# Dissolved oxygen responses to weed control works in watercourses on the Wairau Plains

*Prepared for Marlborough District Council*

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*Photo caption: In-stream measurements being taken at Cravens Creek (Rohan Wells, NIWA)*

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# Executive summary

Marlborough District Council (MDC) engaged NIWA to assess the effects of aquatic herbicides use in watercourses of the district, as required by Condition 19 of consent no. U070702 (varied in April 2015). The revised consent decision stipulates monitoring of eight watercourses over two years for:

- continuous dissolved oxygen (DO) concentration
- air and water temperatures
- vegetation biomass
- assessment of the % of open water in proportion to the treatment areas and an assessment of water movement

NIWA undertook monitoring in both herbicide Treated and Untreated reaches within Caseys Creek, Drain C, Kellys Drain and Murphys Creek over November to December 2015 and Cravens Creek, Drain Q, Fairhall and Woolley and Jones in October to November 2016.

Monitoring was specified for three weeks, starting 10 days following herbicide application. The herbicides used were diquat (five watercourses ) or glyphosate (three watercourses).

Effects of herbicide application on measures of surface area and/or cross sectional area/volume occupied by vegetation varied from an apparent reduction in some watercourses (Caseys, Cravens, Drain Q), a biostatic effect (Murphys Creek), to little discernible effect (Kellys Drain, Fairhall, Woolley & Jones). Drying of Drain C during the monitoring period complicated our ability to detect the effects of herbicide application, because measurement of DO at this site was not possible when the channel was dry.

No statistically significant impacts on DO concentration associated with herbicide application were identified for the seven watercourses that were assessed. However, a change in DO concentration with time that was unrelated to herbicide application was detected. During 2016, these changes were associated with the 14$^{th}$ November Kaikoura earthquake.

DO concentrations in four watercourses failed to achieve suggested critical ecosystem health thresholds. Guideline DO levels were never attained in Woolley & Jones during the three-week monitoring period. Apart from the influence of the Kaikoura earthquake on both reaches of Drain Q, reasons for departure from desired DO conditions were not identified. In the untreated reach of Caseys Creek, spring inflows of DO depleted water was probably the dominant factor determining DO status.

Risk of herbicide-related DO impacts in watercourses of the Wairau Plains are likely to be reduced by:

- ongoing control of instream vegetation by manual clearance and herbicide control
- water aeration being provided by lower water levels, effective water conveyance and reduced vegetation canopy, and
- the naturally low and constant water temperatures in these spring-fed systems.

These results suggest current vegetation management practices in the watercourses of the Wairau Plains pose low risk of causing unacceptable decreases in DO concentrations. In contrast, natural

background factors such as meteorological influences or seismic activity were shown to have a greater influence than these vegetation management practices on watercourse DO status.

In conclusion, monitoring of the eight Wairau Plains watercourses stipulated by Condition 19 of consent no. U070702 did not reveal any consistent, statistically significant impacts on DO following application of diquat or glyphosate. From these results NIWA conclude that the risk of deoxygenation of watercourses on the Wairau Plains following herbicide application is likely to be low. Ecological impacts following herbicide application would be most likely where a very high in-stream plant biomass exists, DO status is already reduced, flows are low, a large standing water volume exists, and where high temperatures are likely to promote rapid decay of vegetation.

Taking on board these findings, MDC's Rivers Section has agreed to consider further scheduling waterways and drainage systems in its herbicide management programme known or considered to be at risk during the summer for: 1; high weed growth, 2; elevated water levels, 3; low levels of DO. The Rivers Engineering Section can recommend herbicide application techniques or other intervention to attempt to minimise adverse effects of low DO and water quality in waterways identified in this report as having an Attribute State for DO that is below the national bottom line according to the National Policy Statement for Freshwater.

# 1 Introduction

MDC is a Unitary Authority charged with protection and management of the District's environment. These responsibilities include management of watercourses for drainage and the conveyance of flood flows, and maintaining or improving water quality in waterways within their area National Policy Statement – Freshwater Management (NPSFM, 2014).

The drainage network on the Wairau Plains includes natural spring-fed streams, highly modified watercourses and man-made drains (Young et al. 2002). Excessive vegetation development in some of these systems, including those invaded by exotic aquatic weeds, is managed by control methods that include hand clearing, mechanical excavation, weed cutting, and the use of aquatic herbicides (MDC Code of Practice for Application of Herbicide and Associated Additives Into or Over Water, 2008).

