7/2003 and approximately low-flow for Poukawa 21/1/2006).

Using static estimates of slope is valid for this study because spatial comparability was largely achieved and the magnitude of change in slope with flow is small under baseflow conditions (cf. rapidly varying flood flows). Tidal reaches are an exception, where slope is not steady during base flows. Slope can decrease in tidal reaches, to the point of reversing, twice a day with each high tide (Wilding *et al.*, 2012). The reach slope was used for investigating oxygen response, with the exception of six oxygen sites where more localised estimates of slope were needed. Those six sites coincided with local anomalies, such as weir backwaters (Figure 2-2), so slope was revised to better reflect conditions upstream of the sampling point.

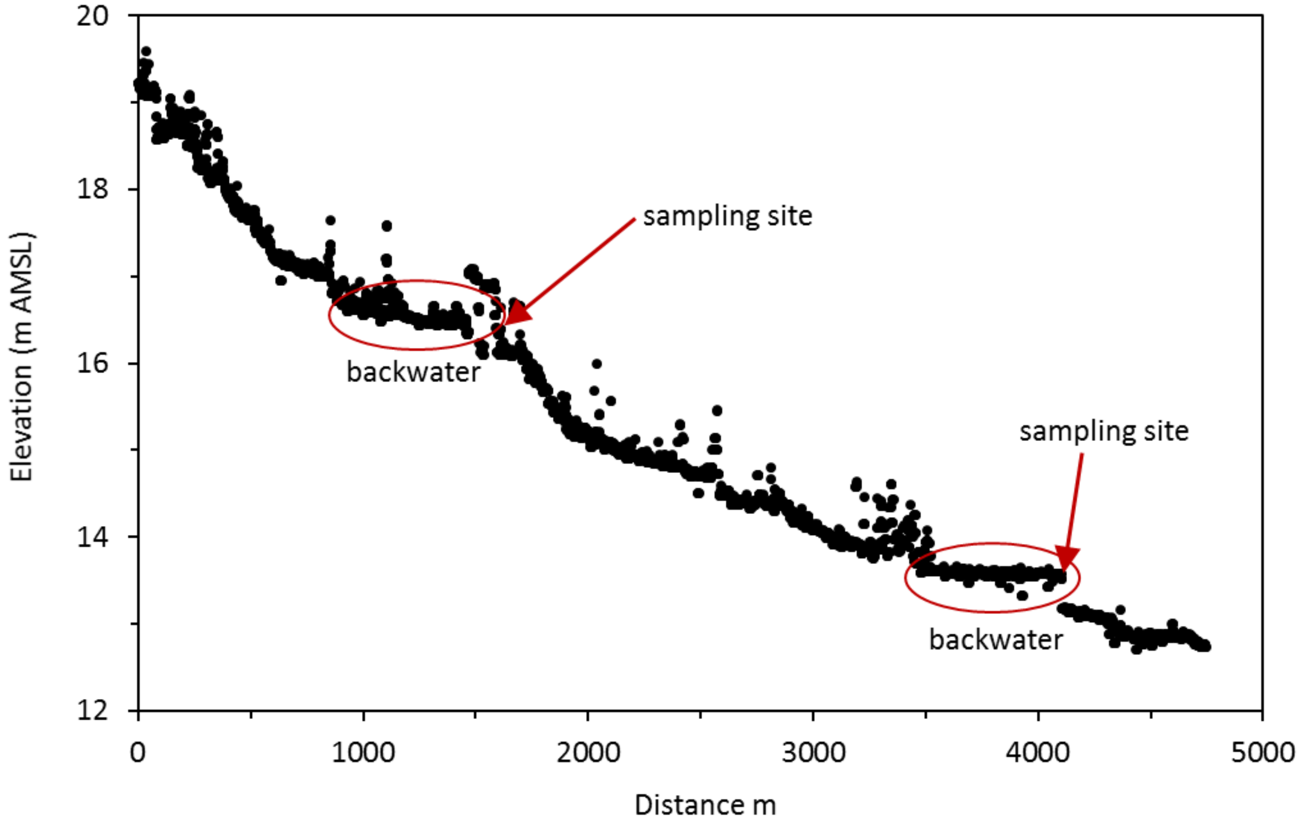

Figure 2-2: Poukawa Stream elevation profile. A different slope was used for the two sites where oxygen was sampled (arrowed), because of backwaters created by a weir (lower Te Mahanga bridge) and an unknown control structure (upper Te Mahanga bridge). The backwater sections are circled. Elevation above mean sea level is plotted against the distance downstream of Douglas Rd.

2.4 Estimating Stream Width, Depth and Froude number

Stream width was calculated as a static estimate. Width is expected to change little in low-gradient, U-shaped channels under baseflow conditions. This is not the case for gravel-bed rivers, such as the Ngaruroro, where width decreases more rapidly with flow. For example, there is a 7.5% reduction in width when flow reduces from MALF to half of MALF for the Ngaruroro, compared to 1.7% reduction for Raupare Stream. For three of the oxygen sites, stream width was changed to represent a shorter section of channel up to 500 m upstream of the oxygen sampling point.

The Heretaunga Plains are small enough that stream width could be measured for most reaches from aerial photographs and LiDAR, rather than REC based models such as Booker (2010). The benefits of estimating width from aerial photographs were demonstrated by Wilding *et al.* (2014), who reported that width estimated from aerial photos gave better predictions of hydraulic habitat than empirical width models.

Stream depth cannot be estimated from aerial photos or LiDAR, and surveying depth in all streams is not practical. So, to estimate depth, hydraulic geometry equations were developed for low-gradient streams of the Heretaunga Plains as a function of flow and reach slope. These were "downstream" hydraulic geometry equations, rather than "at-a-station" equations (or ratings) (Jowett, 1998; Leopold & Maddock, 1953). The

Hydraulic Geometry equations were calibrated to a dataset of 1320 gaugings for 72 sites that were collated from Hawke's Bay Regional Council archives (Hilltop - allsites.hts). Site selection targeted low-gradient streams of the Heretaunga Plains. Sites that may have a different relationship between depth and flow were excluded from analysis. These included gravel-bed rivers (e.g. Ngaruroro), concrete culverts (e.g. Awanui at Pakipaki), and irrigation races. Sites that were only gauged at flood flows were also excluded.

The data were checked for outliers on plots of velocity versus flow, hydraulic radius versus mean depth, maximum depth versus mean depth and wetted perimeter versus width. Outliers were then checked against the original field sheet for errors. Any errors were corrected both for this analysis and in the HBRC archive database. Out of 144 corrected errors, only 10 affected the flow magnitude. The reach slope was obtained for each gauging site from the geomorphic template, as described in Section 2.1. Slope was not available for six sites, leaving 79 sites for analysis.

The median gauged flow and depth were then calculated for each site from the gauging dataset. The median gauging does not necessarily describe the median flow. The resulting function more likely describes the relationship between depth and flow within the normally wetted channel (i.e. not overbank flows), given that 71% of the gaugings were completed during the drier half of the year (November to April). Omitting sites with less than 10 gaugings had little effect on the depth-flow relationship, and reduced the sample size to the point where the effect of slope was difficult to detect. Therefore, all sites were included, regardless of sample size. Width was not used as a depth predictor because it did not perform as well as flow.

Quantile regression was then used to calculate parameters for the hydraulic geometry equation. Quantile regression was performed using RStudio (Version 0.98.953, quantreg package version 5.21, 50 percentile, bootstrap method for standard errors), (Koenker *et al.*, 2013). The output function was:

$$Ln(Depth+10) = 0.0212 \times Ln(flow+0.1) - 0.00260 \times Ln(slope+0.0001) + 2.345 \qquad (1)$$

Note that flow units for equation (1) are m^3/s, mean depth units are metres and reach slope is dimensionless (metre per metre), (n = 79; median flow range 3 to 2222 L/s; slope range 0.000069 to 0.0165; Pr>t < 0.0001 for flow; Pr>t = 0.02 for slope).

It was then possible to estimate Froude number for the oxygen measurement sites (Figure 1-4). Cross-section mean depth was calculated using equation (1). Flow was estimated at the time of the oxygen survey using the methods described in Section 2.2. Mean velocity was derived from mean depth, width and flow using the Continuity Equation (velocity = flow / [width.depth]), to achieve conservation of mass. Froude number could then be calculated using equation (2), as summarised in Figure 1-4.

$$Froude = \frac{velocity}{\sqrt{9.8 \times depth}} \qquad (2)$$

Only three sites from gravel-bed rivers were included in the oxygen predictions, with the sole intention of demonstrating that oxygen is less critical an issue in this river type. Estimating Froude number for those three sites was made possible by hydraulic habitat surveys (lower Ngaruroro, lower Tukituki and Maraekakaho Stream), (Johnson, 2011a; Johnson, 2011b; Wood, 1998). Froude numbers were then estimated from the calibrated hydraulic model using SEFA (System for Environmental Flow Analysis, Version 1.2).

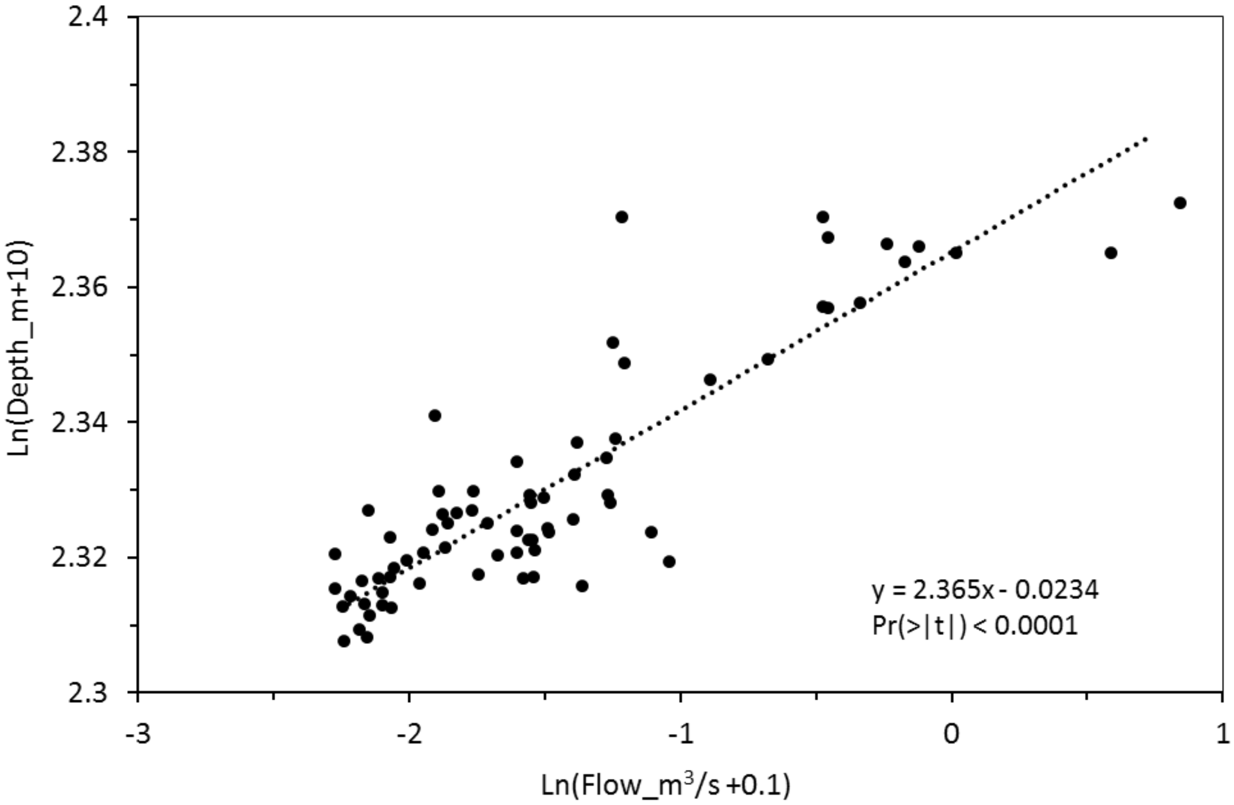

Figure 2-3: Predicting stream depth from flow. The cross-section mean depth is plotted against flow, with a 50% quantile regression line. Both flow and depth values are medians from a time-series of gaugings. Each dot represents a gauging site on the Heretaunga Plains, excluding gravel-bed streams and artificial channels (e.g. flumes, culvert aprons, irrigation supply ditches). Sites were also excluded if only gauged at high flows. Compared to this depth versus flow plot, the final model also uses stream slope (Equation (1) to account for residual variation.

A time-series of Froude number was estimated for two sites used in the validation analysis (Awanui and Raupare Streams). Froude number was estimated as a time series for the Awanui, for which depth and velocity were the necessary inputs. Reach mean depth was estimated from water level monitoring data and the SEFA hydraulic model (Wilding, 2015). The SEFA hydraulic model provided a mean depth on the day of the cross-section survey (0.642 m on 26/4/2013) when the water level was 15.98 m above sea level. Depth (cross-section mean) as a time series was therefore calculated as water level minus 15.338 m (15.98 - 0.642 = 15.338). This could provide a reasonable estimate of depth, provided reach-average channel form did not change significantly over the oxygen monitoring period (2012 to 2015). Velocity was derived from flow and cross-section area (velocity = flow / area). The area was derived from the SEFA Hydraulic Model, which predicted change in area with depth (Area m^2 = 6.85 x depth m – 1.08).

A similar approach was used for Raupare time-series data, with Froude number estimated from water level, SEFA hydraulic model and flow. The time-series flow data were sourced from a velocity meter (Sontek IQ standard) using index velocity ratings. Gauged flow was used for the period prior to installation of the velocity meter (16/11/2012 to 23/5/2013). Depth was again derived from water level. The SEFA hydraulic model provided a mean depth on the day of the cross-section survey (0.545 m on 11/4/2013) when the water level was 13.469 m above sea level. Mean depth as a time series was therefore calculated as water level minus 12.924 m (13.469 - 0.545 = 12.924). The area was derived from the SEFA Hydraulic Model, which predicted change in area with depth (Area m^2 = 5.739 x depth m – 0.554).

2.5 Oxygen Data Collection

Oxygen saturation changes seasonally and fluctuates from day to night (termed “diel” fluctuations). Conventionally, data loggers are deployed overnight to capture daily-minimum oxygen saturation. But relying on data loggers would limit the spatial coverage because of the high cost for purchase and maintenance of the loggers. A spatial snapshot of oxygen minima was therefore achieved by surveying multiple sites at dawn on the same day. By completing all site measurements in one morning, results are more comparable between sites (similar flow recession, temperature, day length, etc.), compared to moving the same logger between sites sequentially. Three people sampled 42 sites on the morning of 21 January 2015 (Figure 2-4), starting pre-dawn (from 03:08 am to 06:02 am NZST; sunrise 05:24 am). Portable oxygen probes were used, including a YSI optic sensor (proODO), Hach optic sensor (HQ40d) and a YSI Clark cell (ProPlus). The YSI Clark cell was only used for sites with higher oxygen saturation because, compared to optic sensors, this sensor type can be less precise for near-zero oxygen saturation (Wilcock *et al.*, 2011).

Probes were left to stabilise with water temperature for 10 minutes at the first site, and for shorter periods at subsequent sites. Stabilisation period was maximised by completing all other tasks prior to recording oxygen and temperature (recording site details, GPS readings, etc.). The potential for sensor warming was minimised by the short travel time between sites (typically less than 10 minutes), and cool air temperatures (approximately 15 °C).

Sites were selected to maximise coverage of perennial streams on the Heretaunga Plains and also to broaden the range of conditions represented (stream slope, flow, etc.). Ease of access was also a requisite for site selection, because all sites required sampling near dawn. Likewise, the order of sampling was chosen to minimize the overall travel-time. Sites were also spaced to avoid sampling the same reach twice.

2.6 Generalized Oxygen Model

The relationships between oxygen saturation and physical predictors were described using least-squares linear regression in Microsoft Excel. Quantile regression of the lower bound was not required because the study design targeted the lowest oxygen conditions (i.e. lower-bound data), with oxygen sampled at the time of diel minimum (concurrent dawn survey) and seasonal minimum (21 January 2015) (see Section 2.5). Predictor variables were provided by the Geomorphic Template for each reach sampled.

Applying the Generalized Oxygen Model to streams of the Heretaunga Plains required predicting the flow necessary to achieve a nominal oxygen saturation (40%). Back calculating Froude number required to achieve 40% oxygen was a straightforward process of rearranging the Generalized Oxygen Model. Calculating the flow to achieve that Froude number was less straightforward. The hydraulic geometry equation calculates depth as a function of flow and reach slope (Section 2.4). The Solver tool in Microsoft Excel was used to iteratively solve a flow value that achieved the target Froude number. Solver was used because a closed-form solution for calculating flow from the hydraulic geometry and Froude equation was not found. The solved flow value was then added to the stream network as an attribute for mapping.

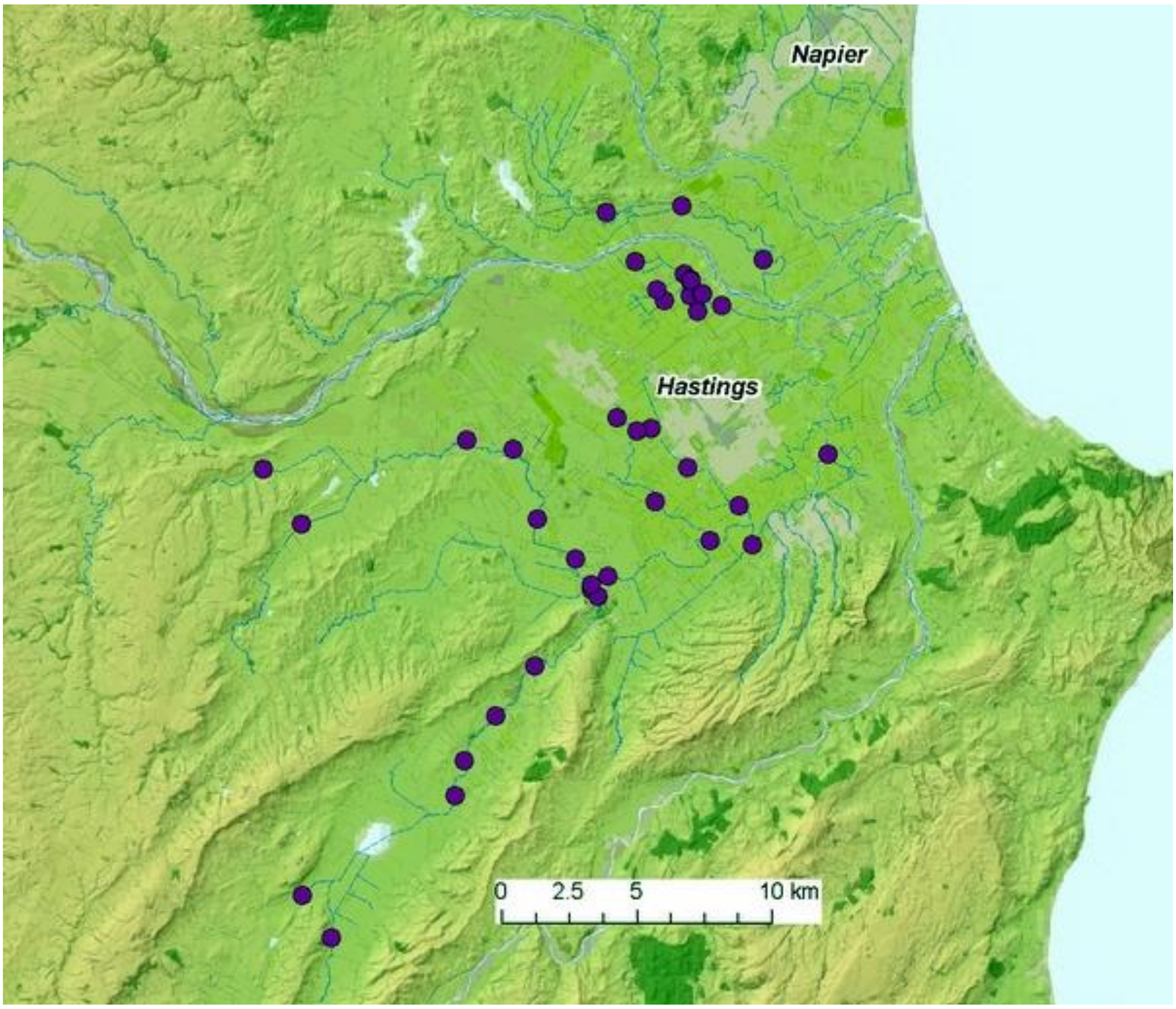

Figure 2-4: Dawn oxygen sites. Dots are locations where oxygen was sampled around dawn on 21 January 2015 (N=42).

2.7 Validation of the Oxygen Model

To validate the Generalized Oxygen Model, predictions were compared to measurements at the same sites on different dates, plus measurements at new sites. Concurrent dawn surveys of oxygen saturation were spread over three years, on five sampling dates (14/2/2013, 25/2/2014, 28/2/2014, 5/3/2014, 5/2/2015). This provided 50 measurements in total. A subset of the calibration sites was sampled on each occasion, in addition to some new sites (e.g. mainstem of the Karamu 5/2/2015).

In addition to concurrent dawn surveys, time-series validation was also performed using long-term monitoring data from the Awanui and Raupare Streams. The oxygen time-series data were filtered to include only higher quality QC600 data (Wilcock *et al.*, 2013), and to exclude any days when flow was changing rapidly. Flow was considered rapidly changing if the difference between daily maximum and daily minimum flow was more than 30% of minimum flow for last 3 days. Monitoring continued over three summers in the Awanui (1/12/2012 to 3/8/2015, N=572). Froude number was estimated as a time series, as described in Section 2.4. A similar approach was used for Raupare time-series data. Oxygen data were again filtered to include only QC600 data and to exclude days with rapidly changing flow. Monitoring also continued over three summers in the Raupare (16/11/2012 to 29/6/2015, N=588). Daily minima oxygen saturation data were calculated from the oxygen time-series data.

2.8 Biological Validation

To determine whether low oxygen resulted in biological impacts, the condition of inanga was investigated, as recommended by Wilding (2015). The condition factor provides a measure of how skinny a fish is, by standardising weight for length (Wilding et al., 2006). Past research indicates that fish stop feeding when low oxygen forces surface breathing (Kramer, 1987; Neilan & Rose, 2014), so loss of condition could precede reduced abundance. Unlike other fish health measures, such as liver somatic index, condition factor is a potentially non-lethal measure for inanga. Another benefit of 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.

Inanga were chosen for this evaluation because they are more abundant and widespread in these streams than common smelt and they also support a valued whitebait fishery. Other species are probably less suited for monitoring because:

- they are less susceptible to effects from low oxygen concentrations (e.g. longfin and shortfin eels, common bully, koura)
- they are less-valued introduced species (e.g. goldfish, *Gambusia*)
- they are not common enough to provide a robust sample (e.g. torrentfish, yelloweyed mullet, patiki, rainbow trout)

The Raupare and Awanui were selected as paired catchments for detailed monitoring and investigation because flow magnitude is the main point of distinction between the two (Table 2-1), (Wilding, 2015). The mean channel width is similar (Awanui = 5.2 m and Raupare = 4.8 m) and stream slope is similar (<1 m/km). Because of their proximity, the two sites experience a similar climate (e.g. timing of rainfall events). Fish access is similar, with both sites less than 10 m above sea level. Both streams lack downstream barriers to migration and migratory access from the sea is via the same river mouth (Waitangi Estuary). Both have mown grass banks that maximise solar access and mean flows at the two sites are similar.

The main point of distinction is lower flows during summer and autumn in the Awanui. The dominant spring-source for the Raupare sustains a MALF of 412 L/s for Raupare Stream, in contrast to 84 L/s for the Awanui, where flow is predominantly runoff from hill-country. Despite the many similarities, other possible confounding effects remain (e.g. fish movement between streams). Therefore, monitoring cannot demonstrate an absence of impacts on fish health from low oxygen. What the monitoring can reveal is the severity of oxygen suppression associated with a measurable impact on fish health.

