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OPTIMISING HABITAT IN A STREAM IMPOUNDED FOR WATER SUPPLY

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ABSTRACT

A large earth-constructed water supply dam releases compensation water to the Mangatangi Stream, in southeast Auckland. The dam owners are seeking a resource consent to continue their operation, and this requires consideration of effects of altering the presently required minimum compensation flow. This has been addressed using a combination of field surveys, experiments, and mathematical modelling. Issues addressed were periphyton-generated dissolved oxygen variation, water temperature and habitat suitability for fishes and invertebrates. It was concluded that the greatest benefit to the stream would accrue from restoring riparian shading, rather than changing the required residual flow.

INTRODUCTION

The Mangatangi Dam (Fig. 1) is the largest earth-constructed water supply dam in New Zealand. Its reservoir is the biggest single water supply for about 800,000 persons in Auckland. To continue its operation of the reservoir, Watercare Services Ltd. (WSL) have applied for a resource consent under the Resource Management Act (1991). Compensation flow from the dam enters the Mangatangi Stream, which flows through indigenous forest (Fig. 1) for approximately 2 km, after which it passes through developed pasture and is largely unshaded for the remainder of its length.

A lack of water resources in the region gives impetus to maximising the storage in the dam, and minimising the compensation flow in the stream. In hearing the application the consent authority (the Auckland Regional Council) must strike a balance between minimising this compensation flow, and avoiding significant adverse effects on aquatic life in the stream.

Figure 1   Location of Mangatangi Stream and study sites (only major tributaries shown).

We were commissioned by WSL to investigate the present environmental status of the Mangatangi Stream, and to advise on the consequences of either lowering or raising the present residual flow requirement (283 l s^{-1} in summer). There are significant economic consequences to WSL associated with changing the compensation flow from the dam. An economic benefit could accrue by decreasing the compensation flow, as this would lead to the deferment of the development of a new water source (estimated capital cost NZ$100,000,000). Calculations by WSL, based on their expected growth in water demand compared with their sustainable yield, indicated an annual value for the compensation flow of NZ$125,000 per l s^{-1}. Conversely, any increase in compensation flow needed to mitigate against environmental impacts would bring forward the development of a new water source and would increase the total costs of water supply.

In this paper, we briefly document perceived environmental problems in this stream, and then discuss the use of three simulation models, coupled with a whole-stream experiment, to address the question of varying the compensation flow to optimise instream conditions.

DETERMINING PERCEIVED ENVIRONMENTAL PROBLEMS

To clarify issues involved with the resource consent application, we held discussions with the public and local authorities. This revealed that the dam was generally held to cause three main effects in the stream.

Excessive Periphyton

Excessive and unsightly growths of periphyton were reported in the stream below the bushline. It was suggested that release of more water from the dam would help alleviate this problem by sloughing the periphyton from the streambed and diluting nutrient concentrations in the stream. Subsequent investigations also showed that the respiratory activity of these growths caused excessive night-time depression of dissolved oxygen (DO).

Elevated Water Temperatures

Being a subsurface withdrawal, the compensation flow from the dam is of rather constant temperature; 13 ± 2°C. In summer, the water temperature at Stubbs Bridge (Site 5 on Fig. 1) can climb to about 25°C. It is believed that this causes native and introduced fishes to avoid using the stream, and also degrades aquatic life. It was argued that release of more water from the dam would help in maintaining a cooler and more desirable water temperature regime down the stream channel.

Hydraulic Habitat Requirements for Fish and Invertebrates

The controlled nature of the stream was perceived to limit the range of hydraulic environments (pools, runs and riffles). It was argued that the release of more compensation flow would significantly increase the amount of habitat available for invertebrates and fish.

METHODS

Details of methods used are reported in Cooke *et al*. (1992); we give a brief outline here.

Surveys and Monitoring

After historical data were reviewed, monitoring programmes were established to determine how perceived environmental problems matched with reality. Six surveys of periphyton biomass, DO and water clarity were carried out over the summer period from January–April 1992. Dissolved oxygen was also monitored at Site 3 (downstream of a periphyton impacted reach) at 15 minute intervals over a 48 hour period using a DATASONDE™ water quality monitor, at normal compensation flow and at varying compensation flows (see later).