Procedures and Standards for application of herbicides onto or into water are described in the Councils Code of Practice (MDC, 2008). The herbicide for the control of submersed water weeds is diquat dibromide (or potentially dipotassium endothall), which is applied in November to December or April to May. Also commonly applied near or over water is glyphosate, which may be applied from December to February. Use of aquatic herbicides in the district is a discretionary activity for which Resource Consent was granted in 2009 (Consent no. U070702). Recently (7th April 2015), Condition 19 of the Consent was amended to stipulate monitoring of DO, changes in vegetation and water temperature in periods associated with herbicide application.

Specifically, Condition 19 now reads (in italics):

*Information shall be gathered on a daily basis from waterways for at least a period of three weeks no sooner than 10 days after the application of herbicide. Information shall include:*

- *Changes in DO levels as a result of application of herbicide into or onto waterways. A remote logger shall be used to record fluctuations in oxygen levels throughout the day shall be used rather than an individual sample*
- *The assessment of the biomass of the target treatment area.*
- *Assessment of the % of open water in proportion to the treatment areas; assessment of the degree of water movement.*
- *Measurement of water and air temperature.*
- *Such other information as considered material to assessment of the effects of the activities permitted by this consent on the environment.*

*In 2016 the consent holder will undertake monitoring of Drain C – Sadds, Kellys Drain, Caseys Creek and Murphys Creek.*

*In 2017 the consent holder will undertake monitoring of Drain Q – Roses Fairhall, Co-op (below Bells Road), Woolley and Jones and Cravens Creek.*

[NB. exact wording reproduced from Condition 19].

Presumably the focus on DO levels of these consent conditions reflects concerns for deoxygenation in watercourses caused by decomposing vegetation following herbicide control (Young et al. 2004, Greer 2014). Extreme fluctuations in DO concentrations are caused by excessive vegetation growth within waterways (Wilcock et al. 1995, Goodwin et al. 2008, Turner et al. 2010, Davies-Colley et al. 2013, Liu et al. 2015). These contrasting influences alone suggest a range of DO outcomes are possible following management of watercourses for excessive vegetation.

This final report presents the monitoring approach and results for Drain C – Sadds, Kellys Drain, Caseys Creek, and Murphys Creek in 2015, and Cravens Creek, Drain Q, Fairhall Co-op and Woolley & Jones in 2016. Although the Consent Decision suggests these watercourses be monitored in 2016 and 2017, the actual work was undertaken in late 2015 and 2016 to fit in with planned MDC operations. An interim report (de Winton et al. 2016) covered findings for the watercourses monitored in 2015.

# 2 Methods

## 2.1 Sites and timing

Appendix A identifies the sites and location of the eight watercourses. In each case an Untreated reach was located upstream of a section treated with herbicide; the latter termed the Treated reach. Kellys Drain was Y-shaped with two upper reaches, one of which was also treated. In this case the Treated reach still represented maximum potential herbicide effect. For the four waterbodies treated in 2015, the Treated reach was sprayed with diquat (Reglone®) at recommended label rates on the 13th November. The additional four waterbodies were treated on 27th October 2016. The Treated reach of Cravens Creek was treated with diquat (Reglone®) at recommended label rates and the remainder were treated with Glyphosate (Polaris® 450) at the label rate with a penetrant/surfactant (Penatra™). DO and temperature logger position was documented by GPS coordinates (Appendix A).

Logging instruments were installed in each reach prior to spraying to establish baseline conditions. Data were therefore collected for a longer period than stipulated in the Consent Condition.

Additional information required by the Consent (abundance of aquatic vegetation, water depth and velocity) were assessed:

- before spraying
- c. 6-14 days after treatment
- c. 14-19 days after treatment
- c. 21-26 days after treatment
- c. 28-33 days after treatment.

In addition to indicating the timing of events above, this report also notes the 7.8 (moment magnitude scale) Kaikoura earthquake that took place at 00:02 DST on 14 November 2016. This event had impacts on aquifer levels and turbidity of the ground water[1] that may have been relevant to changes in conditions in these spring-fed streams.

## 2.2 Logging dissolved oxygen and temperature

Logging instruments (D-Opto DO logger, Zebra-Tech Ltd) were deployed at half the ambient water depth. These loggers use a solid-state optical sensing system to measure DO and generally provide highly stable measurements over long periods of time. Before deployment, a solution of sodium sulphite (0% DO saturation) and a completely aerated water sample (100% DO saturation) were used to calibrate the DO loggers. Optical measurements of DO are accurate to 1% between 0.01% and 100% saturation (manufacturers specifications).