Inanga were caught using fine-mesh fyke nets. A total of six nets were deployed at each site, on each occasion, for 2 to 4 hours during daytime, without bait, and with the net-entrance oriented downstream. Fish were anaesthetized using Aqui-S® to reduce handling stress and improve accuracy of length and weight measurements. Fish weight was measured using digital pocket scales (IPS-100; 0-100 gram range, 0.01 gram resolution), after a calibration check using a $2 coin weighing 10.0 g. A tall sided plastic tub was used to shelter the pocket scales from wind on the stream bank. After measurement, fish were placed in a bucket of stream water to recover, before being released back into the section of stream in which they were caught. The total count of fish caught in the fyke nets was also recorded for all species.

A total of three inanga surveys were completed at each site (30/1/2014, 15/12/2014 and 18/2/2015). A fourth survey was attempted on 20 March 2014, but only two fish were caught.

Table 2-1: Flow and channel metrics for the biological validation sites. Flow metrics were sourced from the Karamu Characterisation report (HBRC, 2014). Larger values for mean/median flow indicate more flow variability. Catchment areas are from the HBRC Envirosites Database. 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.

Stream	**Raupare**	**Awanui**
Site	Ormond Road	Flume
Mean flow (L/s)	646	768
Median flow (L/s)	631	395
MALF (L/s)	412	84
Catchment area (km^2)	18	302
Mean/Median flow	102%	194%
MALF/area ($L/s/km^2$)	23.3	0.3
Width (m)	4.8	5.2
Depth (m)	0.55	0.64
Gradient (m/km)	0.8	0.4
Elevation above mean sea level (m)	3.6	6.8

2.9 Aquatic Plants and Riparian Shade

Aquatic plants were surveyed at oxygen monitoring sites using 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** are submerged plants that reach the water surface
- **emergent plants** that protrude above the water surface (e.g. sweet grass, water celery)
- **no plants** (e.g. gravel or silt)
- **filamentous algae** that are long (>2cm) and attached to any substrate, including other plants

At each cross-section, plant abundance was estimated as the 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 observed metres to proportional cover data completed during post-processing. The categories were exclusive (e.g. emergent plants overlaying submerged plants were only counted as emergent), with the exception of filamentous algae which were recorded as an overlay (i.e. do not sum to 100%). Ten cross-sections were sampled, with each cross-section represented by 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). Cross-sections were excluded from data analysis if less than 70% of the stream width (either plants or bare substrate) was visible (excluded 9 out of 390 cross-sections in February-March, and 25 out of 290 in November-December).

The plant surveys were completed twice (Table 2-2). The first survey was completed during February-March 2015, following the dawn oxygen survey (21/1/2015), and represented aquatic plant abundance late in the growing season. The second survey was completed November-December 2015, providing observations of aquatic plants earlier in the growing season (Table 2-2).

The effect of riparian shading on solar access and aquatic plant abundance was also investigated. Solar access was estimated using a Solmetric SunEye™, which predicts solar access to the water surface as a percent of potential direct sunlight over the period of interest (November-April for this study), by excluding periods when the stream is shaded (e.g. by trees, stream banks).

The Solmetric SunEye™ uses a wide-angle camera to capture the image, with photographs taken mid-channel (or as close to, determined by wading limits), a few centimetres above water level, to keep the instrument dry. Solar paths throughout the year were predicted by the SunEye using inbuilt sensors including: a digital compass for direction, a tilt sensor for horizon and a GPS for location, date and time (Figure 2-5). Automatic processing by the SunEye classified image pixels as either shade elements or open sky, then overlaid predicted sun paths to calculate solar access for the November-April period.

Incorrect classification of shade was manually edited, which was straightforward for sites that were mostly unshaded. For example, the cow at bottom left in Figure 2-5 was classified as a shading element by the SunEye, then manually edited to unshaded for this analysis. However, editing was more difficult for heavily shaded sites (<15% solar access) where shading elements were lost from the image to camera over-exposure. Later in the study, a back-up image was captured using a GoPro Hero4 to aid desktop editing of the shade classifications.

Analysis of plant-shade relationships was completed using quantile regression. Many factors contribute to plant growth, including water velocity, substrate, flood regime and seasonal growth (Riis & Biggs, 2003). Shade cannot limit plant growth if water velocities are too high for plants to grow; hence shade was expected to impose a constraint on plant growth only at times and places where other factors were suitable for plant growth. These times and places define an upper bound for the response of biota to flow, which can be described using quantile regression (Dunham *et al.*, 2002; Konrad *et al.*, 2008; Lancaster & Belyea, 2006; Milhous & Bartholow, 2006; Wilding *et al.*, 2014). Quantile regression was therefore used to define the upper bound between aquatic plants and solar access. Quantile regression was performed using RStudio software (Version 0.98.953; package: QuantReg Version 5.19; function: "rq"), (Koenker *et al.*, 2013). The standard error of the slope was estimated using a bootstrap method (se = "boot", bsmethod= "xy").

A 90% quantile was used to describe the upper bound for aquatic plant abundance, and 33% quantile to describe the lower bound for the “no plants” category. Each cross-section was used as the sample replicate because plant growth at one location will be constrained by shade at that location, rather than reach-average shade. In contrast, oxygen saturation at a measuring point is the product of conditions integrated over some length upstream. Therefore, the section-average of plant abundance and shade provides a more appropriate unit of replication (i.e. grain) for oxygen-plant relationships, compared to using individual cross-section data for plant-shade relationships.

Table 2-2: Riparian survey sites. Aquatic plants and solar access were surveyed at dawn-oxygen sites during February-March and again during November-December, with dates and number of sites listed below. Ten cross-sections were surveyed at each site, however plant surveys with less than 70% visibility were excluded from the analysis (the reduced sample number is tabulated).

	Feb-Mar 2015	**Nov-Dec 2015**
start	24/2/2015	24/11/2015
end	25/3/2015	23/12/2015
cross-sections	381	265
sites	39	29

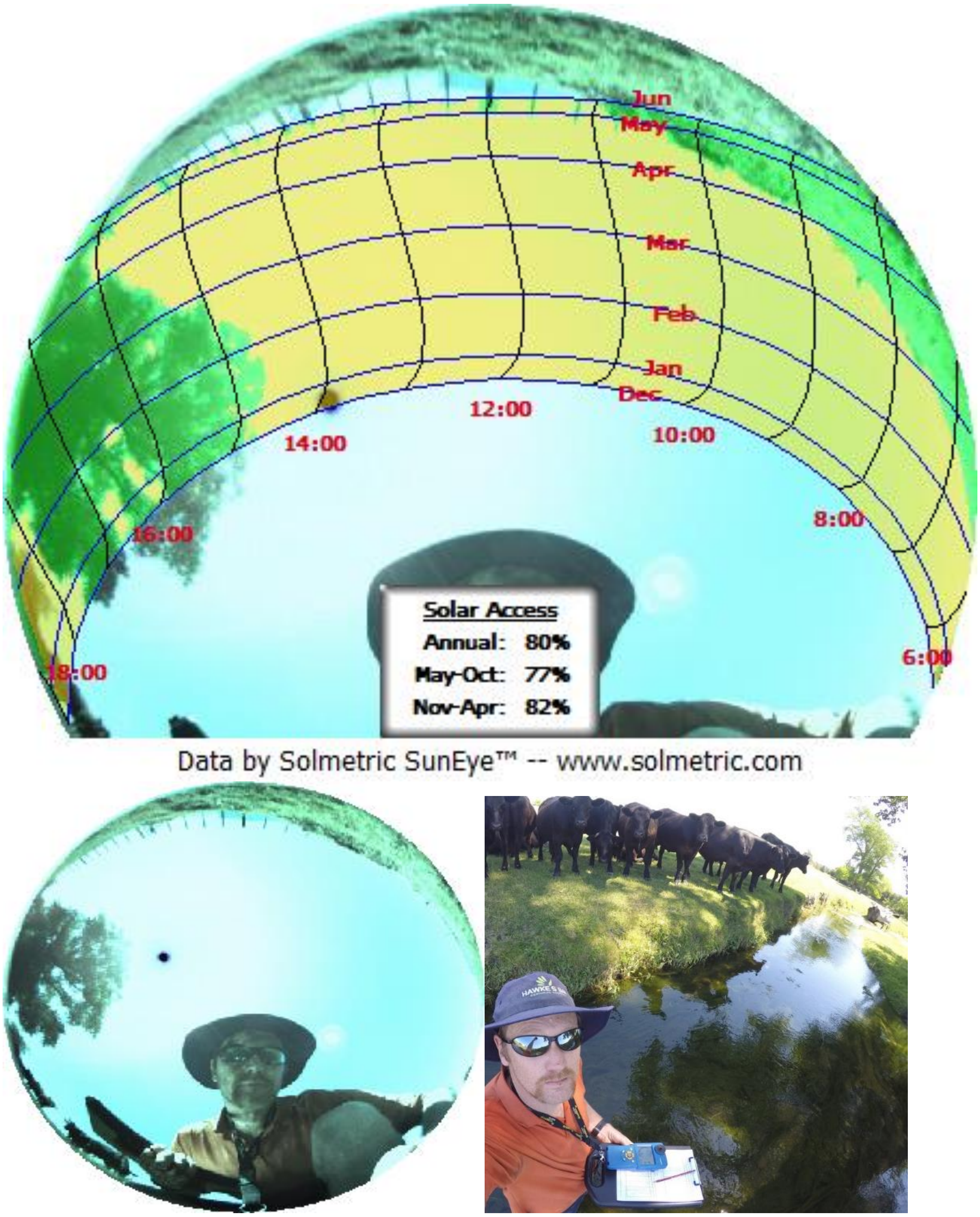

Figure 2-5: Measuring solar access. Example image from Solmetric SunEye™ (Paritua at Raukawa Rd, November 2015) that was processed to determine solar access (yellow colour for solar access, green colour for shade). The unprocessed image is inset at bottom left, and the instrument shown bottom right. Solar access was measured mid-channel at each aquatic-plant cross-section.

3 Results

3.1 Fitting of Generalised Oxygen Model

The streams with the lowest oxygen saturation had a flatter reach slope (Figure 3-1). Of the sites with less than 40% oxygen saturation, all but one had stream slopes less than 2 m/km. The only exception was a spring head (Raupare Spring), where water emerges from the ground with reduced oxygen (11% saturation) regardless of reach slope. Stream slope therefore provides good discrimination of streams where oxygen is not severely depleted.

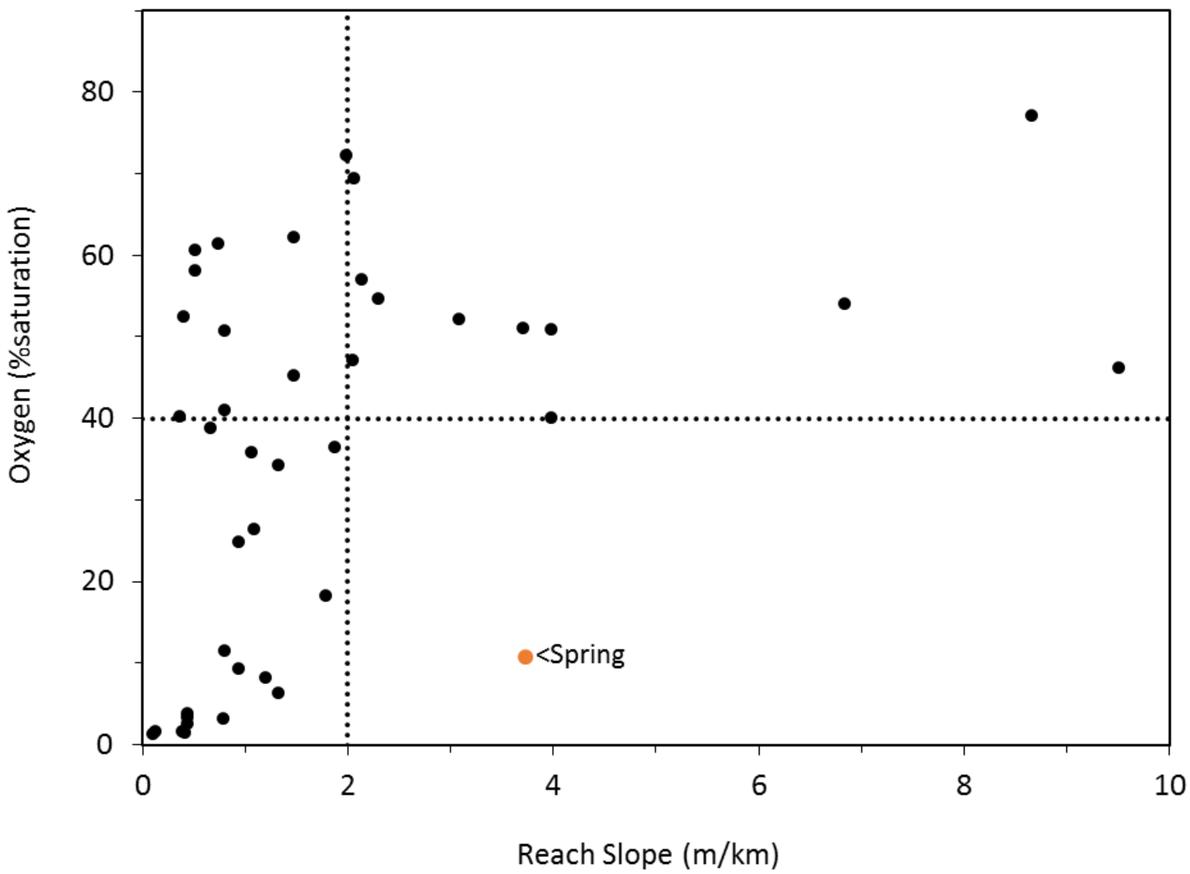

Figure 3-1: Oxygen versus reach slope. Dawn measurements of oxygen saturation (21 January 2015) plotted against reach-slope derived from LiDAR. Reference lines are over-plotted at 2 m/km slope (vertical) and 40% oxygen saturation (horizontal). A measurement from a spring head is labelled (Raupare Spring), with the other measurements taken from streams.

Low reach-slope is not the sole determinant of oxygen saturation. For example, 10 sites exceeded 40% oxygen saturation, despite having a slope less than 2 m/km (10 out of the 37 sites with slope <2 m/km). Another important determinant of oxygen saturation is flow. Flow increases water velocity and turbulence, which increases oxygen reaeration. For example, 58% oxygen saturation was observed at the Tutaekuri-Waimate Stream (Good's Bridge site), despite a reach slope of only 0.5 m/km. This phenomenon may be a consequence of high flow (1600 L/s). Increasing flow will increase water velocities, for a given stream width and reach slope. Better discrimination of low oxygen sites was therefore achieved using Unit Stream Power (Figure 3-2), which combined reach-slope and estimated flow per unit stream width for the survey date (Unit Power = 9793.Flow.Slope/Width). This plot demonstrates the importance of flow, for a given channel size and slope. However, there remains a wide scatter of data points.

There are many possible reasons for this scatter. For a given slope and flow per unit width, the velocity and depth can still vary depending on the roughness of the channel. The effects of velocity and depth were investigated further because both affect reaeration. The Froude number combines both velocity and depth as an index that should increase with reaeration, all else being equal (Froude = Velocity / sqrt(9.8.Depth)). Froude number provided better discrimination of sites with the least oxygen, when comparing sites with Froude numbers less than 0.05 (Figure 3-3) to sites with stream power less than 0.2 watt/m^2 (Figure 3-2), to sites with reach slopes less than 2 m/km (Figure 3-1). Note that this is an estimate of Froude number, rather than a measured value. For example, mean velocity and depth cannot be determined for all sites and for all times, so these variables were estimated using flow, slope and width (see Section 2.4).

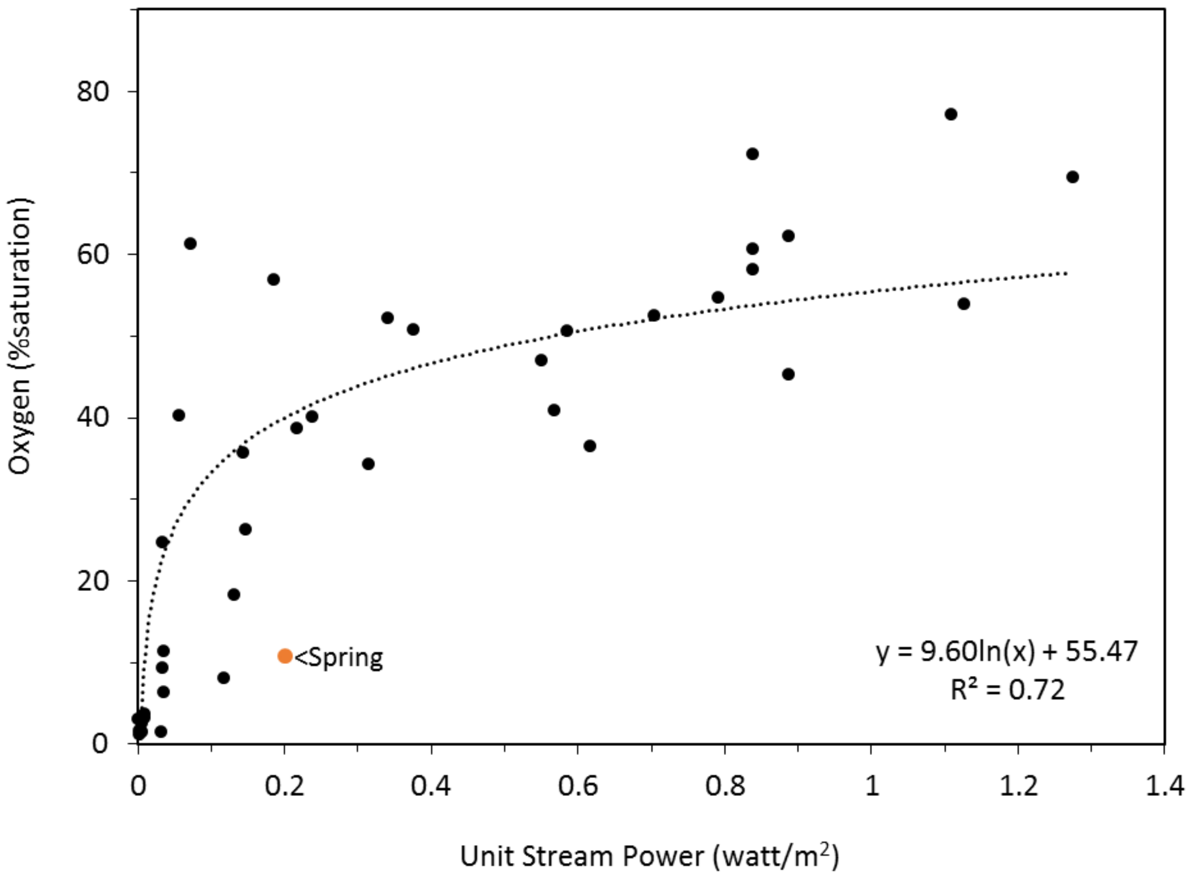

Figure 3-2: Oxygen versus Stream Power. Dawn measurements of oxygen saturation plotted against Unit Stream Power. This measure of power combines reach slope with stream flow for the date of the oxygen survey. The trendline was fitted after excluding the labelled "Spring" site (Raupare Spring), because it was sampled at the spring head, reflecting groundwater conditions rather than the stream environment.

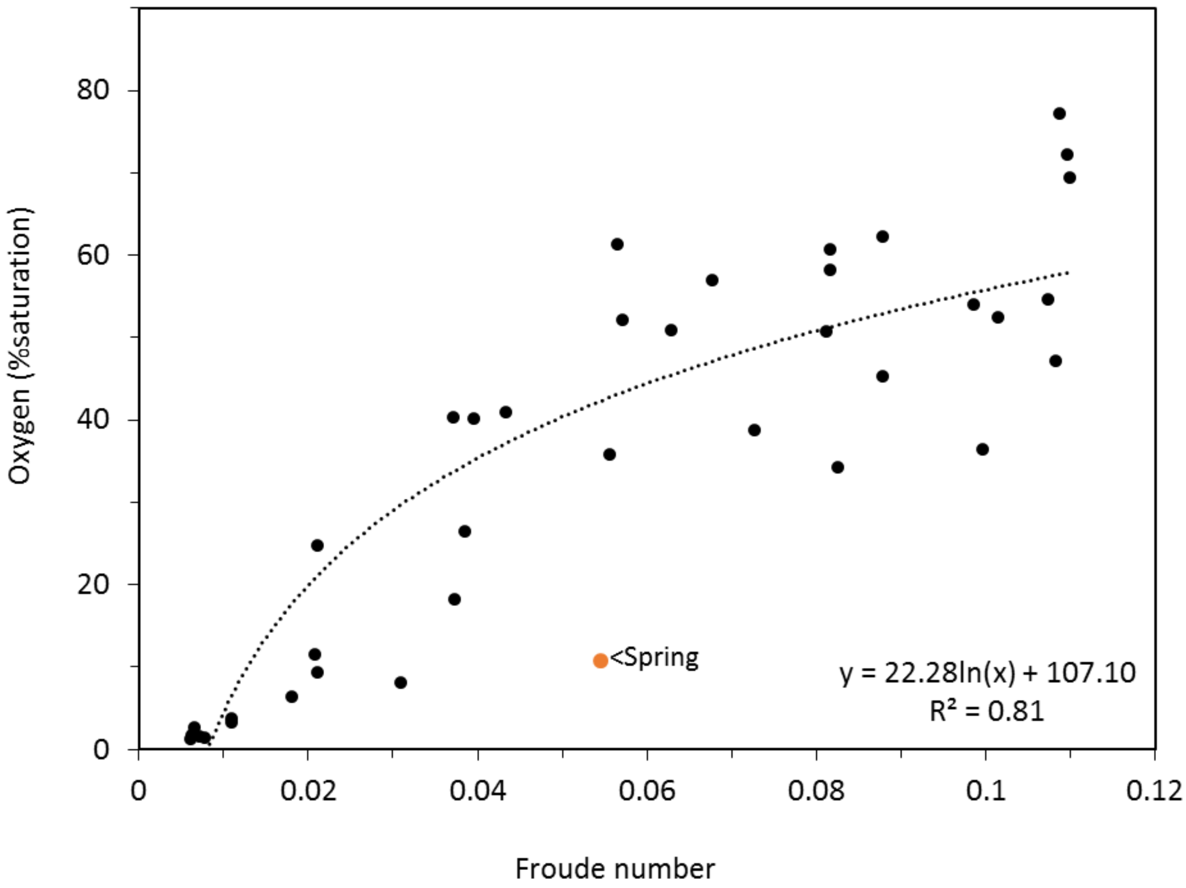

Figure 3-3: Oxygen versus Froude number. Dawn measurements of oxygen saturation plotted against Froude number (n = 37). Froude number increases with water velocity and decreases with increasing depth (Froude = velocity / sqrt[9.8.depth]). The trendline was fitted after excluding the labelled "Spring" site (Raupare Spring), because it was sampled at the spring head, reflecting groundwater conditions, rather than the stream environment.

3.2 Validation of Generalised Oxygen Model

The model calibration dataset was collected on one day (21/1/2015) to examine how oxygen stress varies across the riverscape under similar climatic conditions. This spatial comparison is intended to inform policy development for instream flow requirements across the Heretaunga Plain. The model is not intended to numerically predict the actual minimum oxygen saturation on any particular day. To assess whether the spatial pattern observed on 21 January 2015 is representative of different dates, validation of the generalized oxygen-flow model was investigated using a new dataset collected over three years (14/2/2013, 25/2/2014, 28/2/2014, 5/3/2014, 5/2/2015). The slope of the response function for the validation samples is equivalent (slope 21.44 for calibration data versus 22.28 for validation data). This supports the spatial pattern detected by the Generalised Oxygen Model.