Water and air temperature were monitored continuously at Site 4 over the summer of 1991–92. The water thermistor was fixed just above the stream bed, approximately 3 m from the left bank, and the air thermistor was enclosed in a standard meteorological reflector baffle mounted 2 m above ground level. Standardisation checks were carried out fortnightly. Additional summer water temperature records were obtained from Sites 1 and 5 to characterise the stream temperature response under a range of climatological conditions. Incoming solar radiation (W m^{-2}) was monitored at the unshaded Site 4, using a LICOR™ pyranometer on a levelled platform, approximately 1 m above the water surface at the centre of the stream. During the controlled release experiment (see later), temperature recording data loggers were installed at Sites 1, 3, 4 and 5 and at two sites approximately 200 m from either end of the riparian shaded reach (Fig. 1). Continuous water level records were available from the weirs at Site 1 and at Site 6.

Three representative reaches were established (labelled F1, F2 and F3 in Fig. 1) for the purposes of establishing the effects of flow on habitat preference of a range of native and introduced fish and the invertebrates upon which they feed. Twenty cross-sections were surveyed along each 110–130 m reach. Depth, velocity and substrate measurements were taken at 18-23 equally spaced verticals across each section, and the extent of the bed covered in periphyton or macrophytes was estimated.

Controlled Release Experiment

With the cooperation of WSL, the amount of compensation flow being released from the dam was regulated to approximately 25%, 50%, 100%, 200% and 400% of normal compensation flow for periods of 48 hours at each flow. This time was calculated to be sufficient to allow the flow to reach equilibrium at each of the three study reaches for a period of 24 hours. DO was monitored at Site 3 during each experiment, and stream water temperature was monitored as described above. Streamflow was gauged at each of the three habitat reaches, and at supplementary points along the length of the stream.

Modelling the Effects of Changed Compensation Flow

Dissolved oxygen The DO monitoring was carried out when both periphyton biomass and stream temperatures were significantly less than values measured during mid-summer. Nevertheless, the monitoring showed significant diurnal DO variations attributable to the respiratory demands of periphyton growing on the streambed. Under mid-summer conditions we therefore expected these variations to be greater and DO minima to be lower. To investigate this further, we developed an in-house computer simulation model written in ACSL (Advanced Continuous Simulation Language, Mitchell and Gauthier Assoc. 1987). This model (called DOFLO) calculates the diurnal DO profile at a site, assuming that downstream gradients of DO can be ignored. It requires data on streamflow, time of sunrise and sunset, and daily water temperature (average, and amplitude and phase of sinusoidal diurnal variation). With these inputs, and stream DO calibration survey data, we derived a unique calibrated value for the stream reaeration coefficient (k_2, day^{-1}), and the daily periphyton photosynthesis and respiration rates (P & R, respectively; mg O_2 day^{-1}). Both k_2 and R vary with the cross-section average water temperature (T, °C), so the model internally adjusts both throughout the diurnal cycle. This uses $k_2 = k_{2,T=20}[1.0241^{T-20}]$ (Elmore and West 1961), and $R = R_{T=20}[1.07^{T-20}]$ (giving a doubling of R every 10 °C rise in temperature).

The model was calibrated for data gathered on 26 March 1992, when compensation flow from the dam was at 50% of normal. The model was then tested using another diurnal DO profile on 2 April 1992, when compensation flow from the dam was 400% of normal and water temperature and meteorological values were significantly different.

Increases in stream flow (Q) cause k_2, P and R all to decrease, and *vice versa*. There are few reported data on the variation of k_2 with Q. We proceeded by assuming, as shown by Wilcock (1988), that the reaeration formula of O'Connor-Dobbins (1956) is appropriate; i.e., $k_2 \propto V^{0.5}/H^{1.5}$, where V is the stream velocity (m s^{-1}) and H is cross-section average stream depth (m). By further assuming the hydrological relationships that $V \propto Q^{0.6}$ and $H \propto Q^{0.4}$, it follows that $k_2 \propto Q^{-0.3}$. This proportionality factor was used to adjust the reaeration coefficient to flows other than that pertaining during calibration of the model. To index P and R to stream flow, it was assumed that the same amount of plant material would be present under a different flow. As a result, for the new flow one simply multiplies the calibrated P and R values by the ratio $Q_{\text{calibration}}/Q_{\text{new}}$.

Water temperature ACSL was also used to develop a model (called THERMOS, THERmal Modelling Of Streams) to predict stream water temperature attained as a function of compensation flow. This solves the heat balance equation for "slugs" of water moving down the stream (Dymond 1984), changing in discharge and depth, and being subject to incoming and outgoing heat fluxes. Specifically, it models cross-section average stream temperature (T) as a function of stream flow (Q), depth (H), and bankside shading (through a shading coefficient, s). All other parameter values are fixed; unlike DOFLO they cannot be adjusted to achieve calibration. The heat flux formulae are summarised in Table 1.