One D-Opto logger was placed in the Treated reach, at least 100 m downstream from the start of herbicide application (range 100 to 170 m distance), the other in the Untreated reach. DO (±3% of saturation) and temperature (±0.1 °C) were logged every 15 minutes for the duration of their deployment. Because of limited depth and the potential for debris to catch on the instrument, the logger was orientated horizontal in the water column with the sensor facing downstream. Loggers

[1] https://issuu.com/ruralnewsgroup/docs/nzwg_feb-mar_102/16

were securely attached to a waratah post, with additional waratahs deployed 1 m upstream of each logger to deflect vegetation debris washed downstream.

During each assessment period, DO and temperature were measured manually using equipment, the D-Opto loggers were removed and the data downloaded. Debris was removed from the waratahs and the sensor gently cleaned with a soft tissue before redeloyment.

Temperature logging sensors (Hobo loggers, http://www.onsetcomp.com/) were deployed at each watercourse to obtain a record of local air temperature. Independent verification of these air temperature records were made by spot measurements.

All results are presented as New Zealand daylight saving time, 24 hr clock.

## 2.3 Aquatic vegetation

At each assessment, aquatic plants were surveyed within the wetted channel. Five 1 m wide swaths were spaced within a 100 m section of the Untreated reach and the Treated reach. Within each swath the dominant plant species were recorded and two measurements made that are drawn from guidelines for assessing instream plant abundance (Matheson et al. 2012) and the ecological assessment of wadeable streams (Collier et al. 2014). These measures meet the Consent criteria for assessing proportion (%) of open water, and also indicate the likely occlusion of the channel that is the focus of MDC’s weed control programme.

Surface Area (SA%) of the wetted channel that is covered by emergent aquatic plants, and/or submerged plants that are surface reaching and covering the water surface, were estimated from plan view. Cross sectional area/volume (CAV%), also referred to as “channel clogginess”, provides a measure of the proportion of the channel that is occupied by submerged aquatic plants that are not necessarily surface reaching. CAV was estimated from five or more measurements of the depth to the top of the plant canopy and depth to bed in each swath using a tape measure. Photographs of each swath were made at every assessment.

Because vegetation occluding the channel may originate from the banks of a watercourse, we estimated the average cover and height of riparian plants in the lower 1/3$^{rd}$ of the batter at each of the swaths assessed.

## 2.4 Manual physico-chemical measurements

At each swath and watercourse width measurement, water velocity measurements of 30 seconds duration were made near the water surface (c. 0.1 m depth) using a velocity meter (SonTech FlowTracker ADV).

Measurements of DO and temperature were made using a hand held optical probe (YSI ProODO) close to but downstream of the logger during each assessment, while recording the time. Air temperature was also measured (Appendix B).

## 2.5 Data analysis

To identify statistical significance between DO levels in Treated and Untreated reaches over the Consent monitoring period (23rd November to 13th December 2015 and 6th November to 27th November 2016), we carried out a Repeated Measures Analysis of Variance analysis (RMANOVA) using Statistica (v 12). Daily minima for each reach were selected for analysis, with the sites treated as replicates, two treatments and a time component.

To identify the ecological significance of DO results in Treated and Untreated reaches over the Consent monitoring period, we compared measured values with thresholds required to protect ecosystem health (Davies-Colley et al. 2013) and attribute state (grades from A to D) proposed for rivers under the National Policy Statement for Freshwater (NPS-FM 2014).

# 3 Results

## 3.1 Caseys Creek

This moderate sized watercourse averaged 5.52 m width (all assessments) and a maximum depth of 0.57 m. It was flanked by batters covered by pasture grasses (Figure 1) that were mown in some areas. Spring inflows were noted within the Untreated reach.

In-stream vegetation was initially dominated by bentgrass (*Agrostis stolonifera*), lagarosiphon (*Lagarosiphon major*), watercress (*Nasturtium* sp.), floating duckweed *Lemna* sp.) and azolla (*Azolla rubra*), a dichotomous liverwort (*Riccia?*) and charophyte (*Nitella* sp. aff. *cristata*). Observations of herbicide symptoms in lagarosiphon and bentgrass were apparent in the Treated reach from the 28$^{th}$ November 2015, 15 days after diquat application.

**Figure 1: Caseys Creek viewed from the road and looking upstream.**

Following diquat application the SA (%) and CAV (%) both declined in the Treated reach relative to the Untreated reach (Figure 2). It appeared that vegetation changes in the Treated reach were accompanied by a decrease in both water depth and maximum velocity.

Unfortunately, the early portion of logged data was lost during download, but the subsequent record (Figure 3) shows the Treated reach had a wider temperature range (11.8 to 20 °C) with higher peaks than the Untreated reach (12.8 to 16.2 °C).