The validation oxygen saturation measurements were typically higher than predicted by the Generalized Oxygen Model (compare red and black lines in Figure 3-4; intercept 112.37 versus 107.10; Nash-Sutcliffe coefficient 0.44). This difference in oxygen magnitude indicates that the model calibration data were collected during seasonally-low oxygen conditions. This seasonal-low is also supported by three years of continuous monitoring data from Raupare Stream, where the sampling date for calibrating the model (21/1/2015) recorded oxygen within the bottom 2% of all daily minima (rank 13 from n = 864 days). This could be described as the most extreme week during the oxygen monitoring period (November 2012 to June 2015). Considering that the oxygen monitoring period coincided with drought years (2013 and 2015), the long-term recurrence could be less often. For example, flows in the Ngaruroro River during 2013 reached the lowest recorded since 1983 (at Whanawhana) and the Ministry of Primary industries declared drought across Hawke's Bay and the entire North Island (Porteous & Mullan, 2013).

Streams that recorded substantially more oxygen than expected included Paritua Stream at Valley Rd (76% oxygen, Froude 0.069) and Ongaru Stream at Wenley Rd (90% oxygen, Froude 0.148). These sites had tall riparian trees, which may have increased oxygen by shading out aquatic plants. The role of aquatic plants and riparian shading in the response of oxygen to flow is investigated in Section 3.4.

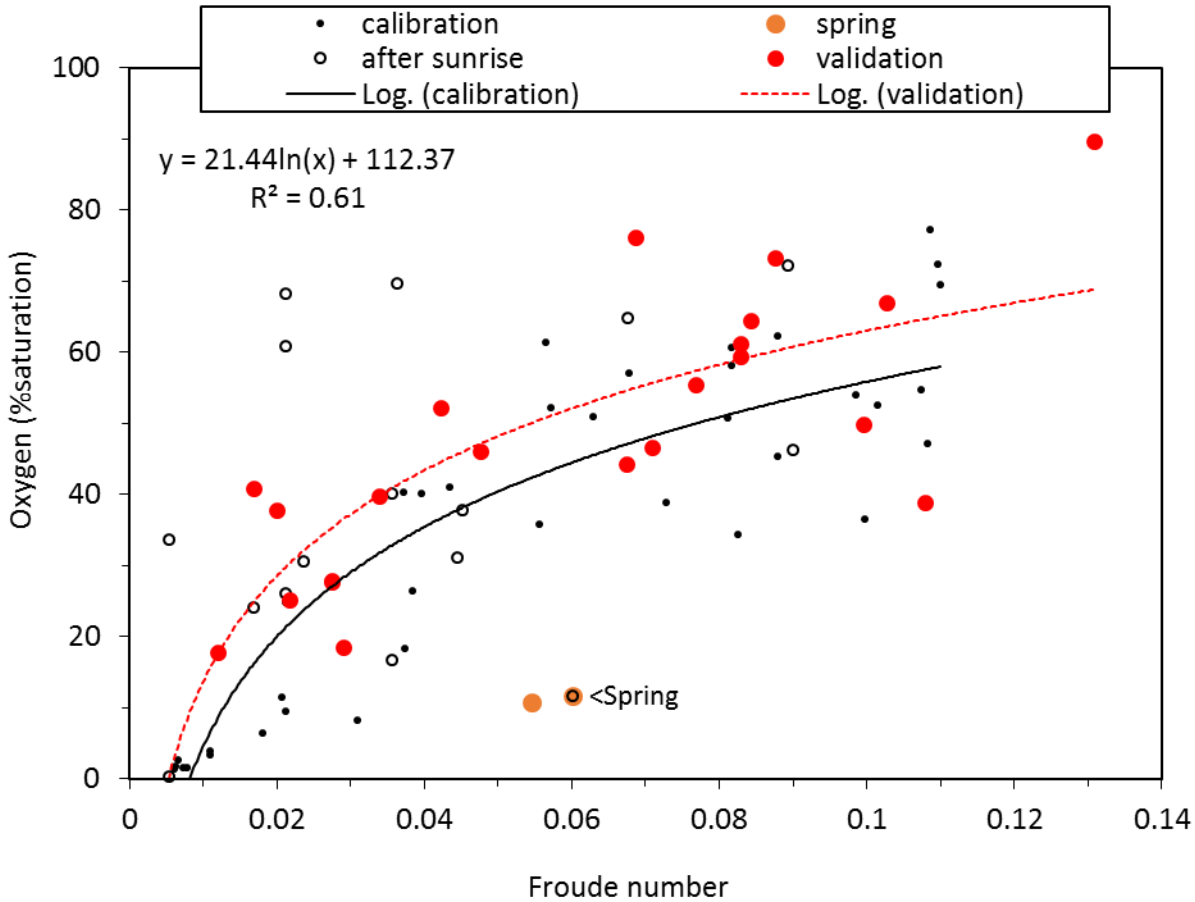

Figure 3-4: Validation of oxygen-flow relationship. New data (red dots) were used to validate the model (represented by the black line). The original calibration data are also plotted (black dots). Note that some validation points were sampled more than 75 minutes after sunrise (black circles), so were omitted from the validation trendline (red dashed line).

The Generalised Oxygen Model was developed to describe spatial variation in oxygen stress, rather than changes in oxygen over time at one site. To evaluate this limitation on model application, model predictions were compared to changes in oxygen over time at-a-site. Oxygen was monitored continuously at two sites from 2012 to 2015 (Raupare and Awanui). Froude number was estimated as a time-series for these sites from continuous flow data, combined with SEFA hydraulic modelling (methods described in Section 2.4). Observed data from the Awanui Stream demonstrate a steep decline in oxygen when Froude numbers were less than

0.05, which is consistent with the Generalized Oxygen Model (Figure 3-5). The oxygen saturation was generally higher than predicted, but the shape of the oxygen-Froude response is comparable. Consequently, the model fitted to the validation data (red dotted line) is a better predictor of the lower bound of observed oxygen saturation (Figure 3-5).

For Raupare Stream, the Generalized Oxygen Model fits the lower bound of observed oxygen saturation at Froude numbers >0.05 (Figure 3-6). Raupare Stream did not experience the extreme lows needed to test the lower range of model predictions (Figure 3-6).

From the spatial analysis, Froude number was a better predictor than flow of daily minimum oxygen (R^2 = 0.81 using Froude versus R^2 = 0.41 using flow). The advantage of Froude number, over flow, was less clear from the temporal studies. For the Awanui Stream, the model based on Froude number explained slightly more oxygen variability than flow (R^2 = 0.85 for Froude number, R^2 = 0.81 for flow). But that was not the case for Raupare Stream, where the model based on flow explained slightly more variability in daily minimum oxygen (R^2 = 0.47 for flow, R^2 = 0.44 for Froude number). However, the Generalised Oxygen Model performed well in approximating the observed change in oxygen over time, considering it was not calibrated to time-series data. If the flow required for Froude number to exceed 0.05 is relatively high for the stream in question, then it is reasonable to conclude that oxygen will be a critical issue for flow management and further investigation of this issue is justified.

Froude number estimates are likely to be the greatest source of uncertainty when applying the Generalized Oxygen Model. The same can be said of the variables that are used in estimating Froude number. Increasing stream depth, at a given flow, also decreases velocity (Froude = velocity/sqrt(9.8*depth). For example, water depths in the Raupare Stream can double (from 0.45 to 0.85m at 300 L/s), presumably as a result of aquatic plant growth that increases channel roughness (from the time-series of depths estimated for Figure 3-6). That increase in depth halves the mean velocity (from 0.15 to 0.08 m/s at 300 L/s), and hence the Froude number would be less than half as a consequence (reduced from 0.071 to 0.027). This lower Froude number would reduce predicted oxygen from 55% to 35%. Even a more typical depth-range for the Raupare (depth 0.45 to 0.7 m at 300 L/s) generates a wide range of oxygen predictions (41% to 56% oxygen). To put those oxygen ranges in context, that is about double the difference between the calibrated model and the validation data (median 8% deviance of validation data from predicted oxygen). There are other potential sources of error, including variability in respiration that is not correlated with the predictor variables. However, uncertainty in Froude estimates is clearly significant in its own right.

The sensitivity of model predictions to spatial autocorrelation was also investigated. The concern here would be generating a pattern as an artefact of sites' proximity to each other, rather than the physical driver under investigation (Legendre, 1993). The model predictions were not sensitive to site proximity, as demonstrated by obtaining equivalent predictions after omitting close sites. Oxygen predicted for a Froude number of 0.05 went from 40.4% to 40.6%, after omitting close sites (sample size reduced from 42 to 21). Note that sites only 100 m apart, but on different tributaries, can drain entirely different catchments and hence be more independent than those distant within the same sub-catchment. That is why the omitted sites were manually selected as close in environmental space (e.g. same tributary), rather than automated selection of sites close in a straight-line distance.

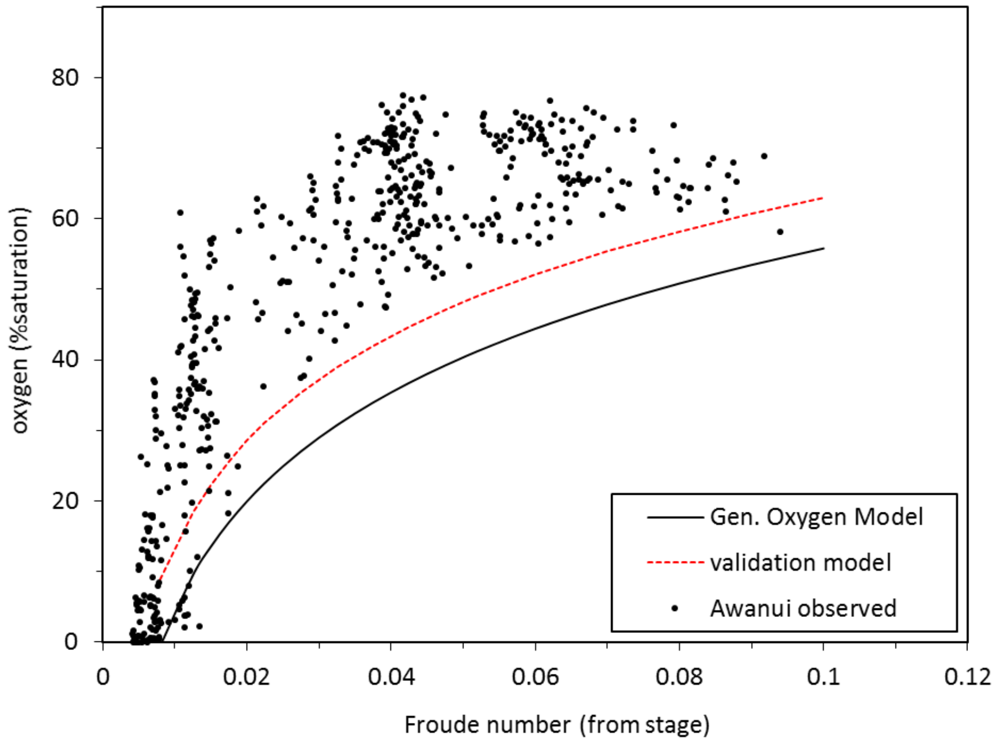

Figure 3-5: Predicted oxygen compared to observed oxygen for Awanui. Daily minimum oxygen saturation, comparing observations from Awanui Stream (n = 572 days) to oxygen predicted using the Generalized Oxygen Model (solid black line).

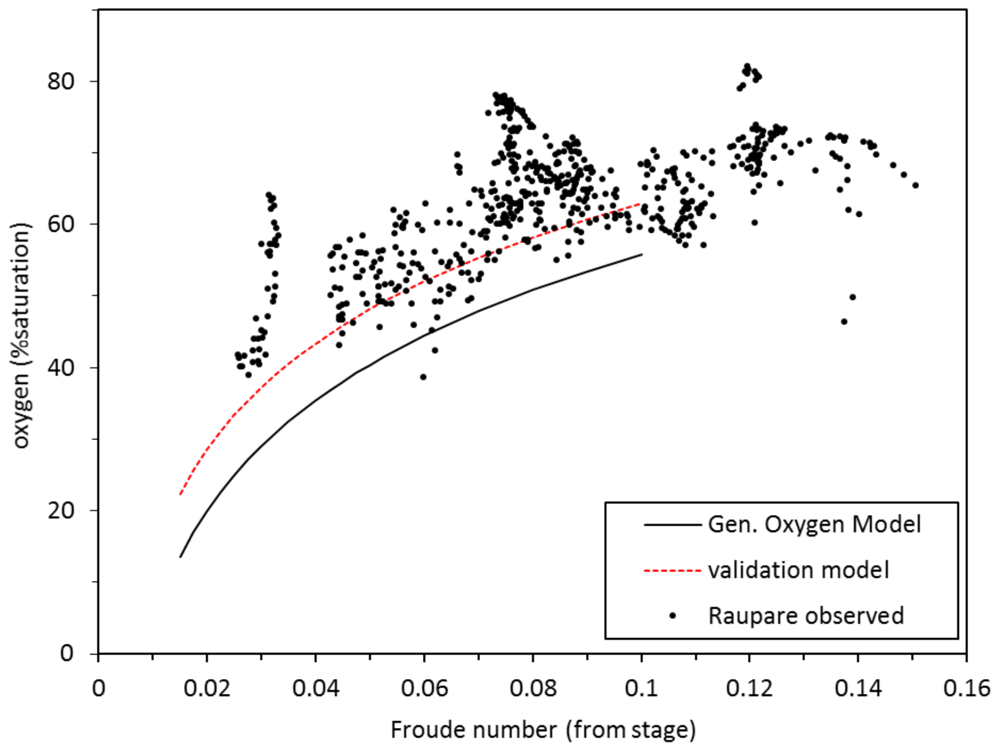

Figure 3-6: Predicted oxygen compared to observed oxygen for Raupare Stream. Daily minimum oxygen saturation, comparing observations from Raupare Stream (n = 588 days) to oxygen predicted using the Generalized Oxygen Model (solid black line).

3.3 Biological Validation

The Awanui and Raupare have been the focus of in-depth study (Wilding, 2015). These two sites were chosen for this study because of the contrast in oxygen and low flows, between otherwise similar streams (Table 2-1). Despite the similarities, other confounding effects remain (e.g. floods, fish movement between streams). Therefore, monitoring cannot demonstrate an absence of impacts on fish health from low 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).

The Generalized Oxygen Model predicted lower oxygen in the Awanui Stream at MALF than in the Raupare at MALF (see Section 3.5). The long-term, continuous oxygen monitoring (2012 to date) confirms that the Awanui does experience overnight anoxia (77 days in 2013) during low flows, compared to the Raupare that typically exceeds 40% oxygen overnight. This contrast in oxygen conditions, in otherwise similar streams, provided a rare opportunity for examining the consequences of low oxygen conditions for fish. To investigate whether lower oxygen in the Awanui translated to biological impacts, inanga were compared between the Awanui and Raupare streams using Condition Factor. The Condition Factor provides a measure of how skinny a fish is, by standardising weight for length (Wilding *et al.*, 2006).

In early summer, the condition of inanga was marginally better in the Awanui than the Raupare (15/12/2014, Kruskall Wallis $p = 0.01$, $n = 50$ and 22 respectively). But, by late summer, the condition of inanga in Awanui Stream was lower than inanga condition in Raupare Stream (18/2/2015, Kruskall Wallis $p = 0.00001$, $n = 33$ and 50 respectively). Lower condition of inanga was coincident with the observed decrease in oxygen saturation for Awanui, which dropped below 5% every morning for the 30 days preceding the February inanga survey. Oxygen was higher in Raupare Stream, with daily minima averaging 38% over the 30 days prior to the survey (lowest daily minimum 27% saturation).

Inanga sampling was also undertaken the previous summer at Raupare and Awanui (30/1/2014). Again, the condition of inanga in the Awanui was significantly less than inanga in the Raupare (Kruskall Wallis $p = 0.00003$, $n = 13$ and 51 respectively). Daily minimum oxygen had averaged 28% in the Awanui for the preceding 30 days, with the lowest daily minimum just 4.5%. Again oxygen remained higher in the Raupare, with an average daily minimum of 51% saturation, and a lowest daily minimum of 46%.

In addition to reduced condition of inanga, a less diverse fish community was recorded in the Awanui Stream compared to Raupare Stream. Fish inhabiting the Awanui included 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 3-1). A turtle was seen on two occasions in the Awanui (presumably *Trachemys scripta*). A more diverse fish community inhabits the Raupare Stream, including inanga, longfin and shortfin eels, common bully, patiki (black flounder), yelloweyed mullet, common smelt, rainbow trout, *Gambusia* and goldfish (HBRC, 2014). Torrentfish were recorded from a gravel reach upstream of the Raupare monitoring site (adjacent to Nicholl Road), which offers more suitable habitat (gravel riffles) than the Awanui site and the Raupare monitoring site at Ormond Rd. Other stream-life observed in the Raupare included koura (crayfish) and freshwater mussels.

For Awanui stream, the greater distance inland (Table 2-1) may have limited access for yelloweyed mullet, which typically stay within short reach of the estuary (McDowall, 2000). All other species inhabiting the Raupare should find the Awanui accessible, given the low elevation (6.8 m above sea level) and shared river mouth (Waitangi Estuary). For example, patiki (black flounder) are found further upstream in the Ngaruroro River (to Whanawhana), which is steeper than the Awanui and accessed from the same river mouth. Ease of access to the Awanui for the migratory fish is further confirmed by the dominance of inanga, which are relatively weak migrants (Leathwick *et al.*, 2008).

Table 3-1: Species observed during site visits to the Raupare and Awanui Streams. Records were kept of the species observed during plant surveys and oxygen calibration 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 sited in the Awanui. Benthic and nocturnal species, such as koura, eel and bully are probably underestimated by this method. Species recorded using other methods are tabulated only as "present" to avoid comparing abundance from different methods.

Species	Raupare	Awanui
yelloweyed mullet	66%	
inanga	27%	96%
patiki (black flounder)	1%	
rainbow trout	3%	0.4%
koura	1%	
eels (shortfin & longfin)	1%	2%
common bully	0.4%	present
Gambusia	present	1%
common smelt	present	
goldfish	present	present
freshwater mussel	present	

3.4 Aquatic Plants and Riparian Shading

Aquatic plants play an important role in oxygen dynamics: as oxygen producers; as oxygen consumers (net consumption at night); and because of their physical effect on stream depths and velocities (Champion & Tanner, 2004; Madsen *et al.*, 2001; Wilcock *et al.*, 1999). The growth of aquatic plants is fuelled by sunlight, which can be reduced by shade from trees growing alongside the stream. The potential for riparian trees to reduce plant growth was investigated by measuring plant abundance and solar access at sites across the Heretaunga Plains. Solar access was expected to impose a constraint on plant growth only at times and places where other factors are suitable for plant growth. Those other factors that can constrain plant growth include water velocity, substrate type and flood regime (Riis & Biggs, 2003). In recognition of those other constraints, quantile regression was used to define the upper bound between aquatic plants and solar access (Figure 3-7). The upper bound is expected to define the plant response to shade where growth is not constrained by other factors. Solar access less than 30% constrained plant abundance, as described by the 90% quantile (Figure 3-7), and few plants were observed at cross-sections with less than 10% solar access. But abundant aquatic plants were observed in streams with partial shading (30 to 60% solar access), in addition to those poorly shaded streams (>60% solar access).

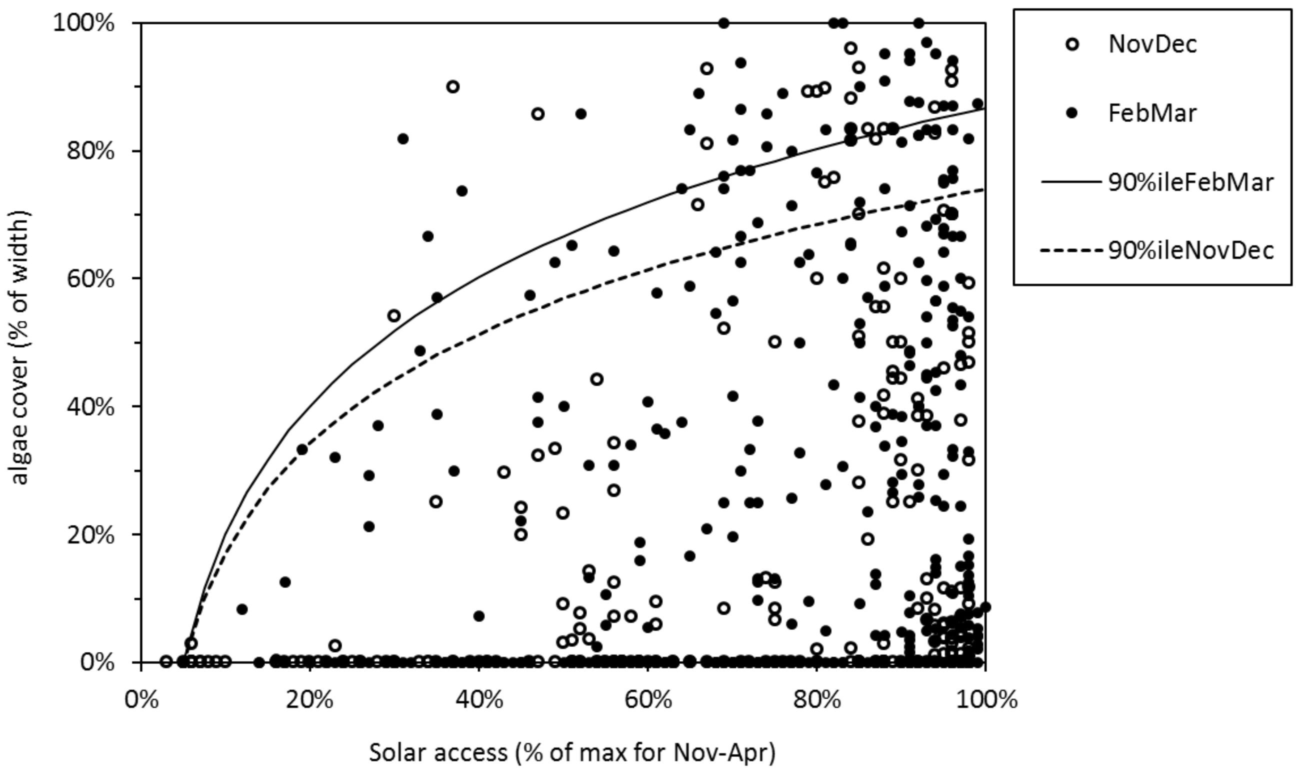

Figure 3-7: Response of algae to solar access. The cover of filamentous algae plotted against solar access. Algae were surveyed as a percent cover across the stream width, with solar access measured mid-channel (% of maximum solar access for the November to April period). Each dot represents a cross-section (see Table 2-2 for sample size). The 90% quantiles were fitted separately for each season ($p < 0.0001$, t-statistic for quantile regression slope).

Of the measured categories of aquatic plants, filamentous algae demonstrated the strongest response to solar access, followed by submerged plants and “no plants” ($p < 0.0001$, from quantile regression t-statistic). The least response to solar access was displayed by emergent plants ($p > 0.5$, from quantile regression t-statistic) and surface-reaching plants ($p > 0.01$, from quantile regression t-statistic). There was little difference in plant abundance between early and late growing season (blue and red dots respectively in Figure 3-7). The seasonal difference was greatest for algae abundance (19% less algae cover in Nov-Dec, for a given solar access, on average). That difference was only apparent after excluding samples with <10% solar access.

The effect of solar access on oxygen saturation was assessed after removing the effect of Froude number (residuals calculated from equation in Figure 3-3). Solar access explains some, but not all, of the scatter in the relationship between oxygen and Froude number (Figure 3-8). On average, oxygen was 10-15% better at the sites with less than 30% solar access (i.e. shaded), compared to sites with more than 80% solar access, using the February-March measurements of solar access. The effect was less pronounced using the November-December measurements of solar access (Figure 3-8).