Figure 2 Heat flux components for the Mangatangi Stream (W m^{-2}) (numbers are all summer daily averages, except that short-wave fluxes are daily extremes).

Hydrologic relationships (power functions) between *Q* and *H*, and between *Q* and *V* were developed for each of the sections used for the habitat simulation modelling. Linear scaling was used to calculate *H* and *V* between sections. The model enabled us to quickly examine the stream temperature in response to *Q*, lateral inflow, bankside shading (through the parameter *s*, see Table 1), and time of year.

The model was run using the environmental conditions prevailing at the time of the controlled release experiments. Inputs to the model were: solar radiation; T and Q at Site 1; s (estimated from aerial photos and observation); air temperature (daily average, and amplitude and phase of sinusoidal diurnal variation); cloud cover (visual assessment); relative humidity; atmospheric pressure and wind speed. The last three were estimated from records at a nearby site. Tributary inputs were assumed to be constant. Typical heat fluxes, as calculated by the model, are shown in Figure 2.

Stream habitat We used a hydraulic model (RHYHABSIM, River HYdraulic HABitat SIMulation, Jowett 1989) to predict the effect of changing compensation flows on stream habitat. Unlike the previous two models, it does not deal with cross-section averages. It predicts changes in water depth and velocity **across the channel**, and at various sites downstream, as a function of stream flow (Q). This enables it to make quantitative estimates of changes in stream habitat. It also compares these predictions with tables of physical preference data for specific species or groups. The model calculates the *weighted usable area* (WUA) of instream habitat, being the area within a reach whose physical character meets the criteria specified in the habitat preference data. Habitat preference

Table 1 Heat flux formulae (W m^{-2}) in the THERMOS model.

Component	Formula	Reference
Net short-wave radiation	$S(t)[0.2(1-s\_)(1-r_{s\_}) + 0.8(1-s)(1-r_s)]$	TVA (1972)
Long-wave back radiation	$\varepsilon\sigma(T_K)^4$	Bowie *et al.* (198
Net incident long-wave radiation	$5.31\text{x}10^{-13}(1+0.17C^2)(T_{aK})^6(1-r_{s\_})$ (modified Swinbank formula)	Jirka *et al.* (197
Evaporation flux	$\rho L_v\psi(e_s-e_a)$	Bowie *et al.* (198
Conduction	$R_b\rho L_v\psi(e_s-e_a)$	Jirka *et al.* (197

t = time;
S = measured short-wave radiation [W m^{-2}: 20% diffuse, 80% direct];
$s\_$ & s = diffuse and direct radiation shading coefficients [$s\_\approx 0.05$, $0\leq s\leq 1$];
$r_{s\_}$ & r_s = diffuse and direct water surface reflectivity [$r_{s\_}\approx 0.03$, r_s calculated from solar elevation, Bowie *et al.* 1985];
ε = atmospheric emissivity [≈ 0.97];
σ = Stefan-Boltzman constant [$=5.67\text{x}10^{-8}$ W m^{-2} (°K)$^{-4}$];
T_K = water temperature in °K [$=T+273.16$];
C = fraction of cloud cover;
T_{aK} = dry-bulb air temperature [°K];
ρ = water density [g m^{-3}];
L_v = latent heat of vaporisation [$\approx$2460 J g^{-1}];
ψ = wind function [$=1.16\text{x}10^{-8}(0.211+0.079U)$ m s^{-1} mbar^{-1}, Jobson *et al.* 1979];
U = wind speed [m s^{-1}],
e_s = saturation vapour pressure of the air at the water surface [$=\exp(63.042-7139.6/T_K-6.2558\ln T_K)$ mbar, Jobson 1973];
e_a = vapour pressure of the overlying atmosphere [$=\eta\exp(63.042-7139.6/T_{aK}-6.2558\ln T_{aK})$ mbar, Jobson 1973];
η = relative humidity;
R_b = Bowen's ratio [$=6.19\text{x}10^{-4}p(T-T_{a,2m})/(e_s-e_{a,2m})$];
p = atmospheric pressure [mbar];
$T_{a,2m}$ & $e_{a,2m}$ = values of T_a & e_a at 2 m above the water surface (Jirka *et al.* 1975).