The Treated reach also had a more pronounced diurnal DO pattern, with a stable range over time (5.1 to 10.8 mg $L^{-1}$), compared to the lower and declining DO value range (3.2 to 8.6 mg $L^{-1}$) in the untreated reach (Figure 3). Manual measurements supported these differences in the logged data (Table 1).

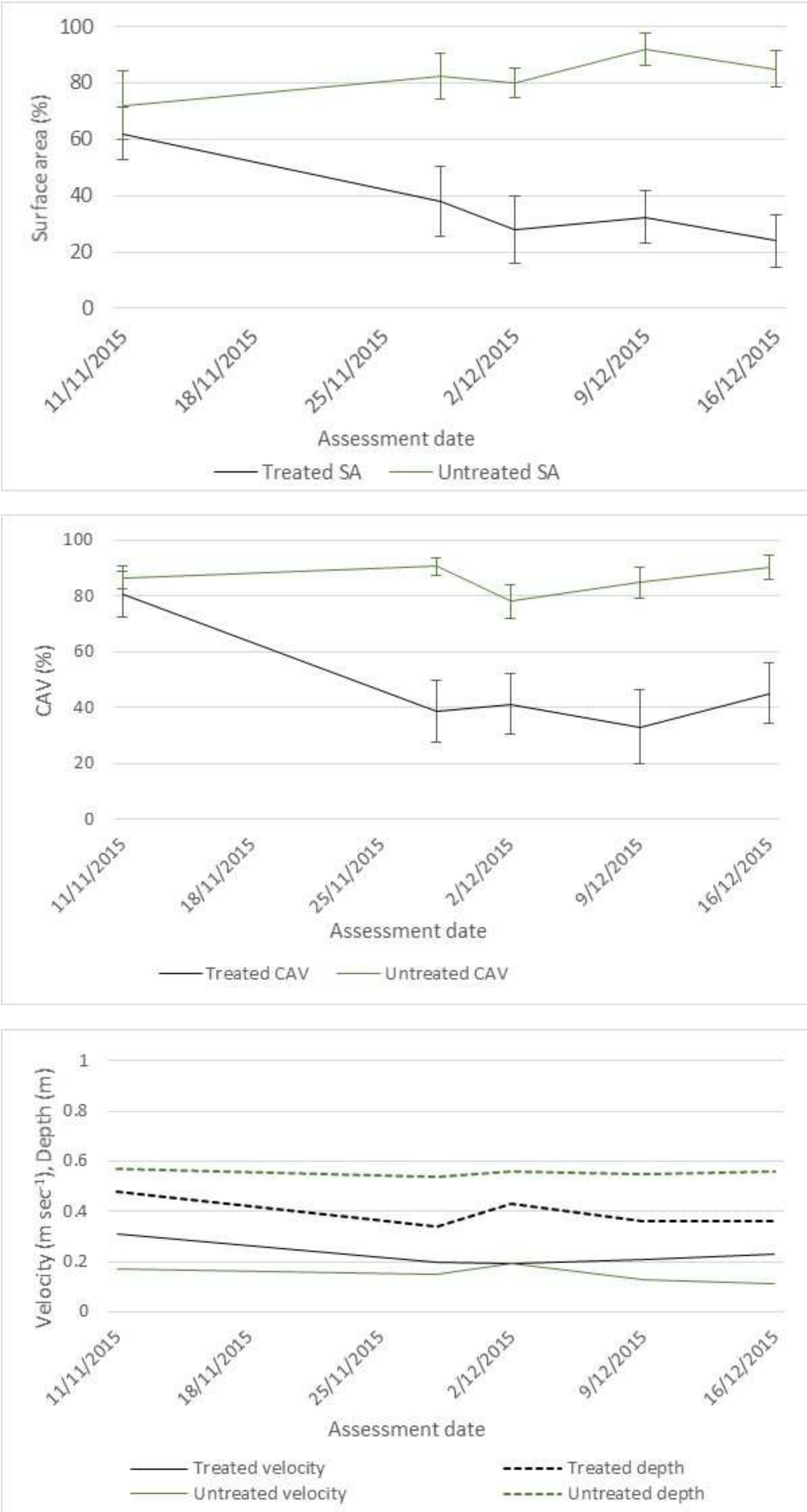



**Figure 2: Plots from consecutive assessments at Caseys Creek.** Top, average SA (%), middle, average CAV (%) and bottom, average maximum water velocity (m/sec) and average maximum depth (m). Error bars are ±1 SE, (n=5).