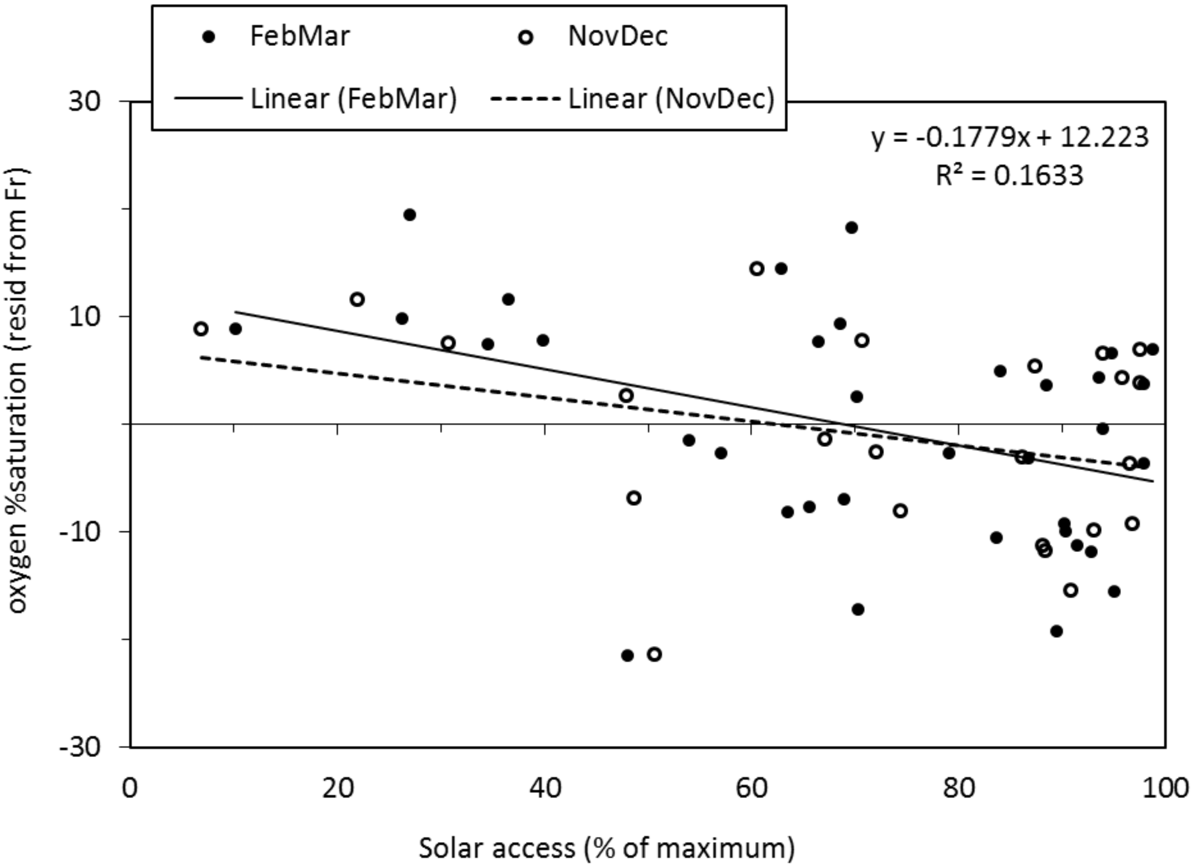

Figure 3-8: Oxygen versus solar access. Oxygen variability that was not explained by the relationship with Froude number (residuals from Figure 3-3 equation) is plotted against solar access (mean of 10 cross-sections). Solar access was measured February to March (dots) and again in November-December 2015 (circles), while oxygen was measured 21 January 2015.

3.5 Applying the Generalised Oxygen Model to the Heretaunga streams

The relationship between oxygen saturation and Froude number can be used to predict oxygen saturation for streams of the Heretaunga Plains under low-flow conditions. A map was produced (Figure 3-9) that identifies the proportion of MALF (mean annual 7-day low flow) predicted to achieve 40% daily minimum oxygen saturation. Calculation methods are described in Section 2.6. The reaches coloured red in Figure 3-9 are predicted to require more than triple the MALF to exceed 40% saturation, in contrast to the blue reaches where flow can drop to less than MALF and still exceed 40% saturation. Notably, the lower risk for Tutaekuri-Waimate Stream is a consequence of higher stream flow that can produce high velocities, despite the flatter gradient.

Many streams are not represented on the map because the information needed for the calculation (e.g. MALF, width) was not available (black dashed lines in Figure 3-9). In addition, the Paritua Stream was not mapped where MALF declines from 80 L/s to 0 L/s over the losing reach (about 5 to 10 L/s predicted to achieve 40% oxygen). Flow requirements for the large gravel-bed rivers were mostly excluded because the hydraulic geometry equations were not calibrated for this river type. Froude numbers for selected reaches of the Tukituki and Ngaruroro were estimated using pre-existing hydraulic models (RHYHABSIM) (Johnson, 2011a; Johnson, 2011b; Wood, 1998). The oxygen models were not calibrated to gravel-bed rivers, so should not be used for setting minimum flows for these rivers. However, the predictions are informative in deciding if oxygen is a critical issue in this river type (compared to hydraulic habitat, temperature, etc.).

The Generalised Oxygen Model can be used to guide the selection of minimum flow sites (i.e. monitoring sites for triggering restrictions on water use). Methods for prioritising sites, plus a prioritised list of potential monitoring sites is presented for each sub-catchment on the Heretaunga Plains in Appendix B.

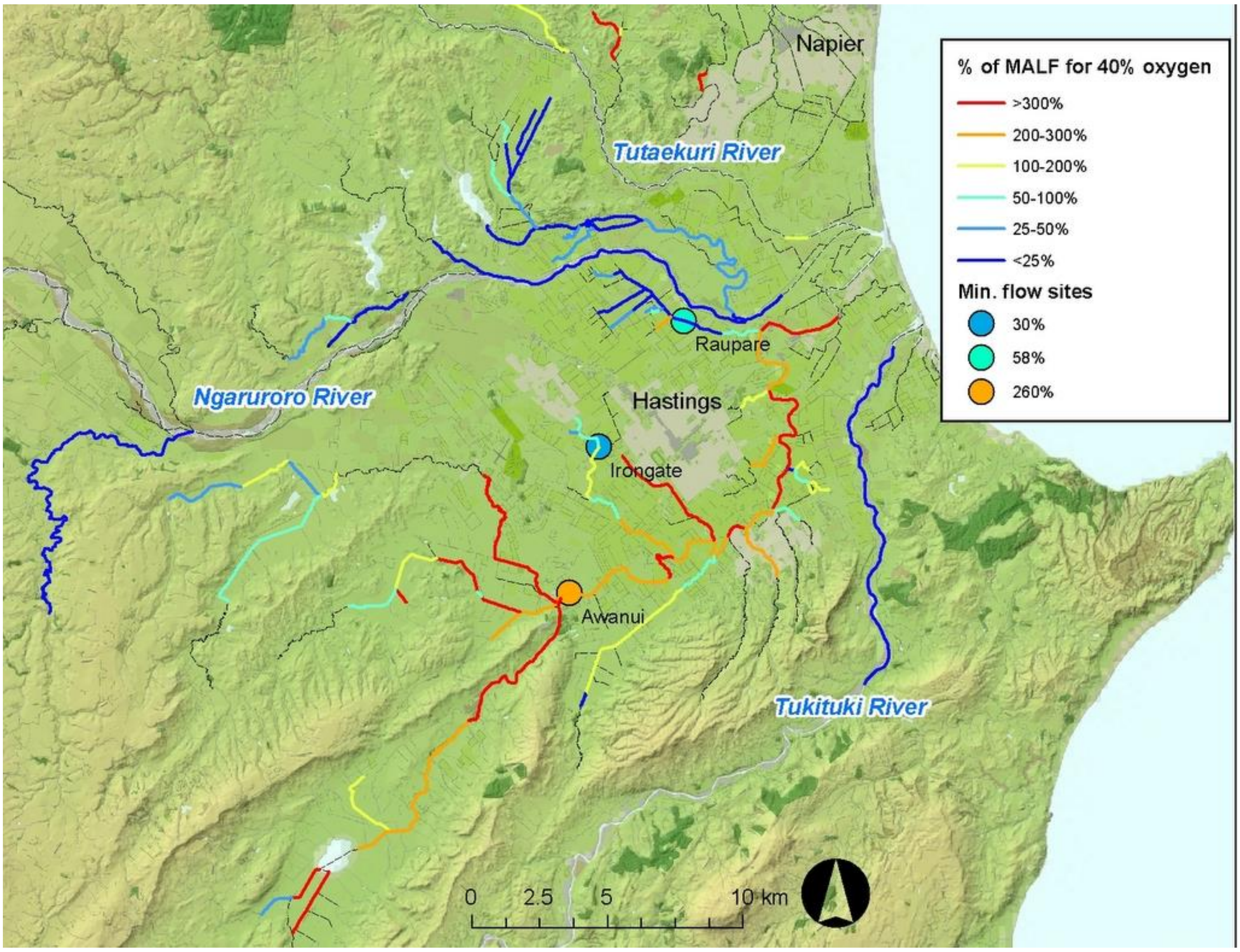

Figure 3-9: Flow required for 40% oxygen. The flow predicted to achieve a daily minimum 40% oxygen saturation is mapped as a percent of mean annual low flow (MALF). Stream reaches mapped in red are expected to experience the worst oxygen conditions during low-flow periods. The three minimum-flow sites are also mapped, with point colour representing the percent of MALF required for 40% oxygen (from intensive site-specific studies, (Wilding, 2015).

4 Discussion

4.1 A Model for Flow Management

A Generalized Oxygen Model was successfully developed for streams of the Heretaunga Plains. The model uses Froude number to predict oxygen, measured as a daily minimum oxygen saturation on 21 January 2015. Froude number increases with velocity and decreases with increasing depth, so is higher for fast, shallow riffles and lower for slow, deep pools.

The Generalized Oxygen Model was validated using another set of dawn oxygen measurements, spread over three years (total 50 samples across 5 occasions between 2013 and 2015). The validation data exhibited a similar rate of decline in oxygen with decreasing Froude number, so the predicted spatial pattern observed on 21 January 2015 is expected to be representative of the spatial pattern on different dates. The validation analysis indicated some difference in the magnitude of oxygen associated with a given Froude number. The Generalized Oxygen Model was predicting annual minima, rather than typical summer conditions. Supporting this conclusion, oxygen in the Raupare Stream on the sampling date for calibrating the model (21/1/2015) fell within the bottom 2% of daily minima (rank 13 from n = 864 days). The return period for such low oxygen conditions, for a given Froude number, could be even longer, given the severe droughts during that oxygen study period (e.g. Ngaruroro River during 2013 reached the lowest recorded since 1983). The long recession period required to reach such lows also reflects a lack of preceding flood events. Without those scouring flood events, long accrual of plant biomass and organic matter could increase the amount of oxygen consumed at a given Froude number. Validity of the Generalized Oxygen Model was also supported by time-series data (as opposed to spatial data) from Awanui Stream, which demonstrated a similar rate of decline in oxygen with Froude number compared to the spatial Generalized Oxygen Model. Flow was a better predictor than Froude number, for oxygen time-series data from Raupare Stream.

The relationship between oxygen and Froude number is valid for predicting spatial oxygen patterns for the Heretaunga Plains. However, a potential challenge with applying the Generalised Oxygen Model is the prediction of Froude number. Model sensitivity to Froude number has implications beyond model error. It is also about real-world drivers of oxygen dynamics. For example, if weed growth increased depths in the Raupare by 0.25 m at 300 L/s, this would decrease predicted oxygen from 56% to 41% saturation. One benefit of simpler oxygen-Froude models, compared to more complex process-models (e.g. SEFA), could be to foster research more focussed on seasonal changes in channel roughness from aquatic plant growth (e.g. characterisation and prediction), rather than point-in-time reaeration estimates (e.g. gas tracer studies). The potential use of the Generalised Oxygen Model for recommending minimum flows (rather than location) deserves further investigation. This is likely to require on-site measurements to produce accurate estimates of Froude number and how this changes with flow.

The sensitivity of oxygen predictions to variability in Froude number, including the estimated depth and velocity used to calculate Froude, means that a different model should be used if only poor estimates of Froude number are available. For example, the unit stream power model (Figure 3-2) does not require depth or velocity (based on flow, width and reach slope). Another model from this report only requires reach slope (Figure 3-1), with low oxygen more likely in streams that have a slope less than 2 m/km. These models are less able to distinguish streams with low oxygen, compared to the oxygen-Froude model, and the slope model is more likely to predict an oxygen problem where there is not one. That error might be acceptable for some spatial planning purposes, such as national screening for oxygen standards, especially if accurate estimates of Froude number are not possible.

The Generalised Oxygen Model does not predict oxygen in groundwater and, due to the effect of low-oxygen groundwater, one spring site was excluded from analysis. This site was sampled at the spring head, where flow is entirely from groundwater discharge at the observation location. Oxygen at other sites responded more consistently to Froude number, despite many streams also being sourced from upstream springs. This result indicates that oxygen was predominantly constrained by flow and channel hydraulics, with only localized constraints imposed by low-oxygen groundwater.

Those localized effects may be limited to within a few hundred metres of the spring, as demonstrated using experimental discharges of anoxic groundwater to the Harakeke Stream. In this experiment, the effect on oxygen transitioned from negative to positive within a few hundred meters of the groundwater input (Internal Files 1). The higher oxygen levels in the spring-dominated Raupare, compared to the runoff dominated Awanui, provide further evidence of the net benefit of higher groundwater inputs.

The biological consequences of low oxygen were also investigated. The Awanui and Raupare have been the focus of in-depth monitoring and study (Wilding, 2015). The contrast in oxygen conditions, in otherwise similar streams, provided a rare opportunity for examining the effects of low oxygen on fish. Despite the similarities, many possible confounding effects remain, including fish movement between streams. Therefore, monitoring cannot demonstrate an absence of impacts on fish health from low 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).

The Awanui experienced overnight anoxia during low flows (77 days in 2013), compared to the Raupare that remained above 40% oxygen saturation for 99.1% of the time (2013-2015). Inanga in Awanui Stream were found to be in worse condition, when compared to inanga in Raupare Stream. Low oxygen is expected to reduce the rate at which the fish gain weight, and the mechanisms of that reduction can include increased stress and decreased feeding periods (Kramer, 1987). Inanga were observed gulping at the surface in Awanui Stream when oxygen was 2.5% saturation (8:45am 24/2/2015; 20.2 °C; 55 L/s). This gulping behaviour provides further evidence that low oxygen was responsible for reduced inanga condition, as opposed to other differences between the two sites.

There were also differences in the diversity of fish species, with seven native species recorded from the Raupare, compared to four from the Awanui. It is not certain that lower oxygen was the cause of lower diversity for the Awanui Stream, as there are other habitat differences between the two sites. For example, yelloweyed mullet were probably prevented from reaching the Awanui because it is further from the coast (McDowall, 2000). Inanga were the most common fish observed in the Awanui, but only two inanga were observed during an extended period of anoxia (between mid-January 2013 and the following whitebait migration). The loss of populations exposed to low oxygen was demonstrated by a fish kill about 800m upstream of the Awanui flume (Karewarewa Stream at Pakipaki) a week after the dawn oxygen survey (on 26/1/2015), with dead eels and goldfish observed, together with black stream water that had a sulphurous smell. Spot measurements of oxygen and temperature were taken the afternoon after the fish kill was reported, and these indicated that the duration of anoxia had extended throughout the day when water temperatures reached 24 °C.

The Generalised Oxygen Model predicts oxygen using Froude number. The model was only able to achieve its intended purpose for representing many streams because it is a simplification of the real-world. A more complex process model would require detailed data inputs that cannot be measured for the entire stream network. Froude number is likely a proxy for oxygen reaeration (see Section 1.3), and was estimated using stream flow, channel width and channel slope (as predictors of velocity and depth). Other factors that could affect reaeration, but were not measured, include substrate type (e.g. rocks or weed that increase turbulence), wind and surface tension (Cox, 2003; Jowett, 2012). In addition to reaeration, there is likely to be a covariance between Froude number and other oxygen drivers that improve the models predictive success. Those other drivers may include deposition of organic matter and abundance of aquatic plants (Knighton, 1998; Madsen *et al.*, 2001; Riis & Biggs, 2003).

Previous studies have developed similar models for predicting oxygen reaeration, using various combinations of velocity, depth and stream slope (Cox, 2003; Jowett, 2012). However, when applied to the Heretaunga oxygen data, the models from earlier studies did not perform as well as Froude number. Notwithstanding, there are methods that may provide better predictions than the Generalised Oxygen Model. The following list ranks oxygen-flow models, from most to least accurate, based on my opinion:

(1) measured oxygen-flow response specific to each site

(2) process model (e.g. SEFA or night-time respiration) calibrated to each site

(3) Generalised Oxygen Model based on Froude number estimated using rapid survey of each site

(4) Generalised Oxygen Model based on Froude number estimated using hydraulic geometry equations

(5) Channel slope predictive equation (this report)

(6) Default %MALF minimum flows

That order assumes each method is properly implemented. The Generalised Oxygen Model is complimentary to site-specific methods because of the larger scale at which it operates. For example, the Generalised Oxygen Model can be used to guide where a process model should be applied to best represent the stream. The ability to represent stream reaches over larger areas also enables the Generalised Oxygen Model to guide decisions that reach-specific process models cannot. Potential uses of the Generalised Oxygen Model include:

- Guiding selection of flow monitoring sites that better represent the risk of low oxygen (i.e. “minimum flow sites” that trigger water use restrictions)
- Guiding the selection of sites for more intensive study of oxygen-flow relationships
- Estimating the minimum flow for streams with a lower risk or lower value, if used with Froude-flow models calibrated from site-specific rapid surveys
- Providing a screening tool for deciding if oxygen should be investigated in detail for instream flows, rather than hydraulic habitat, temperature, etc.
- Providing a foundation for oxygen standards that are relevant and achievable for streams of interest (e.g. lower oxygen limit for streams with physical limitations on oxygen potential)
- Providing estimates of oxygen for use in biota-environment studies (e.g. predicting distribution of oxygen sensitive species)
- Providing a Generalized Oxygen Model framework for calibration in other regions. The Generalised Oxygen Model could also be used to inform the selection of validation sites.

The Generalised Oxygen Model was used to guide selection of minimum flow sites on the Heretaunga Plains and a prioritised list of sites for each subcatchment is presented in Appendix B. Site selection is largely a subjective process, and this process is better informed by application of the Generalized Oxygen Model. Priority was based on three principal criteria, including better representation of: reaches at risk of low oxygen; when low-flows occur; and reaches with the highest water demand. See Appendix B for other criteria. The flexibility of a prioritised list allows sites to be added in future, as water demand increases. That flexibility also allows stakeholders to choose sites based on other criteria, such as higher instream values.

Minimum flows for the monitoring sites could be based on the Generalised Oxygen Model, or intensive process models (i.e. SEFA). Only three of the priority sites were the subject of SEFA modelling (Wilding, 2015). More sites could be assessed using SEFA modelling, where resource use and instream values justify the cost.

4.2 Implications for Management of Riparian Shade and Aquatic Plants

Aquatic plants can constrain oxygen saturation at dawn by reducing reaeration and increasing respiration. Seasonal growth of aquatic plants increases channel roughness and this increase translates to deeper water, with slower velocities for a given flow (Champion & Tanner, 2004; Madsen *et al.*, 2001; Wilcock *et al.*, 1999). This is a negative for Froude number, and therefore a negative for oxygen minima, as predicted by the Generalised Oxygen Model. In addition to reducing reaeration, more aquatic plants will also consume more oxygen through respiration. The change in respiration over time is complex, reflecting water temperature and the accrual of rooted aquatic plants, filamentous algae and organic matter in the sediment (Cox, 2003). The slowing of water by aquatic plants introduces a positive feedback, by further promoting the deposition of organic matter (Madsen *et al.*, 2001).

The plant accrual process can be halted by flood disturbance and senescence (Franklin *et al.*, 2008; Riis & Biggs, 2003). By measuring oxygen on the same day at all sites, the Generalised Oxygen Model was controlled for some of the complex temporal variation, including seasonal and diel changes in sunlight and temperature, plus seasonal accrual of plants. The Generalised Oxygen Model predicted oxygen at the time of day and at the worst time of year when oxygen is lowest.

The model incorporates the respiration effects of a typical plant community (average plant abundance across the study sites). The hydraulic geometry model used to predict depth also incorporates channel roughness produced by a typical abundance of aquatic plants. Aquatic plants are generally more abundant in deeper, slower flowing streams (Franklin *et al.*, 2008; Riis & Biggs, 2003), so it is reasonable to expect a plant-Froude response to be incorporated into the Generalised Oxygen Model as a useful autocorrelation. What is not built into the model is shade. Shading from riparian vegetation has the potential to constrain plant abundance (Dawson & Haslam, 1983) independently of Froude number. Variability in solar access would therefore increase variability in the oxygen-Froude relationship. The effect of solar access was investigated by measuring solar access and plant abundance at the oxygen sampling sites.

Dawson and Kern-Hansen (1979) expressed concern that more than “half-shade” would be undesirable as it was likely to eliminate aquatic plants altogether, which provide important habitat. That concern was not supported by results from Heretaunga streams, where only streams with less than 10% solar access were associated with few or no plants. Rutherford *et al.* (1997) recommended 70% shade for reducing stream temperatures. Heretaunga results support 70% shade as a target, with cover of filamentous algae and submerged aquatic plants constrained at sites with less than 30% solar access. Oxygen was also higher; averaging 10-15% more oxygen at sites with less than 30% solar access, for a given Froude number.

The benefits of riparian shade and flow management can also extend to the aquatic plants themselves. Aquatic plants may be responsible for oxygen dropping below 50% saturation, but the health of the plants themselves may be all that prevents a low-oxygen stream from collapsing to a persistently anoxic stream. The health of aquatic plants is compromised at velocities less than 0.1 m/s (Franklin *et al.*, 2008; Riis & Biggs, 2003) because plants also depend on reaeration of oxygen and carbon dioxide for survival (Crawford, 1992). As velocities drop below 0.04 m/s, filamentous algae can proliferate and ultimately smother the aquatic plants (Franklin *et al.*, 2008). This velocity threshold was supported by aquatic plant monitoring in the Awanui Stream (Wilding, 2015). The maximum daily oxygen, instead of minimum, provides a measure of plant productivity. For a given level of plant production, maximum oxygen should increase as flow recedes because of reduced dilution of photosynthetic production. But, in the Awanui, maximum oxygen started to decline at very low flows (e.g. 22/12/2012, 7/1/2015). These declines in daily maxima from >150% to <80% saturation coincided with flows dropping below 80 L/s. This decline in productivity provides further evidence of stress on aquatic plants under low flow conditions.

The anticipated benefits of riparian shading for improved oxygen supply are likely to under-estimate the benefits of riparian shading for fish. The other potential benefit of riparian shading, which was not investigated for this report, is reduced oxygen demand (Figure 1-2). Oxygen demand is how much oxygen fish require to meet metabolic requirements (Verberk *et al.*, 2011) and oxygen demand increases with temperature (Clarke & Fraser, 2004). Climate and riparian shading are expected to be the primary constraints on stream temperature for small low-gradient streams (Bartholow, 1989; Poole & Berman, 2001). Flow can also affect temperature, but the effect is relatively small in streams that are narrow enough to be shaded by riparian vegetation. Along with flow management, riparian shade may be used as an instream management tool by Hawke's Bay Regional Council. In my opinion, riparian shading should be given higher priority where flow management alone cannot achieve adequate oxygen supply.

Carefully timed herbicide application could be complimentary to riparian planting. Rather than eliminate aquatic plants altogether, if herbicide is applied at a time of year when flow and reaeration is high enough to offset plant decomposition (e.g. spring), the plant biomass could be reduced to a level that would delay the accrual of biomass to nuisance levels. Note, my recommendation for herbicide application when flows are higher is contrary to advice from the New Zealand Environmental Protection Agency, which advocates applying herbicides when oxygen is less than 4 mg/L (EPA, 2013). The Environmental Protection Agency have perhaps confused protection levels with lethal levels, when they conclude that "fish and other organisms are unlikely to be present" at less than 4 mg/L of oxygen (EPA, 2013). Personal observations from Heretaunga streams, and results from ecotoxicity testing (Dean & Richardson, 1999; Franklin, 2013; Landman *et al.*, 2005), demonstrate that most native fish and trout are alive when oxygen drops below 4 mg/L, but are at their most susceptible to further oxygen reductions (e.g. from decomposing plants).