Figure 4 Predicted summer dissolved oxygen (DO) for high and low periphyton biomass (high and low biomass—70 & 15 g AFDW.m^{-2}—denoted by HB and LB, minimum and maximum DO cases shown also).

curves are then generated over a given range of flows, data being available for both rainbow and brown trout at various stages of their life cycles, and also for a limited range of New Zealand native fish and invertebrates. It must be recognised that the physical characteristics of a river (which define WUA) are not necessarily the only, or even the dominant, control on instream uses. Estimation of WUA merely provides predictions of potential habitat available for selected instream species. Whether the habitat is used depends upon a range of factors, such as flood flows, food supply and temperature.

We used the survey data for each of three study reaches mentioned above. The hydraulic component of the model was calibrated using data from the cross-sections at the downstream end of each reach for the range of compensation flows examined.

RESULTS

Periphyton induced DO deficits

Periphyton surveys showed that nuisance growths (where biomass exceeded 100 mg

Figure 3 Calibration and prediction results of the dissolved oxygen model DOFLO (data shown as squares).

Figure 5 Predicted temperature for a slug of water released from Site 1.

chlorophyll *a* m^{-2} or 40 g ash-free dry weight (AFDW) m^{-2}) occurred during the summer at Sites 3, 4 and 5. These values are held to compromise contact recreation (MfE 1992). Diurnal DO data obtained at Site 3 during the controlled release experiment showed DO minima of <80% saturation during the 25% and 50% compensation flow periods, but minima just above 80% saturation during the 200% and 400% compensation flow periods. A minimum DO of 80% saturation is a requirement of the Resource Management Act (1991) for waters managed as a fishery. DOFLO calibrations (at 50% compensation flow) and predictions (at 400% compensation flow) are shown in Figure 3. This satisfactory level of prediction allowed us to use the model to make predictions of mid-summer DO for different compensation flows, with high and low periphyton biomass, as summarised in Figure 4.

The simulations predicted that:

- under present compensation flow and high biomass conditions, the night time DO minimum is 59% saturation and DO <80% saturation occurs for about 13 hours each day;

- under present summer biomass conditions, reducing compensation flows will markedly decrease the DO minimum, but raising compensation flows will have only a small effect (e.g., doubling the compensation flow will raise the DO minimum to 65% and DO <80% saturation will occur for about 12 hours each day);

- reducing the summer periphyton biomass will significantly reduce diurnal DO variations and is more effective in protecting the stream from low DO than altering compensation flows. With 100% compensation flow and low biomass the predicted DO minimum is 77% saturation and the predicted length of time <80% saturation is 5 hours.

Stream Temperature

The maximum spatial temperature difference observed was approximately 13°C (Site 1 – Site 5), with the most rapid heating occurring between Sites 1 and 3. Between Sites 3 and 4, maximum stream temperatures cooled by up to 3°C. This coincided with a 1 km reach where the stream was totally shaded due to incised banks bordered by mature pine trees (see Fig. 1). Stream heating occurred between Sites 4 and 5, and by Site 5 maximum recorded water temperature was coincident with maximum air temperature, ≈26°C. No further significant heating occurred downstream.

A typical model run is shown in Figure 5, indicating the strong effect of the short shaded reach. THERMOS accurately predicted the time and location of maximum stream temperatures. In most cases, this was within 30 minutes of the measured maximum, and accurately predicted where maximum temperature would be achieved. For example, at 25% compensation flow, the model predicted that maximum temperature (17.2°C) would occur 4.8 km from the flume. The maximum temperature measured (16.8°C) was at Site 3 (5.1 km from Site 1). At 400% compensation flow it predicted that maximum temperature (15.5°C) would occur at 15 km. We measured the maximum temperature (15.3°C) at Site 5 (15.75 km).

However, the model under-predicted the effect of riparian shading. Our routine summer observations and the more detailed observations during the flow release experiment showed there to be a marked decrease in temperature associated with the riparian shaded reach during the day. Even in summer conditions, with the slug release timed to arrive at the riparian reach at midday, the model predicted that the temperature would merely stabilise. This appears to reflect our lack of understanding of micrometeorological conditions operating within such a riparian shaded reach. Also, the model overestimated heat loss in unshaded reaches at night; this could be attributable to bed conduction effects in shallow streams (Jobson 1977).