Available herbicides, including Diquat and Metsulfuron, are relatively ineffective against algae, when applied at the recommended dose for rooted plants (Phlips *et al.*, 1992; Wendt-Rasch *et al.*, 2003). Conversely, riparian shading appears more effective in controlling filamentous algae, than controlling rooted aquatic plants. Hence, shading could reduce the chance of an herbicide-induced flip from macrophyte-dominated to filamentous algae in sluggish streams.

4.3 Other Management Options

Engineering options for rapid reaeration include weirs and bubblers. Weirs create long sections of still backwater that would reduce oxygen. For example, a weir that is 0.5 m high would propagate backwater 500 m long, if the channel slope is 1 m/km (Figure 2-2). That backwater of reduced oxygen is undesirable, especially if it is longer than the downstream section of stream that experiences increased oxygen. Bubblers are costly to install, power and maintain in a stream environment where damage from floods is inevitable, as is weed blockage during low flows. These engineering options also lack many of the benefits that riparian planting offers, including reduced stream temperature and improved scenic and recreational opportunities for people.

4.4 Oxygen Standards for Low-Gradient Streams

The "National Bottom Line" for oxygen is 5 mg/L and, at typical summer dawn temperatures of 15°C, 5 mg/L equals 50% saturation. That bottom line is stipulated in the National Policy Statement for freshwater as a 7-day mean of daily minima (MfE, 2014). A lower standard of 40% oxygen (4 mg/L at °15 C) is included in the standards. But the application of the lower standard is extremely limited, given it is specified as the lowest the stream can drop to, as an instantaneous measurement, for the entire year (i.e. a 1-day minimum for 1 November to 30 April). Despite these standards only applying below point discharges (i.e. not below water takes), the National Policy Statement still represents the obvious first choice for selecting limits. The oxygen limits proposed below depart from these standards. A peer reviewer of this report, who also developed the oxygen thresholds that were adopted in the National Policy Statement, did not agree with the lower standards proposed here. The reviewer argued that oxygen less than the National Bottom Line would not sustain a healthy fish community, taking into account sub-lethal effects. The reviewer also argued that low-gradient streams were unlikely to drop below the national standards, except as a consequence of land use, water use and introduced aquatic plants. While this report provides a rationale for alternative oxygen standards, the decision on which to use rests with resource managers.

The National Policy Statement standards may be more appropriate if macroinvertebrates are selected as the target value for management. Observed oxygen in Raupare Stream is unlikely to be adequate for invertebrates, as demonstrated by Haidekker (2016), who revealed low MCI scores in Raupare Stream. Additionally, high temperatures and low oxygen were correlated with degraded MCI scores in streams of the Heretaunga Plains. But, if the values to be sustained are native freshwater fish, then I recommend oxygen limits that are lower than the national standards for three reasons:

1. Low-gradient streams of the Heretaunga Plains will not meet NPS standards because of physical constraints. Using the Generalised Oxygen Model, many low-gradient streams are predicted to require flows well in excess of MALF in order to meet the national standards (e.g. Karewarewa, Poukawa).

2. Monitoring for this report indicated that fish communities in the Raupare Stream are diverse, and inanga are in relatively good health, despite this stream failing to meet the NPS standards for oxygen.

3. In my opinion, the NPS standards are overly conservative for this application. I expect lower oxygen levels to provide adequate protection during low-flow periods for native freshwater fish that inhabit low-gradient streams, dominated by aquatic plants.

Expanding on the third point, the National Bottom Line of 50% oxygen is more conservative than the 40% oxygen standard that I have recommended in the past for low-gradient streams (Wilding, 2007), and more conservative than USEPA standards for non-salmonid streams (USEPA, 1986). Any national standards must cater for all species and life-stages because of the wide range of potential applications (e.g. discharge consents, water use). However, limit-setting for water allocation on the Heretaunga Plains can be more targeted, and I recommend targeting adult native freshwater fish. Summer low-flows for low-gradient streams of the Heretaunga Plains are unlikely to coincide with whitebait migration, which peaks in spring (Wilding, 2000). It is difficult to justify setting oxygen limits for trout, or their developing eggs, because: i) these low-gradient streams do not support a valued trout fishery (Booth *et al.*, 2012); and ii) spawning and egg development is unlikely to coincide with low flows (Wilding, 2000).

Table 4-1: Oxygen standards from the NPS. This table is reproduced from the 2014 National Policy Statement for Freshwater Management (MfE, 2014). "It is up to communities and iwi to determine the pathway and timeframe for ensuring freshwater management units meet the national bottom lines". These standards apply to rivers below "point discharges", not below water takes.

Value	Ecosystem health		
Freshwater Body Type	Rivers (below point sources)		
Attribute	**Dissolved Oxygen**		
Attribute Unit	mg/L (milligrams per litre)		
Attribute State	**Numeric Attribute State**		**Narrative Attribute State**
	7-day mean minimum[1] (Summer Period: 1 November to 30th April)	1-day minimum[2] (Summer Period: 1 November to 30th April)	
A	≥8.0	≥7.5	No stress caused by low dissolved oxygen on any aquatic organisms that are present at matched reference (near-pristine) sites.
B	≥7.0 and <8.0	≥5.0 and <7.5	Occasional minor stress on sensitive organisms caused by short periods (a few hours each day) of lower dissolved oxygen. Risk of reduced abundance of sensitive fish and macroinvertebrate species.
C	≥5.0 and <7.0	≥4.0 and <5.0	Moderate stress on a number of aquatic organisms caused by dissolved oxygen levels exceeding preference levels for periods of several hours each day. Risk of sensitive fish and macroinvertebrate species being lost.
National Bottom Line	**5.0**	**4.0**	
D	<5.0	<4.0	Significant, persistent stress on a range of aquatic organisms caused by dissolved oxygen exceeding tolerance levels. Likelihood of local extinctions of keystone species and loss of ecological integrity.

1. The mean value of 7 consecutive daily minimum values.

2. The lowest daily minimum across the whole summer period.

The first consideration in establishing adequate oxygen levels for adult native fish is their tolerance of low oxygen. Scientific research into the oxygen tolerances of fish has determined the lowest oxygen concentration that can be tolerated before death results. For example, the 48h LC50 is the concentration lethal to 50% of organisms after 48 hours of continual exposure. For adult native fish, the acute tolerances were less than 20% oxygen, when given access to the water surface (Dean & Richardson, 1999; Landman *et al.*, 2005; Urbina *et al.*, 2012). These acute tolerances are still conservative, given the 48-hour duration of tests, compared to the 6 to 12-hour duration of oxygen minima typically observed in streams dominated by aquatic plants on the Heretaunga Plains. Longer duration anoxia was observed in Awanui Stream, but this only occurred after the day when diel minimum oxygen first dropped to 0% oxygen (if ongoing recession was not interrupted by rain). So, daily minimum standards would be breached as a precursor to an extended duration of low oxygen in streams where aquatic plants drive the oxygen dynamics. The longer-duration acute tests remain relevant for any standards based on daily means, rather than daily minima.

Oxygen limits are conventionally set to be more protective (i.e. more oxygen) than acute tolerances because of the sub-lethal effects that can impact population viability (Davies-Colley *et al.*, 2013; Franklin, 2013). For example, exposure to low-oxygen could enable a fatal disease to spread through a weakened population. For adult native fish, all but one of the studies did not detect sub-lethal effects on inanga at more than 30% oxygen. The one exception was a study of burst swimming speed of whitebait (juvenile inanga) that detected a decline from 5 to 4.1 body lengths per second when oxygen dropped from >96% to 75% at 15 °C (Bannon and Ling, 2003, cited in (Franklin, 2013). Although a good method for determining optimum conditions for juvenile inanga, I would not use optimum oxygen levels in the setting of regulatory bottom lines. In justifying higher oxygen standards that minimise sub-lethal effects, Franklin (2013) also cited a study by Urbina *et al.* (2011) of behavioural response of adult inanga to low oxygen. But that study only found a detectable increase in surface respiration at 20% oxygen, relative to normoxia (100% oxygen). The small increase in surface respiration at 30% oxygen was not statistically significant.

In developing alternative oxygen standards for low-gradient streams, a definition of low-gradient streams is first required. We can use the National Bottom Line for defining the low-gradient streams. The Generalised Oxygen Model predicts that, on average, streams with a Froude number of 0.075 or less (reach average) would not meet the National Bottom Line of 50% oxygen at 15 °C. About half of the reaches in the Heretaunga stream network are not expected to exceed 0.075 at mean annual low flow. To put that Froude number in more tangible terms, most of the Heretaunga reaches with a Froude number less than 0.075 have a slope less than 2 m/km and mean annual low flow less than 400 L/s.

I propose two standards for low-gradient streams where aquatic plants drive oxygen dynamics. First, an **oxygen standard of 40% oxygen** is proposed to protect adult native freshwater fish. The Raupare Stream remained above 40% oxygen saturation for 99.1% of the time (2013-2015), and this stream supported a diverse range of native fish, as well as freshwater mussels, crayfish and aquatic plants. The Raupare supported abundant inanga in better condition than the Awanui. Oxygen sensitive species like rainbow trout and common smelt were also present. This standard is also expected to provide velocities over 0.1 m/s (from the Raupare hydraulic model), which is within the preferred range for aquatic plant communities (Franklin *et al.*, 2008; Riis & Biggs, 2003). The Raupare is also representative of typical flow alteration on the Heretaunga Plains (timing and duration), with stream flows that are depleted via groundwater wells used to irrigate orchards and crops, plus instream abstractions (HBRC, 2014). It is therefore reasonable to expect that low-gradient streams exceeding 40% oxygen saturation can support a diverse and functioning ecosystem. This is recommended as a diel minimum in low-gradient streams dominated by aquatic plants, where oxygen saturation increases during the day with water temperature. This limit would not provide adequate protection during the whitebait migration season, when more sensitive juvenile inanga are present. The NPS standards are more appropriate during the whitebait migration period (inanga and common smelt) of August to mid-November (Hamer, 2007; Smith, 2014; Wilding, 2000).

In streams that are far from meeting the National Bottom line, or even the 40% standard, there are critical thresholds for survival that can be transgressed as a consequence of reduced flow. To reinforce the point that these streams should not be written off, but rather prioritised for flow and riparian management, I propose a second standard. This standard is intended to protect against collapse of aquatic plant biomass because such a collapse can have lethal consequences for fish. A biomass collapse can be lethal when it results in the duration of anoxia extending from morning to late in the afternoon, to coincide with maximum temperature and peak oxygen demand by fish. This standard is a **water velocity of 0.04 m/s** (reach average), which is a threshold below which filamentous algae can proliferate and, given a long enough accrual period, ultimately smother the rooted aquatic plants (Franklin *et al.*, 2008; Wilding, 2015).

Smothering can trigger the collapse of the entire plant biomass, which can result in enduring anoxia that even the most tolerant fishes cannot survive. Such a collapse was observed in the Karewarewa Stream, where the death of tolerant fish (eels and goldfish) followed the collapse of the aquatic plant community (26/1/2015). For low-gradient streams, maintaining healthy communities of aquatic plants recognises the plants themselves as an important component of the stream ecosystem, both intrinsically and as habitat for other species. The benefit of the standard is the reduced duration of anoxia, rather than the magnitude of daily minimum oxygen. Mitigation measures are recommended for water use that cannot comply with this lowest of standards (see Section 4.2).

The Awanui Stream at the flume is a good example of the type of stream where the velocity standard could be applied. Here, the reach average velocity of 0.04 m/s was exceeded at flows greater than 110 L/s (from SEFA hydraulic model), compared to mean annual low flow of 84 L/s. The Awanui does not support a fish community as diverse as the Raupare. Inanga were still alive in the Awanui at flows as low as 40 L/s, but the condition factor of inanga was impacted. Hence, these fish would benefit from restricted water use during these periods.

Oxygen standards are discussed here in units of percent saturation. Oxygen saturation is a better measure of oxygen supply than oxygen concentration, so better aligns with flow management as a driver of oxygen supply. Some standards use oxygen concentration instead (MfE, 2014; USEPA, 1986). The use of oxygen concentration for limit setting by the United States Environmental Protection Agency (USEPA, 1986) was arguably an attempt to simplify the effect of temperature on the biological demand for oxygen (see also section 4.7.2 in (Canada_MoELP, 1997). Respiratory demand increases with temperature for any given species. Hence, oxygen concentration gives a more linear response for each species. But, between species, there is large variability in respiratory demand that is not accounted for by temperature (Clarke & Johnston, 1999).

The USEPA made some attempt to incorporate this variability between species using lower concentration limits for “warmwater fish”. The single New Zealand standards make no such attempt (Davies-Colley *et al.*, 2013; Franklin, 2013). One problem with simplified concentration-based standards is that variation between species is ignored and, further, the importance of temperature becomes concealed in the derivation of concentration. In this report, I recommend a change from managing oxygen concentration to instead explicitly managing both oxygen demand and oxygen supply. This highlights the importance of both flow management and riparian management in determining the biological response (Figure 1-2).

4.5 Future Research and Investigations

New innovations in science were required to develop the Generalized Oxygen Model, which brought together concurrent dawn surveys of oxygen saturation, developing new hydraulic geometry equations for predicting Froude number, plus creating new stream maps for the Heretaunga Plains. Previous studies have investigated spatial risk of low oxygen (Wilding *et al.*, 2012), which were improved on here using high-resolution elevation data (LiDAR), concurrent dawn surveys and validation surveys. It is anticipated that the Generalized Oxygen Model will inform the process of reviewing flow and allocation limits that considers ecological response to reduced flow. However, the results from this study leave room for further work in several areas, including evaluation of climate change effects.

Several decades could separate when the model was calibrated (2015) from when resource consents expire that were informed by the Generalized Oxygen Model. The climate is expected to change over that timeframe. The model predictions can be rerun if stream flow or channel form changes. However, increasing temperatures could increase respiration rates (directly or via more rapid accrual of biomass), and therefore decrease the oxygen achieved by a given Froude number. State of environment monitoring plays an important role in determining if the Generalised Oxygen Model requires revisiting. In addition, future development of the Generalised Oxygen Model could incorporate large-scale temperature drivers by calibration at larger spatial scales (e.g. from Southland to Northland). A larger-scale model could provide better insight to the effects of long-term increases in temperature, provided it controls for finer scale variables (e.g. channel slope, seasonal and diurnal solar cycles).

The introduction of National Environmental Monitoring Standards (NEMS) (Wilcock *et al.*, 2013) will likely improve the quality and comparability of oxygen monitoring across New Zealand. However, the national standards focus on quality of data for each site in isolation, so have the potential to incentivise councils toward better monitoring at fewer sites. The push toward sites where high quality standards are obtainable could bias the monitoring network away from resource stressed sites to, for example, locations where aquatic plants do not foul the sensor housing. What is needed, in addition to site-specific monitoring standards, is guidance on the appropriate scale for measuring environmental response to resource use (Wilding, 2012). For example, concurrent dawn sampling across an area the size of the Heretaunga Plains revealed the role of geomorphic drivers (e.g. channel slope and width) in determining oxygen response to water use.

Channel slope changes little at a site, so would not appear important from monitoring one site to a high NEMS standard. For example, oxygen was better correlated with flow than Froude number for Raupare Stream, which is not surprising given the lack of change in slope and width over time. Likewise, the spatial scale of the Generalized Oxygen Model was too small to reveal the role of climatic drivers because it focused on one climatic zone (Heretaunga Plains). Hence the appropriate scale for investigating the response to climatic drivers would be larger (e.g. national extent). Large dams can alter a climate driver by changing the disturbance regime of a river, and the role of floods is also more likely to be revealed by large-scale studies (Wilding, 2012).

The different scales of investigation are complimentary, with the finer-scale investigations revealing the patterns that need to be accounted for in larger-scale investigations. For example, time-series oxygen monitoring in Awanui Stream demonstrated a diel pattern that needs to be accounted for when making spatial comparison across streams of the Heretaunga Plains (e.g. using dawn surveys of diel minima). Conversely, spatial models can tell us where time-series monitoring is most useful. Accounting for Froude number improved our ability to resolve the influence of riparian shade. Future investigations into the effect of riparian shade on oxygen saturation may benefit from measuring solar access over a longer reach, given that oxygen saturation at a single measuring point integrates conditions over a long section of stream (Chapra & DiToro, 1991).

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Internal Files

Links to internal documents, for HBRC staff use.

Internal File 1

http://herbi.hbrc.govt.nz/site/hydro/311SWRI/Reaeration%20experiment%20Harakeke%20well.docx

Internal File 2

\\fileserv\Enviro\E_Science\Projects\311 SW R&I Hydro\600_Karamu\01 IFIM\GIS\Geomorphic template

Internal File 3

\\fileserv\Enviro\E_Science\Projects\311 SW R&I Hydro\600_Karamu\01 IFIM\Analysis\hyd geometry\MALF estimates for Heretaunga streams V2.xlsx

Internal File 4

M:\E_Science\Projects\311 SW R&I Hydro\600_Karamu\01 IFIM\Analysis\oxygen\Spatial oxygen risk\Oxygen dawn spatial analysis version 4.xlsx

Appendix A Stream Mapping Procedures

Topology Steps

Stream reaches were individually inspected to be sure all flowed downstream (symbology "arrow at end", double-click on line – right click – flip). A topology was then used to check that reaches were connecting correctly by working through the following topology rules:

- Must not have dangles
- Must not overlap
- Must not self-overlap
- Must not self-intersect
- Must be single-part

To create a topology, a "feature dataset" was created within the geodatabase (arccatalog-right click on geodatabase heading - new - feature dataset - work through wizard). Copied and pasted feature class (e.g. streams layer) into the new feature dataset (not drag and drop). Then created the topology (Right click on feature dataset - new – topology). Added topology rules (right click on Heretaunga_Streams_Topology, properties – rules tab). Then right clicked on topology (arccatalog-geodatabase-feature dataset – topology feature), clicked validate (beware software bug - the "no errors" dialogue hides behind arcmap window and prevents all menus working – so close dialogue). Dragged "Heretaunga_topology" layer from arccatalog onto workspace layers, then it highlighted errors.

These checks were recommended for streams in Digitizing Procedures (page 13). I completed "must not have dangles" first, and this revealed a few places where reaches did not connect properly. I corrected the mistakes in the original feature ("Editing Streams") because the arcmap topology edit tools were causing me headaches. To add the other rules listed above, right click on topology – properties – rules tab. I did not include the stream area polygons in the topology simply because I do not know the benefits of doing so.

Added "Heretaunga_Springs" to topology, then added rule for all points to intersect "Streams Editing" line ("must coincide with endpoint of" streams layer). Moved those that did not (in some cases I moved the stream line).

Length

"Shape_Length" of polyline (reach length, metres) auto-populates and auto-update after changes are saved. Autopopulated fields like Shape_Length are not transferred across in spatial joins, so additional attribute "Length" was created for joins, which required manual updates (right click on field heading "Length" – calculate geometry – property dropdown – length).

Width

First created a polygon for most reaches in a shapefile called "stream_polygons". Each polygon outlined the active channel that was wet and attempted to include emergent vegetation but exclude terrestrial vegetation (using aerial photo plus LiDAR). Exposed gravel or sand bars were included as active bed (especially Maraekakaho, Ngaruroro, Tukituki, Tutaekuri). Some wetlands on Raupare Stream on Pakowhai Regional Park were excluded (assume excavated as part of landscaping old Ngaruroro bed). Polygons were not drawn for the smallest drains because it was hard to distinguish water. I included the smallest tributaries in width calculations only if spring-dominated (e.g. Raupare, Tutaekuri-Waimate, Irongate and Mangateretere).

Polygon area and length was automatically generated by ARCMAP when I converted this shapefile to a geodatabase feature class (confirmed correct using Calculate geometry option). But I did need to keep an attribute called “AreaImp” (field calculator = shape_area) in order for area to be copied over in spatial join (ARCMAP refused to import shape_area with join).

I manually went through every polygon to check that the reach delineation matched the stream polyline delineations and that no polylines had more than one overlapping polygon. Also, the join generates a “Count_” attribute which counts the number of area polygons joined (checked and repaired any with more than one).

Joined polygon area attribute to Editing_Streams layer using:

Arctoolbox-analysis tools-overlay-Spatial join:

Set Editing_Streams as target, Stream_Polygons as join feature, Editing_Streams_width as output, join one to one, keep all features, match option “intersect”.

The other match options returned too few or too many joins.

Width was then calculated using the following script:

Width_m = [Area] / [Shape_Length]   VB script

This width was a reasonable representation of width at mean flow for single thread channels, but overestimates width for braided rivers (see quick checks). Therefore I classified streams in a new field “StreamClass” (most are class “Single”; class “Braided” for Tutaekuri, Ngaruroro, Maraekakaho and Tukituki; class "Wetland" and class "Tidal"). A width at mean flow (“Width_Mean_m”) was created that uses “Width_m” values for all stream classes, except "Braided" where Width_m/2.8 was used (calculated in excel formula =IF(X2="<NULL>","<NULL>",IF(Z2="Braided",X2/2.8,X2)). Pasted back into Arcmap.

Note that the active channel width appears to approximate annual flood flow width. The stream length was longer than polygon length (describing low and high flow channel length respectively), causing a slight underestimate of active channel width (if corrected to polygon length, then an adjustment factor of 3 could be used instead of 2.8 to get to width at mean flow).

I also checked width against width estimated visually from macrophyte surveys completed for the riparian-macrophyte survey (median of 10 cross-sections).

Elevation Profile

Extract elevation from LiDAR terrain file where the polyline occurs. I had to convert from shapefile to a geodatabase and feature class to get this working.

Using ArcGIS 10 and 3D Analyst and following steps from this website:

http://gis.stackexchange.com/questions/22120/extracting-elevation-from-a-tin-file-with-a-point-shapefile-overlay:

Step 1: *Interpolate Shape tool* (ArcToolbox-->3D Analyst Tools --> Functional Surface --> Interpolate Shape). This will create a 3D Feature class/Shapefile from the 2D shapefile and the TIN input surface (I used conflate ZMIN, pyramid resolution 0). File named “Editing_Streams_Profile_highres”. (Step 2 is not needed)

After running, and new feature class is visible, select the desired polyline (e.g. select in attribute table, or use the select tool to click on reach) - go to 3Danalyst toolbar and click "profile graph" button. Right click on plot to export data for excel, etc.

To produce a low-resolution version that skips over some of the artificial bumps (roads, etc.), repeat step 1, except ticking the option to "interpolate vertices only" which only derives elevation at each vertex/point along line. I manually removed vertices that fell on roads, etc. so that this would represent the stream only. File named "Editing_Streams_Width_Profile".

Reach Slope

3D analyst – functional surface – add surface information (editing drains as polyline, lidar as surface – hbrc_sde_lidar.sdeadmin_heretaungaRutanhia_NZTM_MSL0m_terrainground, tick all outputs except min_slope (always zero), max_slope (too high by 100x).

Quality control for this data involved comparing elevation profile plots for EVERY reach to the automated (3D analyst) elevations. This demonstrated that Z-min was reliable and accurate, but Z-max was overestimated by such a degree to be unusable (even without road crossings, etc.). Because Z_min was reliable, I manually derived Z-max either from the Z-min for the reach upstream or from elevation profile plots. Having an exact match between Z-min from the upstream reach and Z-max for the downstream reach enabled compatibility with some groundwater model packages (elevation match at the point of intersection). To achieve this, I manually added the upstream reach ID (attribute name "ID_Upstream") to enable lookup of Z-min for upstream reach. Then used excel to lookup Z-min for upstream reach into a new column called "Z-max_edit". Where there was no upstream reach, I used the Z-max calculated by "add surface information" (in 3D analyst), plus data checking.

Excel lookup formula: =IF($X2=$A2,$K2,VLOOKUP($X2,$A$2:$J$305,10,FALSE))

For streams that extended beyond the LiDAR extent, I derived elevations from the 20 m contours on the topomap (1:50,000, NZMS260) and typed over the derived value in Z-min and Z-max-edit. Reach divisions on the upper Ngaruroro were carefully interpolated, whereas tributaries were less accurate (eyeballed to the nearest 10m in most cases). Only half a dozen streams extend beyond the LiDAR (e.g. Maraekakaho headwaters).

Stream "Slope_edit" was then calculated using {VB script} as:

([Z_Max_edit]-[Z_Min])/ [Shape_Length]

To check for errors in stream slope estimates, I inspected maps of slope using colour symbology (e.g. blue to red for decreasing slope). Stream slope generally decreases downstream, so any increase in slope for downstream reaches was inspected for errors (e.g. using elevation profiles for each reach). This sometimes revealed errors with polyline vertices rising over the stream bank. The slope was relatively flat for reaches close to sea level, so it was difficult to discern stream slope from noise in the LiDAR elevations. Streams close to the coast can appear to flow upstream – perhaps the tide was coming in at the time of the LiDAR survey.

Sinuosity

Derived coordinates of start and end point for each reach. Create new fields (start x, start y, end x, end y). Right click on each new field heading – calculate geometry – coordinates of line start (repeat for X, Y, start and end). Straight-line length calculated between points using field calculator for a new field named "Strlne_dst". Check python box then:

math.sqrt((!End_X! - !Start_X!)**2+(!End_Y! - !Start_Y!)**2)

Create field “Meander” with sinuosity calculated using field calculator as:

Check “python”

!Shape_Length! / !Strlne_dst!

Aspect

Problem – a 0 to 360 line direction does measure solar aspect (e.g. 2 degrees is equivalent to 358 degrees for solar aspect). So an aspect metric was created so that northerly aspect (either east-west or west-east flowing) had highest number, and easterly aspect (either north-south or south-north flowing) had the lowest number. This provides a monotonic relationship between aspect and solar insolation. I first calculated “line_direction” (0-360) using the following python script in field calculator:

180+ math.atan2((!End_X! - !Start_X!),(!End_Y! - !Start_Y!)) * (180 / math.pi)

source: https://geonet.esri.com/thread/27393

I then copied the output into excel, and converted from 0-360 direction to 0-90 solar aspect using following 2-step formula (i.e. each formula in a separate column):

=IF(AC2>180,AC2-180,AC2)

=IF(AD2>90,180-AD2,AD2)

Resulting output from second formula was then copied back into ARCMAP aspect attribute.

Appendix B Minimum-flow site recommendations

Methods

Flow is conventionally monitored at nominated sites to trigger water-use restrictions when flow drops below the nominated minimum (termed "minimum-flow sites"). Ideally flow would be monitored in every reach because no two reaches are identical. But monitoring everywhere all the time is not feasible. So, a subset of representative sites is required for monitoring. The first application of the Generalized Oxygen Model is to inform decisions on where minimum flow sites should be located. The prioritization of minimum flow sites was based on three principal criteria:

- **Spatial Risk** – the minimum flow sites should be spatially representative of the risk of low oxygen, with priority given to those sites that maximise the length of stream represented.
- **Temporal Risk** – the timing of restrictions on water use, as measured at the minimum flow site, should coincide with periods of low flow for other reaches that are represented by that site. The timing of low flows is not quantified for every reach. I therefore used my knowledge of flow regime drivers (climate, hydrogeology) to provide an informed opinion on which sites are broadly representative.
- **Water Demand** - Representing more reaches can be justified if there is more demand because water use is more likely to increase oxygen stress. Rather than recommend sites based on existing demand, this report provides a prioritised list of sites, so that more minimum flow sites can be added in future if water demand increases.

In addition to the principal criteria, several other factors were taken into consideration for recommending the minimum flow sites:

- Located downstream of takes – locating sites upstream of takes could adequately represent flow recession/timing, but upstream sites do not measure the flow alteration, and associated effects, that results from actual water takes. Additionally, people reducing their water use would not benefit from shortened water restrictions if the monitoring site is located upstream of their take.
- Measurement - site suitability for precise flow monitoring.
- Existing sites - prioritise sites with established record and existing infrastructure. Minimum flows are only one of the reasons we monitor flow (e.g. flood warning, State of Environment monitoring).
- Redundancy - omit a site if there is another minimum flow site further downstream where water restrictions will be first triggered.

These criteria were developed in consultation with the Heretaunga Technical Advisory Group (20 November 2015). This report provides a prioritised list of recommended sites. For the final decision on minimum flows, stakeholders may prioritise sites with higher instream or cultural values.

Awanui catchment

The Awanui River can be divided into four sub-catchments (Figure 6-1):

(1) **Poukawa** – drains hill country, Lake Poukawa and Pekapeka wetland. More intensive cropping is mostly confined to the wide valley (Figure 6-1).

(2) **Upper Awanui** – drains hill country and a drained wetland (Turamoe).

(3) **Karewarewa/Paritua** – the Paritua drains hill country, before passing through drained wetlands. After the Ongaru confluence, the Paritua crosses the Heretaunga Plains, losing water to old river-gravels (abandoned Ngaruroro channel). The 1931 earthquake changed the course of the Paritua downstream of Raukawa Road, and it now flows into the Karewarewa (or Kahu Moko). The Karewarewa channel gains flow from springs and the stream channel was realigned through the lower reaches.

(4) **Lower Awanui** – starts at the confluence of the above three streams at Pakipaki, and flows to the Irongate confluence, where the two form the Karamu Stream.

The lower Awanui site at the flume (Te Aute Rd) was given first priority as a minimum flow site (Figure 6-1). It could represent many stream reaches most at-risk of experiencing low oxygen (orange and red lines in Figure 6-1) including the three high-risk tributaries upstream of the monitoring site (Poukawa, Upper Awanui, Karewarewa). The Awanui flume site also directly represents a long reach that extends downstream as far as the Irongate confluence (Figure 6-1). Flow at the Awanui flume site integrates the effect of all water use upstream of the site (surface water plus groundwater takes).

Timing of low flows is unlikely to be coincident throughout this catchment, hence why other sites are nominated with lower priority. The timing of low flows at the Awanui flume site was close to the timing for Poukawa Stream, with annual 7-day low flows typically occurring late February to early March (median date for Awanui at flume - 5 March; Poukawa at Douglas Rd - 26 February). However, the timing of low flows at Douglas Rd may not be representative of the Poukawa Stream, given a lake-level control gate is operated a short distance upstream of Douglas Rd, plus the effects of storage and evaporation from Lake Poukawa and Pekapeka wetland. Consented water takes at six locations are linked to the Douglas Rd minimum flow site (at the time of writing). For the Karewarewa Stream, spot gaugings indicate that the annual low-flow typically occurs several weeks earlier than at the Awanui flume site (late-January to early-February from 202 spot measurements at Turamoe Rd and Pakipaki).

A minimum flow site is recommended for the Paritua Stream at the waterwheel, to represent the Paritua upstream of the drying reach. The Paritua site is recommended as high priority because the Awanui flume site does not represent Paritua flows at times when a drying reach separates the two. In the Paritua catchment there were four irrigation takes from surface water at the time of writing. These include two takes from the Paritua upstream of Ongaru (2 consents for 9 take points), one take from Ongaru Stream, and one irrigation take from the Paritua downstream of the Ongaru confluence (plus 3 frost protection takes).

The Generalized Oxygen Model does not resolve the question as to whether the Paritua drying reach requires higher minimum flows than upstream reaches of the Paritua. That would require investigation into the flow requirements for intermittent gravel-bed streams. However, the model does highlight the reach immediately downstream of the Paritua (i.e. the Karewarewa Stream) which is at-risk of experiencing low oxygen. The Karewarewa is entirely spring-fed during periods when the Paritua runs dry. Water level in the aquifer that feeds those springs is therefore important for Karewarewa flows when the Paritua is dry. That aquifer is poorly understood and needs further research. For example, there is evidence of negligible recharge of this aquifer from the Ngaruroro River, including the high electrical conductivity of Karewarewa spring water (575 µS/cm on 24/2/2014) compared to Ngaruroro water (150 µS/cm).

Relatively few water takes are linked to the existing minimum flows sites in the Awanui catchment (10 resource consents at the time of writing). It is therefore difficult to justify the five sites where minimum flows are presently monitored (Awanui at Flume, Poukawa at Douglas Rd, Karewarewa at Turamoe Rd, Paritua at waterwheel, Ongaru at Valley Rd). Two minimum flow sites could provide a simplified measure of water restriction periods (Awanui flume, Paritua waterwheel), unless more water takes are linked to instream flows subsequent to this report.

Table 6-1: Awanui minimum flow sites. Potential minimum flow sites recommended in order of priority for the Awanui catchment.

Site	Priority
Awanui at Flume	1
Paritua at waterwheel	2
Karewarewa at Pakipaki	3
Upper Awanui at Pakipaki	4
Poukawa at Stock Rd	5
Paritua at Raukawa Rd	6
Ongaru at Wenley Rd	7

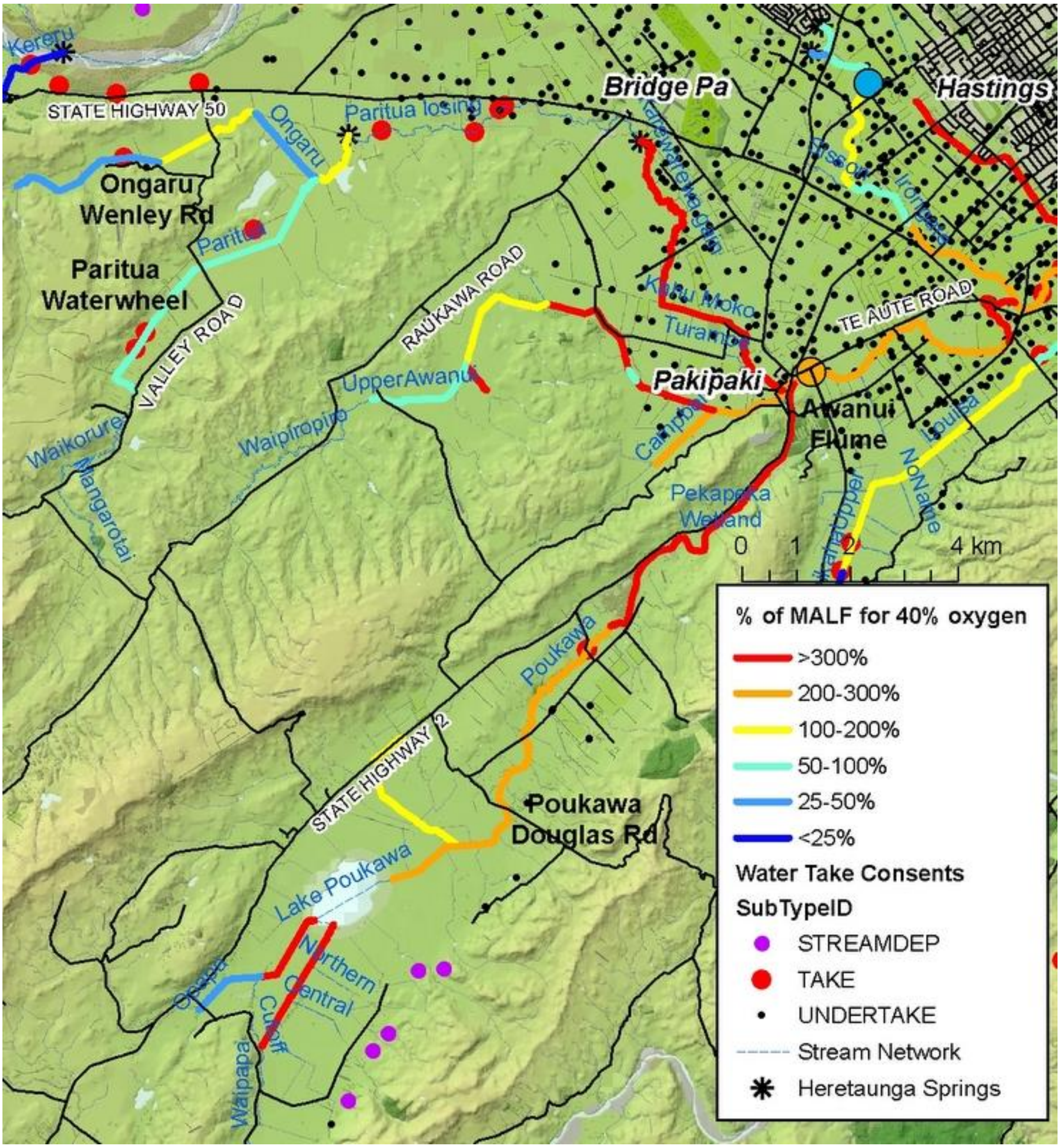

Figure 6-1: Awanui site selection. The flow predicted to achieve a daily minimum 40% oxygen saturation is mapped as a percent of mean annual low flow (MALF), as per Figure 3-9. Some of the existing minimum-flow sites are also labelled (Awanui Flume, Poukawa at Douglas Rd, Paritua Waterwheel, Ongaru at Wenley Rd), with point colour for Awanui using the same scale for % of MALF (from intensive site-specific studies, (Wilding, 2015). Water takes are displayed as black dots for groundwater takes ("UNDERTAKE"), purple dots for groundwater takes presently classed as stream depleting ("STREAMDEP"), and red dots for direct surface water takes ("TAKE").

Raupare Catchment

The headwater tributaries are generally steeper and narrower than the mainstem, meaning that a downstream minimum flow site can adequately represent this catchment (Figure 6-2). The effects of groundwater use are expected to originate upstream of Ormond Rd because all known spring inflows are located upstream of Ormond Rd (springs are depicted in Figure 6-2). The benefits of locating the minimum flow site downstream of all surface takes (e.g. Pakowhai Regional Park) are probably outweighed by the cost of relocating monitoring infrastructure from the existing site at Ormond Rd. Hence the Ormond Rd site remains first priority (Table 6-2).

Flow data collected upstream of Carrick Road (at Twyford Road culvert) indicated more variable flows than Burns tributary. The timing of low-flows is therefore expected to occur earlier than Burns tributary. The Raupare at Carrick Rd is also represents a greater length of stream than Burns tributary. A higher priority was therefore given to Raupare at Carrick Road than Burns tributary.

Table 6-2: Raupare minimum flow sites. Potential minimum flow sites are recommended in order of priority for the Raupare catchment.

Site	Priority
Raupare at Ormond Rd	1
Raupare at Pakowhai	2
Raupare at Carrick Rd	3
Burns at Nicholl Rd	4

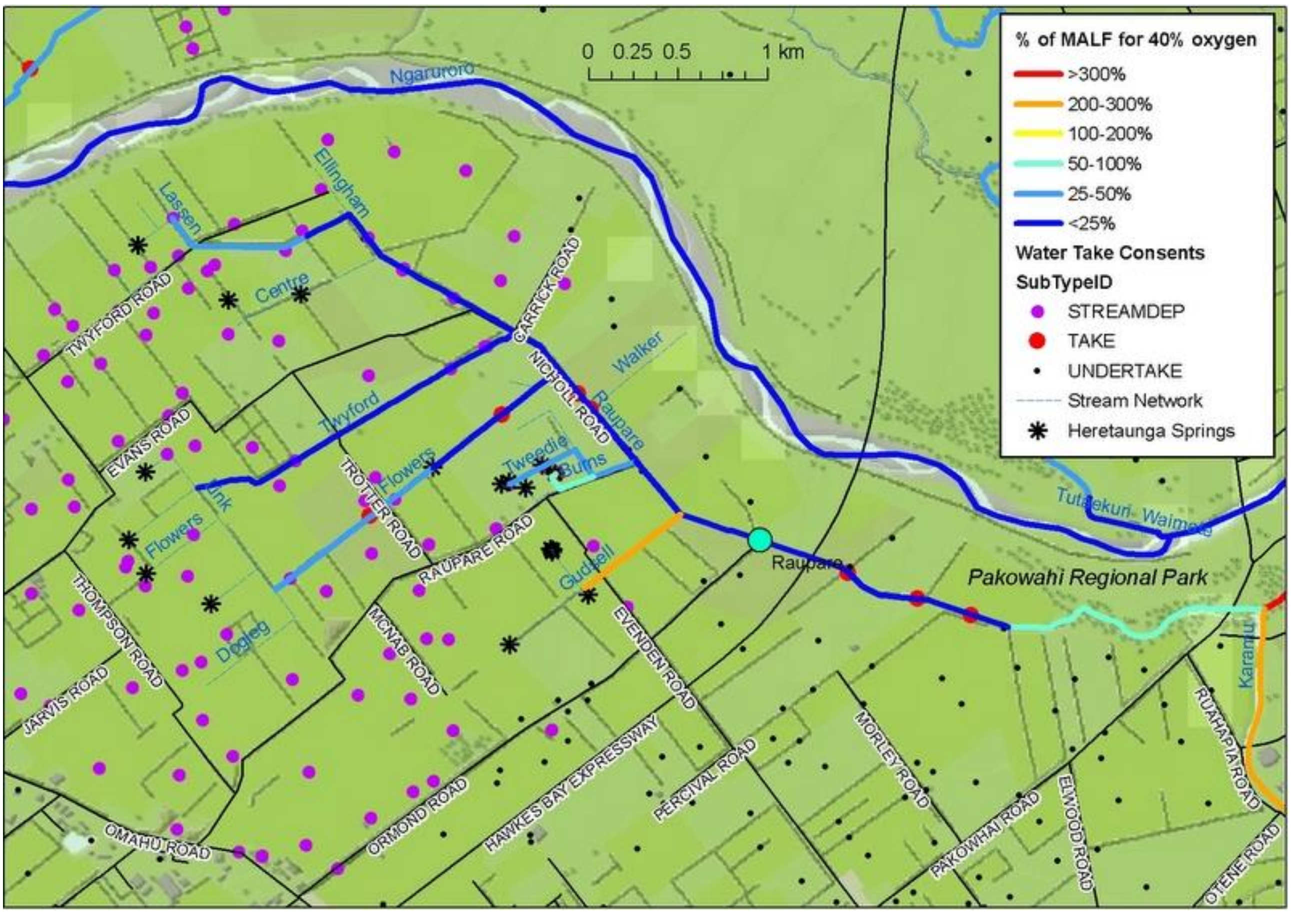

Figure 6-2: Raupare site selection. The flow predicted to achieve a daily minimum 40% oxygen saturation is mapped as a percent of mean annual low flow (MALF), as per Figure 3-9. The existing minimum-flow site (Ormond Rd) is also mapped (blue dot labelled "Raupare"), with point colour using the same scale for % of MALF (from intensive site-specific studies, (Wilding, 2015). Water takes are displayed as black dots for groundwater takes ("UNDERTAKE"), purple dots for groundwater takes presently classed as stream depleting ("STREAMDEP"), and red dots for direct surface water takes ("TAKE"). Streams and roads are labelled.

Irongate Catchment

A site located in the most downstream reach (e.g. Riverslea Road) would fulfil most site-selection criteria for the Irongate Stream, including representing the reach where oxygen is most susceptible to flow reduction and incorporating the effects of upstream water takes (Figure 6-3). The Riverslea Road site is also located downstream of the groundwater inflows that extend as far downstream as Railway Road (concurrent gaugings 2/12/2014). But greater priority was given to the Clarke's weir site (Table 6-3) because of the value of the long-term record here. Clarke's weir has one of the longest flow records on the Heretaunga Plains (March 1978 to present) and site design enables precise stage-to-flow ratings, which are important for detecting long-term trends.

The Clarke's weir site offers two challenges – spatial representation of the flow regime and spatial representation of oxygen risk. The first challenge is easily addressed, with concurrent gaugings demonstrating that flows at Clarke's weir are strongly correlated with flows at Riverslea Road ($R^2 = 0.95$; n = 12). However, the representation of spatial oxygen risk will be more difficult. There is a greater risk of low-oxygen in reaches downstream of Clarke's weir (Figure 6-3), despite the flow increase, because of a lower Froude number (stream slope decreases and channel width increases). Therefore, the magnitude of the minimum flow would need to provide adequate protection for downstream reaches.

There was some disagreement between model predictions, with a higher flow predicted by the Generalized Oxygen Model (60 L/s for 40% oxygen) compared to the flow predicted by the site-specific model at Clarkes weir (SEFA, 30 L/s for 40% oxygen). The difference in oxygen-flow predictions could be a consequence of riparian shading of this reach, reducing the biomass of plants that consume oxygen at night. Basing the minimum flow on the Generalized Oxygen Model is an option. Ideally, SEFA modelling of the oxygen-flow relationship should be completed in the lower reaches (e.g. Riverslea Road).

Table 6-3: Irongate minimum flow sites. Potential minimum flow sites are recommended in order of priority for the Irongate catchment.

Site	Priority
Irongate at Clarke's weir	1
Irongate at Riverslea Rd	2

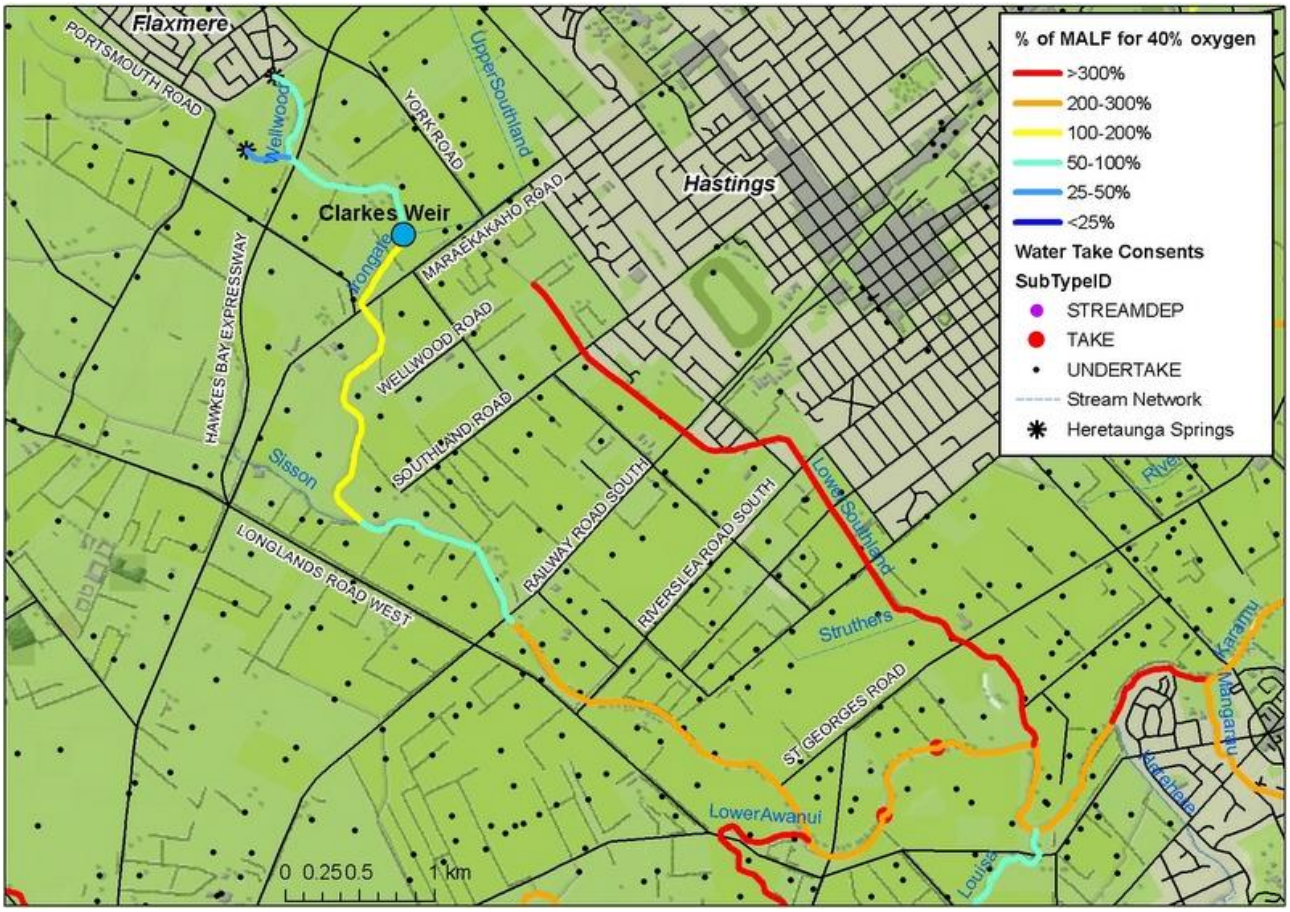

Figure 6-3: Irongate site selection. The flow predicted to achieve a daily minimum 40% oxygen saturation is mapped as a percent of mean annual low flow (MALF), as per Figure 3-9. The existing minimum-flow site (Clarkes Weir) is also mapped, with point colour using the same scale for % of MALF (from intensive site-specific studies, (Wilding, 2015). Water takes are displayed as black dots for groundwater takes ("UNDERTAKE"), purple dots for groundwater takes presently classed as stream depleting ("STREAMDEP"), and red dots for direct surface water takes ("TAKE"). Streams and roads are labelled.