Despite these limitations the model was useful for predicting the effects of compensation flow on maximum stream temperature. Results are usefully summarised as a probability plot; e.g., Figure 6 shows the proportion of time the temperature of a slug moving from Site 4 (the end of the shaded reach) to Site 5 will be less than a given temperature during its passage. It indicates that the stream temperature will exceed 26°C for 50%, 40%, 30%, 10% and 0% of its time of passage for the range of flows shown, so that increasing the present minimum summer compensation flow would have only a small effect in this reach, and have little effect on peak stream temperature. However, reducing that compensation flow would lead to increased thermal stress on biological communities. The model also showed that restoring riparian shading would significantly reduce present peak stream temperature (Fig. 7).

Figure 6 Non-exceedence percentage time-of-passage for summer water temperature. (Slug released at 0800 at Site 4 when T = 18.5°C; 20 ≤ T_a ≤28°C; η = 80%; S_{max}= 830W m^{-2}; bold line corresponds to present minimum allowable compensation flow).

Figure 7 Predicted effect of increased length of riparian shading. (Shaded reach starts 2.5 km downstream from Site 4, and extends for 1, 2, 3, 4, 5 km downstream).

Habitat Simulation

The habitat simulation model predicted only minimal changes in weighted usable area (WUA) for trout food production (desirable invertebrates), trout, and a range of native fish species, if compensation flows were increased 2 to 4 fold. However, if compensation flows (and water velocities) fall below their present levels, the WUA in each reach would decline significantly. An example of the curves generated by RHYHABSIM are shown for the species *Deleatidium* (a desirable invertebrate for trout food) in Figure 8. Additional model runs in which periphyton was removed from the bed showed that significant increases in usable habitat would be attained by control of periphyton (data not shown).

DISCUSSION AND CONCLUSIONS

The modelling approaches used in this study were useful in demonstrating that little benefit, in terms of improving instream conditions, would be gained by raising the compensation flow released from the dam. For example, under present mid-summer conditions, raising the compensation flow from 283 l s^{-1} to 500 l s^{-1} would:

- decrease maximum daily stream temperature by 0.5°C;

- raise the daily minimum DO saturation to 65% (59% under present compensation flow);

- have negligible effect on the usable area of habitat available for resident fish species.

Conversely, decreasing the amount of compensation flow was unanimously predicted by the models to have a significant negative impact. For example, decreasing compensation flow to 150 l s^{-1} under present mid-summer conditions would:

Figure 8 Effect of changing compensation flow on weighted usable area.

- raise the maximum daily stream temperature by approximately 1°C and significantly increase the travel time during which very high (>26°C) stream temperatures would occur;

- decrease the daily minimum DO to 45%;

- significantly decrease the usable area of habitat available for many fish species and food producing invertebrate species now found in the stream. In some cases the reduction could be up to 50%.

Modelling was also useful for pointing to possible mitigation measures which would potentially be more useful than increasing compensation flow. For example, nuisance periphyton growths were found to be the main factor limiting the development of a healthy stream ecosystem. Controlling periphyton would clearly be beneficial to the stream ecosystem, because:

- dissolved oxygen would never go below 80% saturation;

- the usable area of habitat available for fish and invertebrate species commonly found in the stream would increase significantly. For example, the WUA for *Deleatidium* would increase 40-60% and that of desirable alien species such as brown trout would increase similarly.

There are two ways in which periphyton may be realistically controlled in a stream situation such as this: by controlling nutrient inputs, and by limiting the amount of light available for photosynthetic activity. Nutrient limitation did not seem a likely possibility in this situation due to the stream passing through highly fertile pastoral land. However, the totally unshaded nature of the stream pointed to the fact that restoration of riparian shading could be a realistic option for reducing periphyton proliferations. The additional benefits demonstrated by THERMOS in cooling stream water provides an extra incentive for developing this strategy further.

FUTURE DIRECTIONS

Whilst two of the models described in this study (DOFLO and THERMOS) were developed specifically to understand this particular stream system, our work demonstrates the usefulness of the approach for solving any flow-related water quality problem. For example, DOFLO may equally well be used to study DO excursions caused by macrophyte proliferations, such as may occur in soft-bottom streams. Similarly, THERMOS could be used for initial predictions of the effect of leaving a riparian strip adjacent to water courses during forest clearing operations (more detailed predictions may need to include local topography and shading effects). Provided data on habitat preferences can be developed, RHYHABSIM can be used to demonstrate the impact of abstraction or dam construction on aquatic life in any landscape and the flows required to restore optimum instream conditions.

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