Mangateretere Catchment

The existing monitoring site (Mangateretere at Napier Rd) is given a priority 1 because it is located downstream of all water takes, and all major springs and tributaries (Figure 6-4). This site also has an established flow record and is the obvious choice for a minimum flow site (Table 6-4). However, flow requirements for oxygen are proportionally greater for upstream reaches. The minimum flow should therefore be set to provide for the middle reach (blue line crossing Thompson Rd in Figure 6-4).

The stage-to-flow ratings are sometimes inaccurate at Napier Rd due to weed growth and backwater effects from flooding in the Karamu River. Installation of a velocity meter, as used for Raupare, could overcome this problem. The only other candidate site is Thompson Rd (Figure 6-4). Most of the groundwater inflows are located upstream of Thompson Rd (flow is about 10% less than at Napier Rd, from 3 concurrent gaugings). Most water takes are also located upstream of Thompson Rd. This site would be worth considering if problems arose at the Napier Rd site.

Both the Mangateretere and Karamu receive most of their baseflow from a poorly understood aquifer. That aquifer may be fed by the Tukituki River during the low-flow period. If so, then the magnitude and timing of low flows, plus the effects of water use on the two streams will be linked. However, until these linkages are better understood, the two stream will need to be monitored separately.

Table 6-4: Mangateretere minimum flow sites. Potential minimum flow sites are recommended in order or priority for the Mangateretere catchment.

Site	Priority
Mangateretere at Napier Rd	1
Mangateretere at Thompson Rd	2

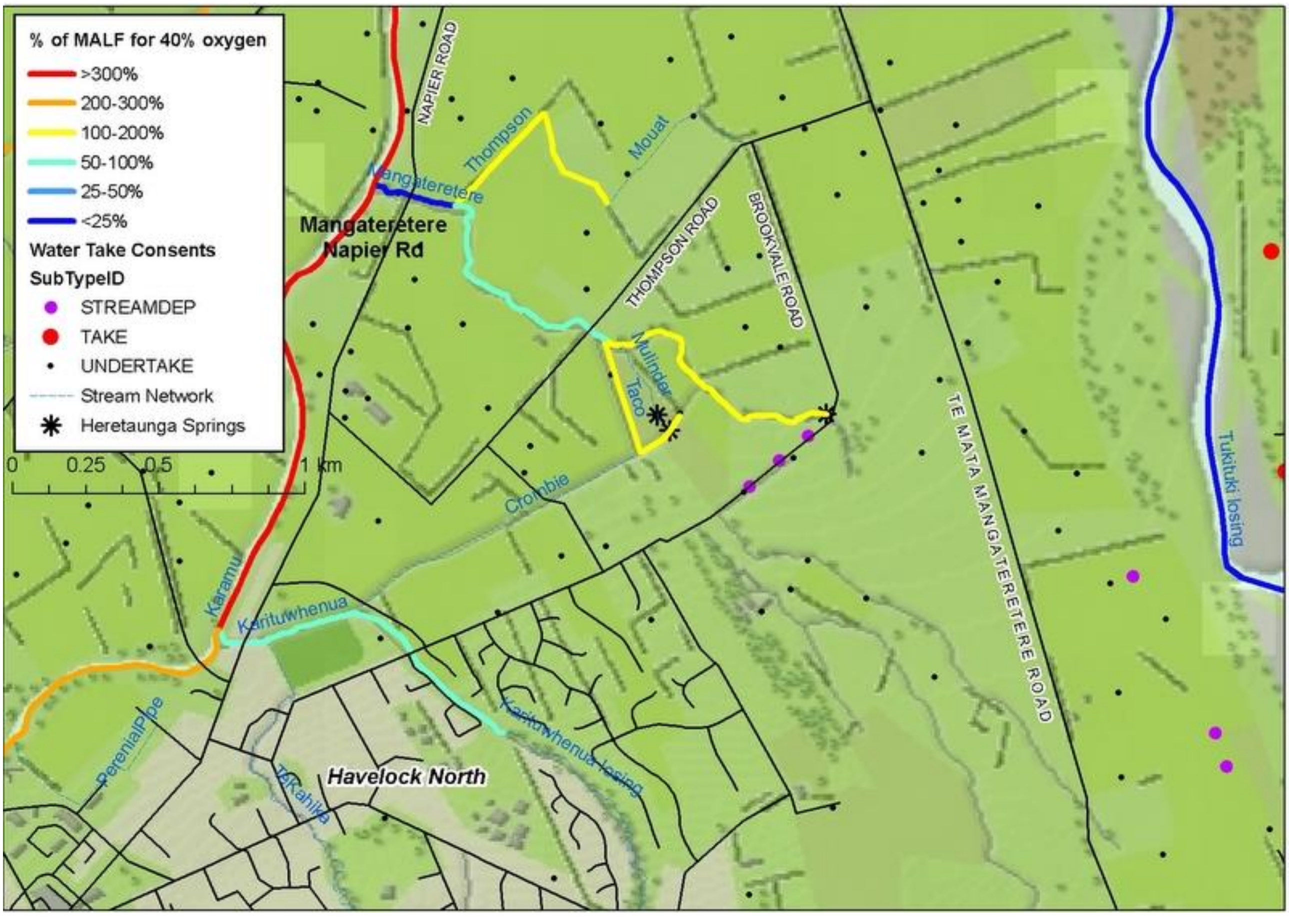

Figure 6-4: Mangateretere site selection. The flow predicted to achieve a daily minimum 40% oxygen saturation is mapped as a percent of mean annual low flow (MALF), as per Figure 3-9. The existing minimum-flow site (Napier Rd) is also labelled. Water takes are displayed as black dots for groundwater takes ("UNDERTAKE"), purple dots for groundwater takes presently classed as stream depleting ("STREAMDEP"), and red dots for direct surface water takes ("TAKE"). Streams and roads are labelled.

Karamu

The Karamu can be divided into three sections (Figure 6-5):

(1) **Upper Karamu** between the Irongate confluence and the Mangateretere confluence. Fed by hill-country tributaries (Awanui, Louisa) and one spring-dominated stream (Irongate).

(2) **Mid Karamu** between the Mangateretere confluence and the Raupare confluence. Summer inflows from the Upper Karamu are small compared to the large springs that feed this reach (both directly and via the Mangateretere).

(3) **Lower Karamu / Clive** between the Raupare confluence and the Waitangi Estuary. The Raupare makes a sizeable flow contribution, with tidal influence increasing downstream of the confluence.

Flow requirements for oxygen exceed the mean annual low flow throughout the Karamu (Figure 6-5). The **Mid Karamu**, monitored at Karamu Floodgates, is given priority 1 for minimum flow monitoring (Table 6-5). The Mid Karamu receives most of its baseflow from a poorly understood shallow aquifer, with some evidence that the aquifer is fed by the Tukituki River (Wilding & Waldron, in prep.). Research on the water source and water use of that shallow aquifer should be a research priority, because it contributes more water to the Karamu than all other aquifers combined.

The setting of a minimum flow for the Mid Karamu is complicated by the variation between reaches in the proportion of MALF predicted for 40% oxygen (red, orange and yellow lines in Figure 6-5). The decreasing proportion of MALF for oxygen requirements further downstream reflects the increasing flow from spring inputs. .

For the **Upper Karamu**, flow alteration is primarily a product of water use in the tributaries, with few water takes direct from the mainstem and insignificant groundwater inflows to the channel itself. Those tributaries have similar or higher flow requirements compared to the Upper Karamu (Figure 3-9), so managing water use to achieve flow requirements in those tributaries could provide an adequate level of protection for the Upper Karamu. A minimum flow site for this reach (e.g. Havelock North flume) is therefore a lower priority (Table 6-5).

The **Lower Karamu** is given the lowest priority for monitoring, despite its high risk of low oxygen. The technical difficulties for monitoring flows in this reach (tide, plant growth, mouth closure) could be overcome, but the expense would be difficult to justify unless water users in the Karamu catchment were restricted by flows in this reach. The question then is should water use be restricted for this reach, given that river diversion is the main source of flow alteration for the Lower Karamu? The entire flow of the Ngaruroro was diverted out of the Lower Karamu in 1969 to address siltation problems in a channel that was constructed in the 1930's only to convey flood overflows (MacGeorge, 1989). That diversion reduced the MALF in the Lower Karamu by about 80%, and hence made a significant contribution to the predicted oxygen problems in the Lower Karamu.

Table 6-5: Karamu minimum flow sites. Potential minimum flow sites are recommended in order or priority for the Karamu catchment.

Site	Priority
Karamu at Floodgates (Mid Karamu)	1
Karamu at Havelock North flume (Upper Karamu)	2
Karamu at Clive (Lower Karamu / Clive)	3

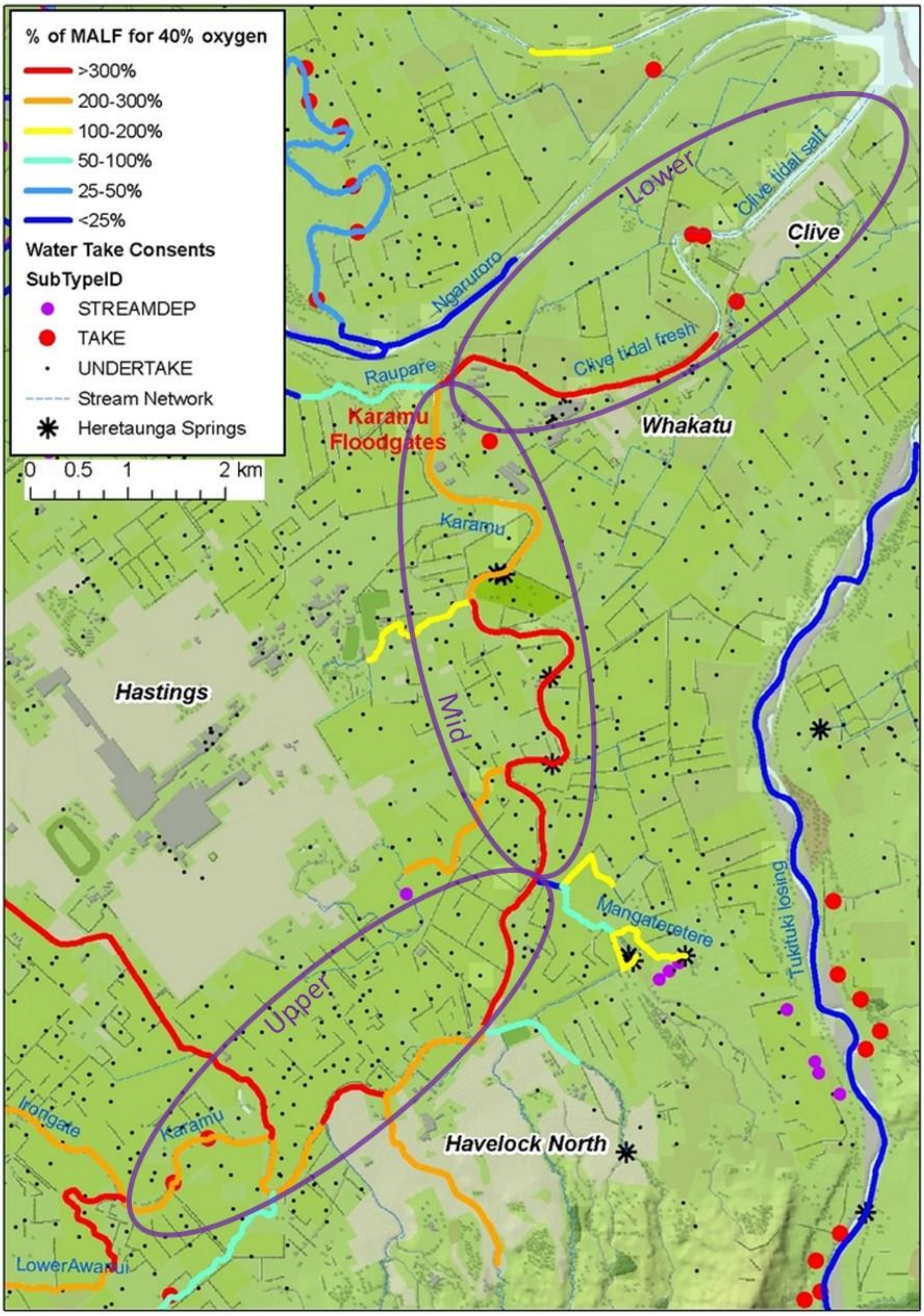

Figure 6-5: Karamu site selection. The flow predicted to achieve a daily minimum 40% oxygen saturation is mapped as a percent of mean annual low flow (MALF), as per Figure 3-9. The existing minimum-flow site (Karamu Floodgates) is also labelled. Water takes are displayed as black dots for groundwater takes ("UNDERTAKE"), purple dots for groundwater takes presently classed as stream depleting ("STREAMDEP"), and red dots for direct surface water takes ("TAKE"). Streams and roads are labelled.

Tutaekuri-Waimate

For the Tutaekuri-Waimate Stream, a minimum flow site closer to the Ngaruroro confluence (e.g. Chesterhope) would be optimal for representing instream flows and the effects of water use (Figure 6-6). However, the existing site at Good's bridge is given priority 1 to ensure continuity of record. The effects of groundwater use are expected to originate upstream of Good's bridge because the known spring-inflows are located upstream (Wilding & Waldron, in prep.). Most surface water takes are located upstream of Good's bridge, though there are several downstream (10 at the time of writing), (Figure 6-6).

The magnitude of the minimum flow at Good's bridge should be set to protect the lower reach (between Good's bridge and Chesterhope), as this would afford adequate protection for most of the catchment.

There are two reaches with higher flow requirements that are located upstream of Swamp Rd (green lines in Figure 6-6). A site to represent these reaches (Repokai te Rotoroa) is given a lower priority because of the short length of stream with higher flow requirements. The Moteo valley aquifer feeds the reaches upstream of Swamp Road (Figure 6-6), compared to the Heretaunga aquifer which likely sustains springs in the lower reaches (Swamp Road to Good's Bridge), (Wilding & Waldron, in prep.). There are insufficient data to determine if the timing of low-flows differs between the two systems.

Table 6-6: Tutaekuri-Waimate minimum flow sites. Potential minimum flow sites are recommended in order or priority for the Tutaekuri-Waimate catchment.

Site	Priority
Tutaekuri-Waimate at Good's bridge	1
Tutaekuri-Waimate at Chesterhope (Ngaruroro confluence)	2
Repokai te Rotoroa upstream of Swamp Rd	3

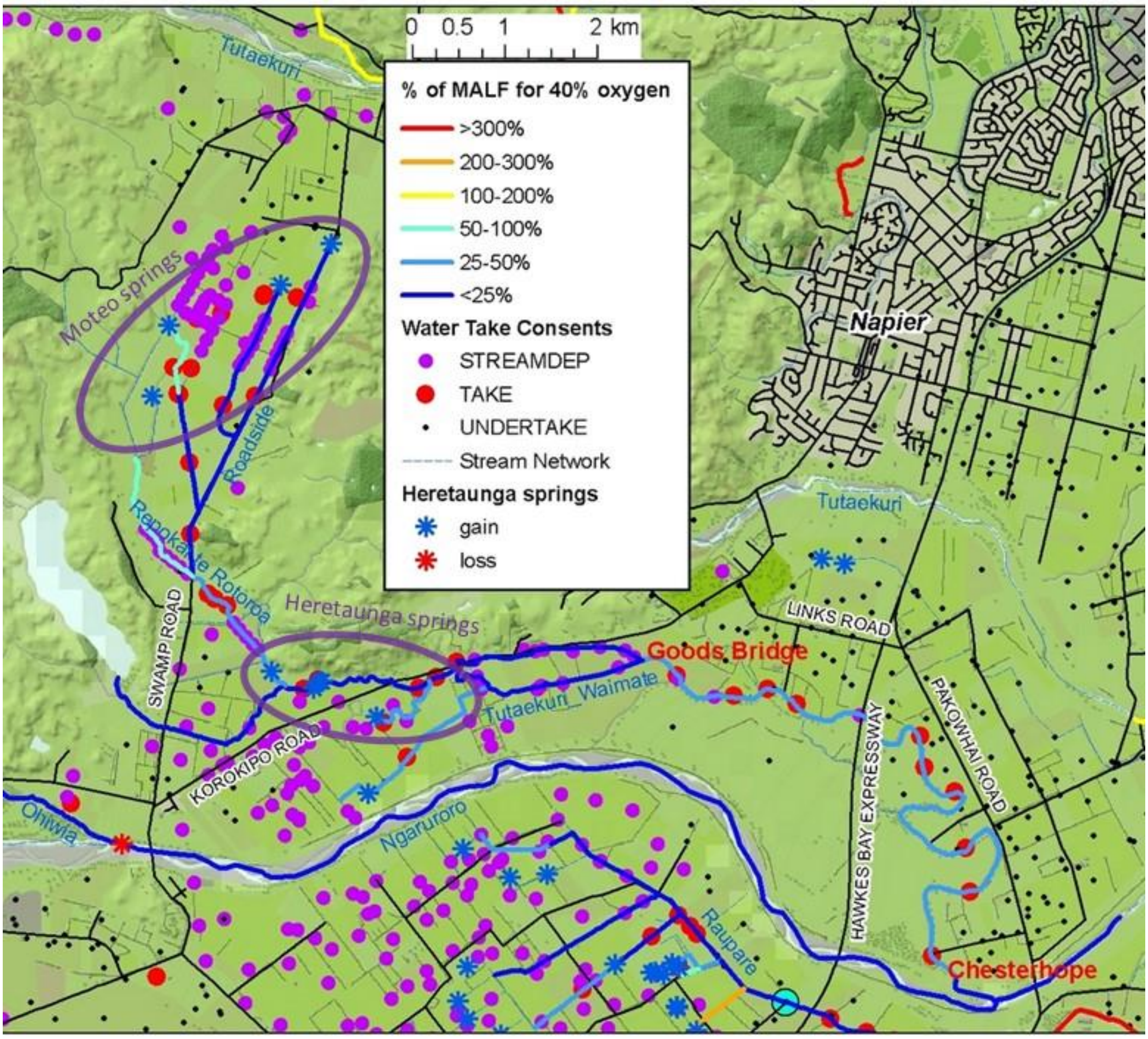

Figure 6-6: Tutaekuri-Waimate site selection. The flow predicted to achieve a daily minimum 40% oxygen saturation is mapped as a percent of mean annual low flow (MALF), as per Figure 3-9. Existing monitoring sites are labelled (Good's bridge, Chesterhope). Water takes are displayed as black dots for groundwater takes ("UNDERTAKE"), purple dots for groundwater takes presently classed as stream depleting ("STREAMDEP"), and red dots for direct surface water takes ("TAKE"). Streams and roads are labelled.

Louisa

The risk of low-oxygen in the Louisa is moderate to high, more than the MALF to exceed 40% oxygen saturation (Figure 6-7). To date, minimum flows have been monitored at two locations – Mutiny Road and Te Aute Road (Figure 6-7). The site at Te Aute Rd is given priority 1 and it could adequately represent this stream, without need for monitoring at Mutiny Rd, because it better represents flow in the low oxygen reaches. There are inflows (tributaries and springs) between Middle Road and Te Aute Road that increase mean annual low flow from 24 to 36 L/s. Minimum flow requirements should be set for the long reach with higher flow requirements, which runs between Mutiny Road and School Rd (Figure 6-7). The Te Aute Rd site also has the benefit of being downstream of all water takes. There were two surface water takes from this catchment at the time of writing, and the consents allow a large proportion of stream flow to be abstracted (19 L/s + 6 L/s, compared to MALF of 36 L/s). There are also four shallow wells taking at high rates (3.5 to 40 L/s).

Note that the stream name changes from Te Waikaha to Louisa, because the Te Waikaha was diverted into the Louisa in the 1960's to alleviate flooding from the Awanui (HBRC, 2004).

Table 6-7: Louisa minimum flow sites. Potential minimum flow sites are recommended in order or priority for the Louisa catchment.

Site	Priority
Louisa at Te Aute Rd	1
Te Waikaha at Mutiny Rd	2

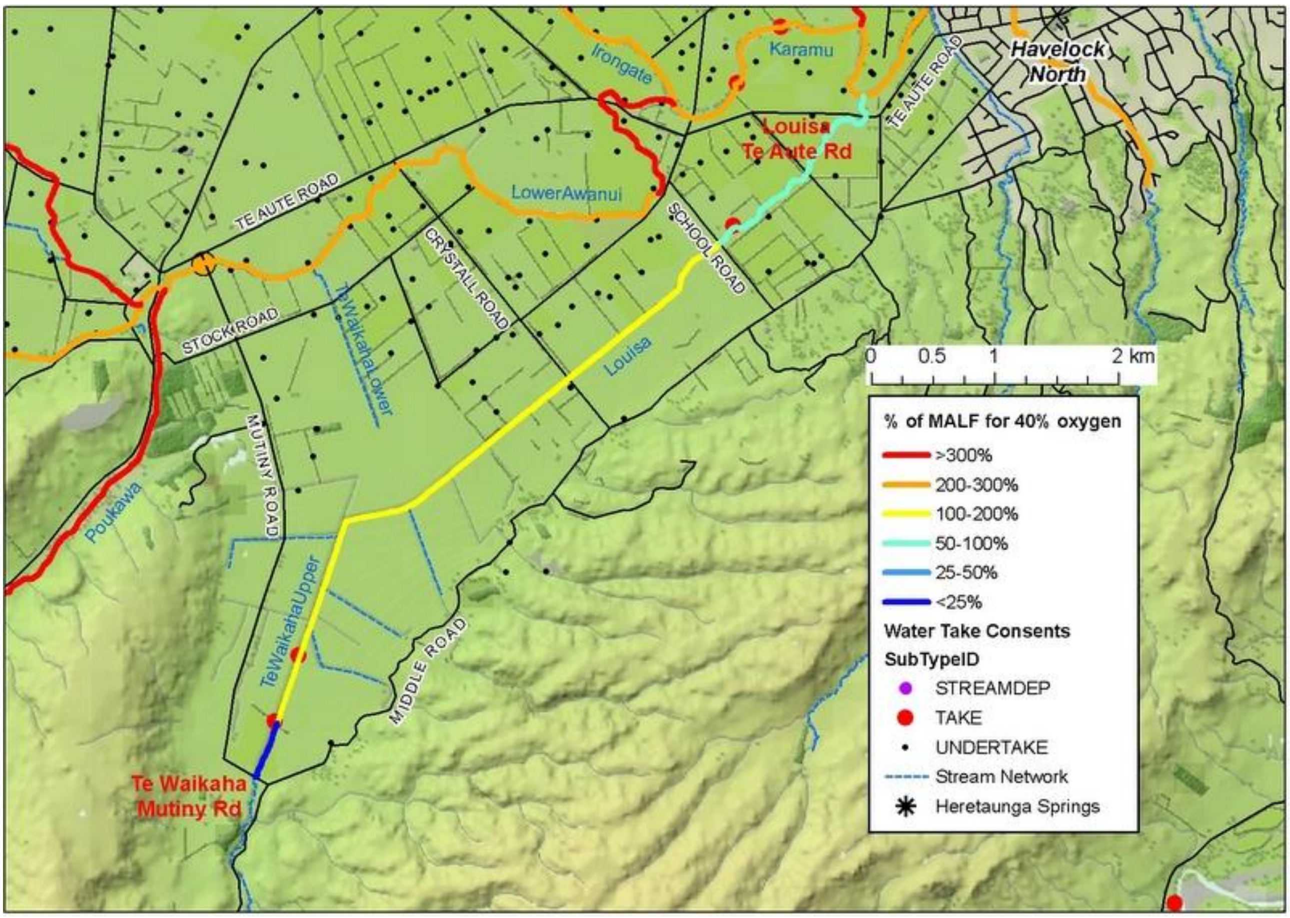

Figure 6-7: Louisa site selection. The flow predicted to achieve a daily minimum 40% oxygen saturation is mapped as a percent of mean annual low flow (MALF), as per Figure 3-9. Existing monitoring sites are labelled (Louisa at Te Aute Rd, Te Waikaha at Mutiny Rd). Water takes are displayed as black dots for groundwater takes ("UNDERTAKE"), and red dots for direct surface water takes ("TAKE"). Streams and roads are labelled.

Waitio

The Waitio Stream does not have a minimum flow site at present. There is a risk of low oxygen, however that risk is lower than most Karamu tributaries (Figure 3-9, Figure 6-8). This stream gains flow from springs as it crosses the Heretaunga Plains (MALF increases from <10 L/s to 570 L/s), and the groundwater feeding these springs is likely sourced from the Ngaruroro River (Wilding & Waldron, in prep.).

Water use in the catchment includes surface takes (10 points of take) plus groundwater takes (4 stream depleting plus 2 other) at the time of writing (Figure 6-8). Given the magnitude of spring inflows (>90% of MALF), groundwater abstractions have the potential to deplete stream flow in the Waitio.

Water takes in this catchment are presently linked to the Ngaruroro at Fernhill, meaning that restrictions on water use are triggered by minimum flows at the Fernhill site to protect flows in the Ngaruroro River (Fernhill site labelled in Figure 6-8). Adding a minimum flow monitoring site for the Waitio itself may be unnecessary. Predicted flow requirements for 40% oxygen are a smaller proportion of MALF for the lower gravel reach of the Waitio (33% of MALF), compared to Ngaruroro at Fernhill (2400 L/s is 57% of MALF). The 1 km reach upstream of Ohiti tributary requires a similar proportion (66% of MALF). There are not enough monitoring data available to confirm if low flows in the Waitio coincide with low flows in the Ngaruroro River. If monitoring the Waitio, then Ohiti Rd would be next priority (Table 6-8) as it is located downstream of most water use and most of the groundwater gains (Figure 6-8). The target reach for deriving a minimum flow would likely be further upstream where flow requirements are a higher proportion of MALF.

Table 6-8: Waitio minimum flow sites. Potential minimum flow sites are recommended in order or priority for the Waitio catchment.

Site	Priority
Ngaruroro at Fernhill	1
Waitio at Ohiti Rd	2

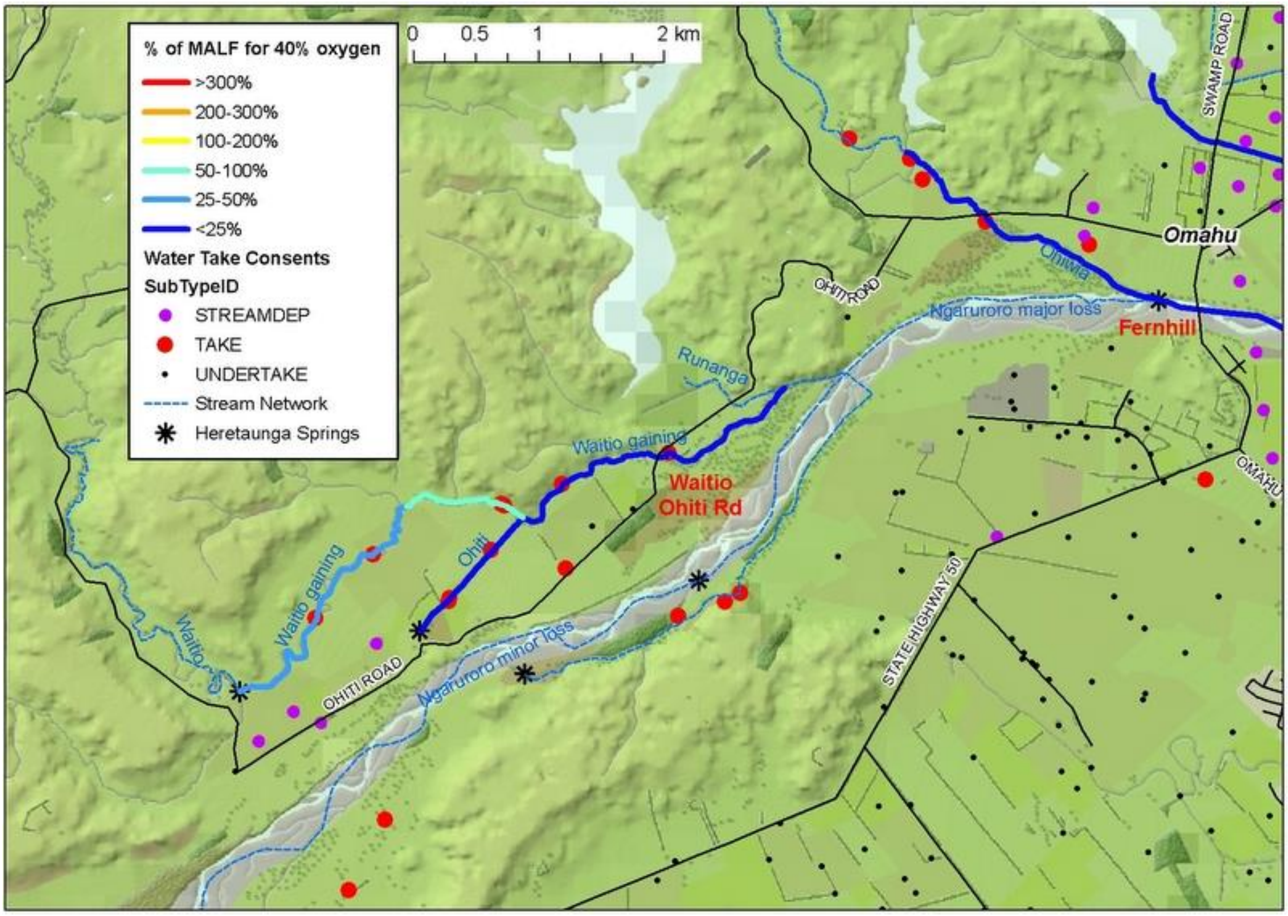

Figure 6-8: Waitio site selection. The flow predicted to achieve a daily minimum 40% oxygen saturation is mapped as a percent of mean annual low flow (MALF), as per Figure 3-9. Water takes are displayed as black dots for groundwater takes ("UNDERTAKE"), purple dots for groundwater takes presently classed as stream depleting ("STREAMDEP"), and red dots for direct surface water takes ("TAKE"). Streams and roads are labelled. This map excludes upstream reaches of the Waitio where flow requirements were not investigated and there are no water use consents.

Ohiwia / Okawa / Ohiwa

The minimum flow site on the Ngaruroro River (Fernhill) is recommended as first priority, as it is expected to provide adequate protection for this catchment (Table 6-9). The Ohiwia Stream itself is predicted to have a low risk of oxygen stress, with oxygen predicted to exceed 40% saturation at flows more than 10% of MALF. There are several water takes from this catchment, including water takes located in the Okawa basin, about 5 km upstream from the Heretaunga Plains (Figure 6-9).

Groundwater takes from the Heretaunga aquifer are not expected to be stream depleting for the Ohiwia because no springs were detected that originate from the Heretaunga aquifer. Evidence for limited interaction includes negligible drop in electrical conductivity (416 to 409 µS/cm between Kawera bridge and Broughton's bridge). There was also little change in flow detected as the stream crossed the Heretaunga Plains (MALF increased from 135 to 169 L/s between Kawera bridge and Broughton's bridge). Surface water interactions with groundwater were not investigated within the smaller Okawa basin.

Minimum flow sites could also be located further upstream (e.g. Kawera bridge, Crownthorpe Rd), depending on where water use increases in the future (Figure 6-9). Flow requirements for oxygen were not investigated for hill country streams, on the assumption that oxygen is not a critical issue in these steeper reaches. Hydraulic habitat is more likely to be a critical issue in the hill country streams. Generally, there are few consents for water takes from hill country streams.

Table 6-9: Ohiwia minimum flow sites. Potential minimum flow sites are recommended in order or priority for the Ohiwia catchment.

Site	Priority
Ngaruroro at Fernhill	1
Ohiwia at Broughton's Bridge (Napier-Taihape Rd)	2
Okawa at Kawera Bridge (Napier-Taihape Rd)	3
Okawa at Crownthorpe Rd	4

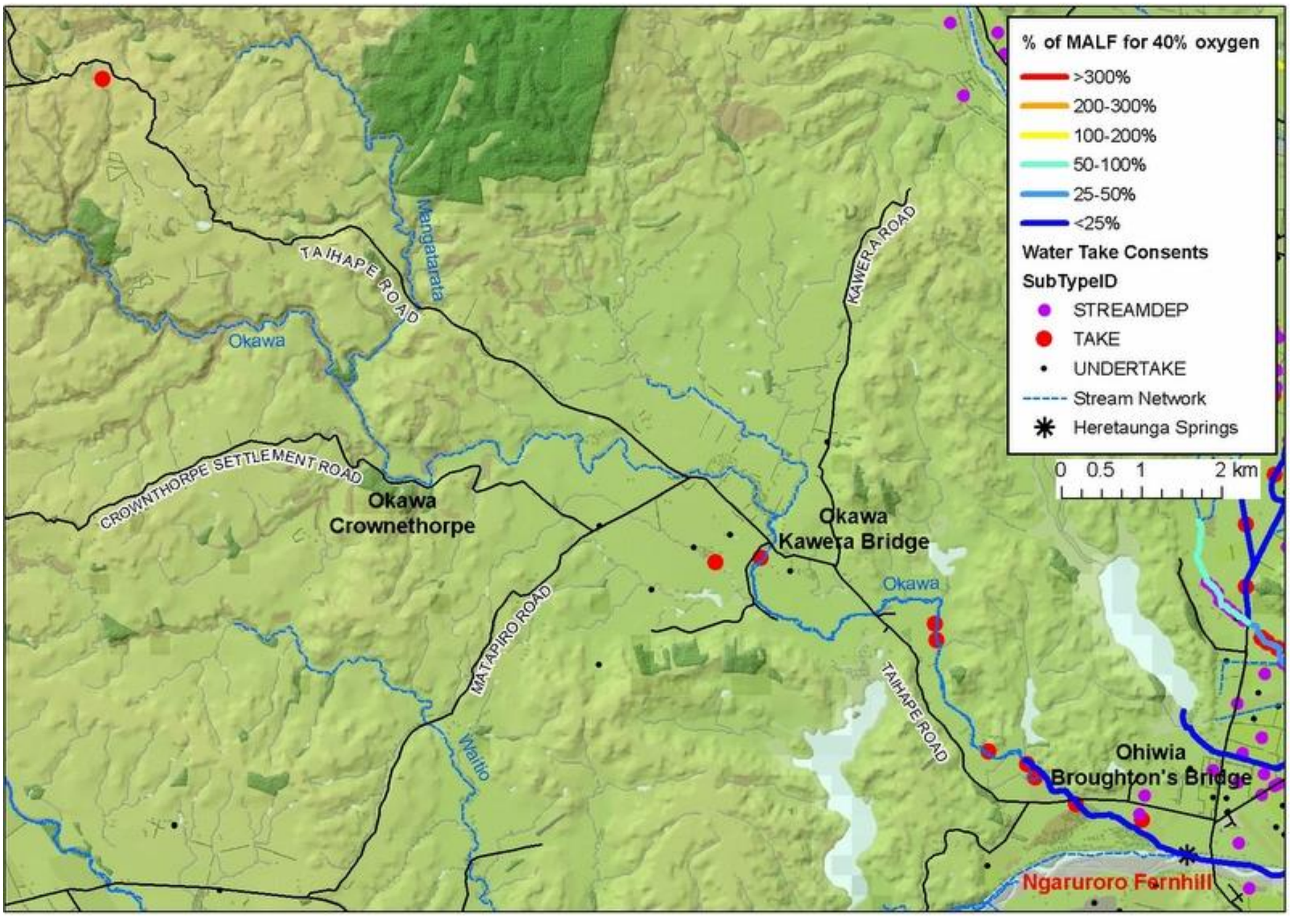

Figure 6-9: Ohiwia/Okawa site selection. The flow predicted to achieve a daily minimum 40% oxygen saturation is mapped as a percent of mean annual low flow (MALF), as per Figure 3-9. Water takes are displayed as black dots for groundwater takes ("UNDERTAKE"), purple dots for groundwater takes presently classed as stream depleting ("STREAMDEP"), and red dots for direct surface water takes ("TAKE"). Streams and roads are labelled.

Maraekakaho

The Generalized Oxygen Model indicates that oxygen is not a critical issue for this stream, with oxygen predicted to exceed 40% saturation at flows less than 15% of MALF. This was true for all reaches of the Maraekakaho that were modelled. By comparison, hydraulic habitat modelling (SEFA) indicated flow requirements exceeding 80% of MALF, which is equivalent to the existing minimum flow of 100 L/s (for 85% of habitat at MALF). The instream flow requirements for oxygen therefore provide no reason to change from the existing minimum flow site at Tait Rd, and no reason to change the magnitude of the minimum flow.

A site at Kereru Rd offers the advantage of being downstream of more water takes. But Kereru Road is given a lower priority than Tait Rd because of poor spatial representation and monitoring difficulty (instability of the gravel banks). The Maraekakaho loses flow to groundwater over the reach downstream of Tait Rd (circled in Figure 6-10). Complete drying can occur over a section starting about 2 km upstream of Kereru Rd (Christie, 2010). When dry, the stream then starts flowing again about 0.5 km further downstream (blue asterisk Figure 6-10), and regains much of its flow before reaching the Ngaruroro River (from concurrent gaugings 31/1/1994 and 19/1/1967). The effects of groundwater use on the Maraekakaho could be monitored at Kereru Road, given the greater influence of groundwater levels on flows in the gaining reach. If adding a second monitoring site is justified, then more concurrent gaugings would be required along the Maraekakaho Stream (Tait Rd to Ngaruroro confluence) to better understand how flow at Kereru Rd relates to the flow losses and gains.

Table 6-10: Maraekakaho minimum flow sites. Potential minimum flow sites are recommended in order or priority for the Maraekakaho catchment.

Site	Priority
Maraekakaho downstream of Tait Rd	1
Maraekakaho at Kereru Rd	2

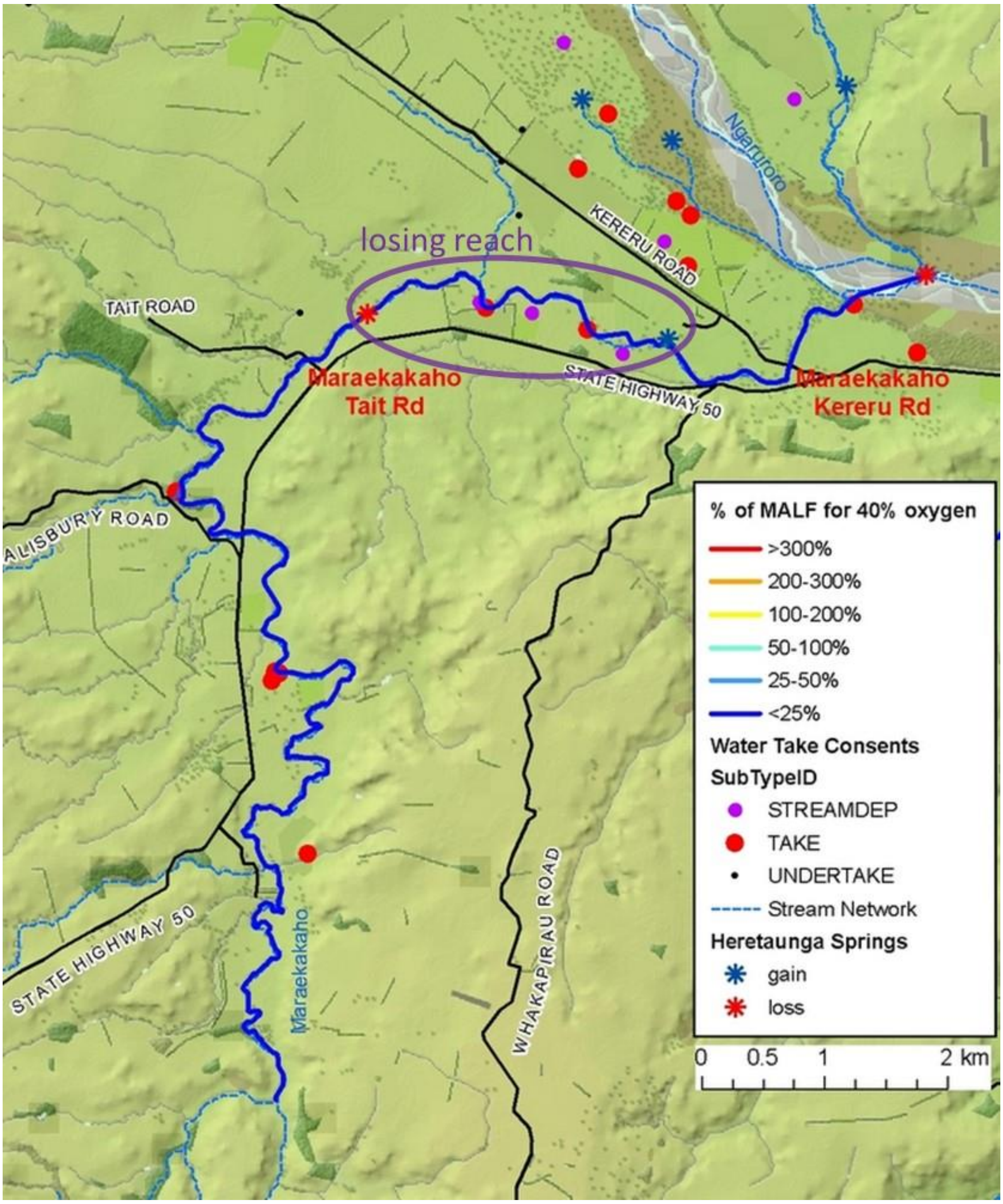

Figure 6-10: Maraekakaho site selection. The flow predicted to achieve a daily minimum 40% oxygen saturation is mapped as a percent of mean annual low flow (MALF), as per Figure 3-9. The existing minimum flow site is labelled (downstream of Tait Rd). Water takes are displayed as black dots for groundwater takes (“UNDERTAKE”), purple dots for groundwater takes presently classed as stream depleting (“STREAMDEP”), and red dots for direct surface water takes (“TAKE”). Streams and roads are labelled.

Small Urban Streams

No minimum flow sites are recommended for the small urban streams (e.g. Southland, Ruahapia, Awahou, Taipo, Plantation, Georges). The flow regime of these streams is poorly understood with potentially unique hydrogeology (e.g. draining heavy alluvial soils of the Heretaunga plains with few or no spring inputs). Flow modifications add to this uncertainty. The baseflow of Ruahapia Stream could be largely sourced from industrial discharges of heat-exchanger water (originating from deep wells). Southland Drain was modified when the spring-dominated headwaters were diverted into the Irongate Stream in 1964 (HBRC, 2004).

Urban streams in the Napier area have extensive tidal influence, and it is possible that springs feeding Georges Stream originate from seawater (electrical conductivity about 10,000 µS/cm). A high risk of low oxygen was predicted for the Napier urban streams, although only a few reaches had the necessary flow data for applying the Generalized Oxygen Model. There are no surface water takes from these streams at present. There is also little conceptual support for depletion of stream flows by groundwater takes from the deeper aquifer, given the separation by a thick confining layer and the lack of surface springs. It is reasonable to conclude that these streams would not support abstraction, because flow would be less than instream flow requirements at times when water abstraction is likely to be required. Monitoring of minimum flows is not justified in the absence of water use.

Small Rural Streams

Minimum flow sites are not recommended for other small rural streams on the Heretaunga Plains. Rationale varies from lack of water use to lack of knowledge of stream flows. Site-specific rationale are briefly outlined below.

Grange (Haumoana) – recommend further investigation. This stream arises from springs that may be sourced from the Tukituki River. The MALF could not be estimated for Grange Stream because flow has not been measured. The flatter gradient of this stream (<2 m/km) indicates the potential for oxygen stress. There are no consents for surface takes, however numerous wells are located close to the springs that feed this stream. Stream depletion could be considered for consent processing, or for next plan change, if more data becomes available.

Muddy (Clive) – Monitoring of minimum flows is not justified due to limited water use. Consented water use is limited to one surface take for frost protection and there are few shallow wells. Spring inputs have not been investigated. The mean annual low flow for this stream could not be estimated due to insufficient gaugings.

Tattersal (Waiohiki) - recommend further investigation. Mean annual flow was not estimated, in the absence of gaugings. There are no consents for surface takes, however there are many shallow wells near the springs that feed this stream. Stream depletion could be considered for consent processing, or for next plan change, if more data becomes available.

Turirau (Puketapu) - recommend further investigation. Flow alterations include wetland drainage and apparent diversion of the headwaters into the Ahuriri estuary. There were no surface takes at the time of writing, but many shallow wells are located near the gaining lower-reaches. Stream depletion could be considered for consent processing, or for next plan change, if more data becomes available.

Wharerangi (Ahuriri trib) - recommend further investigation. This catchment appears to be the headwaters of the Turirau that were diverted into the Ahuriri. There are more than 10 years of flow data for this stream (Wharerangi at Codds, 1977-1988). There were no consented takes for surface water at the time of writing, but several shallow wells are located in the valley aquifer. Spring inputs to the stream have not been investigated. Stream depletion could be considered for consent processing, or for next plan change, if more data becomes available.

Apley (Puketapu) - recommend further investigation. There were no surface water takes, at the time of writing, however many shallow wells are located in the gravel valley between the Tutaekuri River and the Apley Stream. Initial investigations did not reveal spring inflows, and confirmation of this result will require longitudinal concurrent gaugings. Stream depletion could be considered for consent processing, or for next plan change, if more data becomes available.

Kikowhero (Crownthorpe) – no minimum flow site is recommended. There were no surface takes, at the time of writing, and few shallow wells. Spring inputs appear confined to the last 2 kilometres upstream of the Ngaruroro confluence. The stream may lose flow to groundwater upstream of the gaining reach.

Kereru (Maraekakaho) – no minimum flow site is recommended. This stream is likely spring-dominated as it is located within the floodplain of the Ngaruroro, and arises below river level. Large water takes from this stream are used for filling Te Tua reservoir. If the bed level was excavated as part of the water takes, then existing flows would be higher than natural. Arguably the most appropriate time for investigating flow requirements for this tributary would be during consent processing for the Te Tua takes.

Roys Hill – no minimum flow site is recommended. This stream is in a similar setting to Kereru Stream, adjacent to the Ngaruroro River, with channel excavation likely to have increased flow (by dropping bed level below groundwater level). The flow was originally diverted into an artificial groundwater recharge scheme, but that scheme no longer operates. Arguably the most appropriate time for investigating flow requirements for this tributary would be during consent processing for any water takes that depend on this stream. If Ngaruroro fish are dependent on this tributary as a thermal refuge, then there could be merit in considering the flow requirements within a broader context as part of the next plan change.