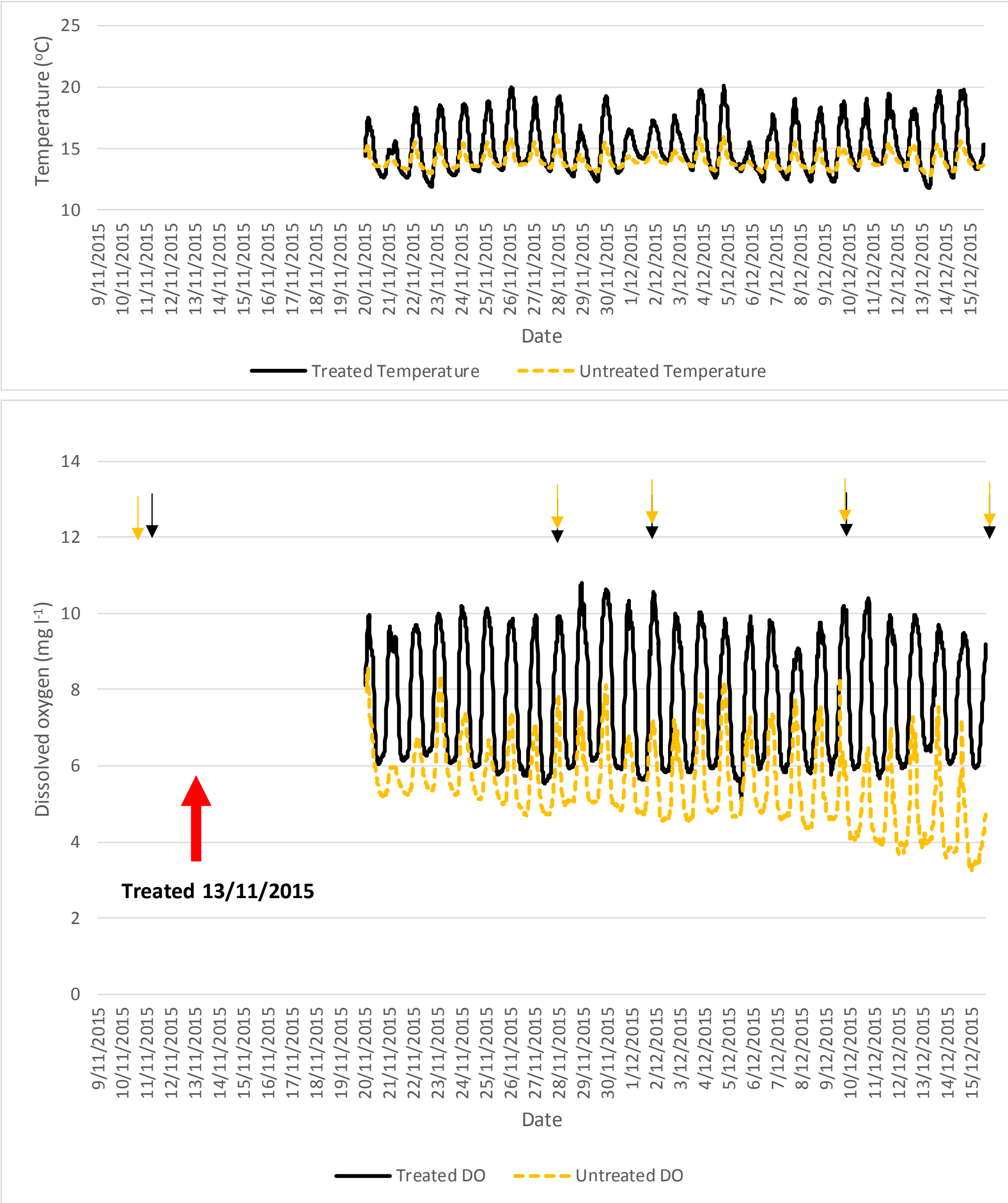



**Figure 3: Water temperature (top) and dissolved oxygen (bottom) for the treated and untreated reach at Caseys Creek.** The timing of diquat treatment (red) and reach assessments (yellow and black) are shown as coloured arrows.

**Table 1: Manual measurements of temperature and DO concentrations in the Treated and Untreated reach.** Data is a spot record for the date and time range that the watercourse was sampled.

| Date and time | Treated temperature | Treated DO mg L$^{-1}$ | Untreated temperature | Untreated DO mg L$^{-1}$ |
|---|---|---|---|---|
| 11/11/2015 15:20-16:30 | 14.1 | 9.0 | 13.5 | 6.33 |
| 28/11/2015 12:30-13:00 | 18.0 | 9.5 | 15.3 | 7.8 |
| 10/12/2015 10:30-10.45 | 15.8 | 8.8 | 14.7 | 7.55 |
| 16/12/2015 13:45-14:15 | 15.0 | 9.4 | 13.8 | 5.6 |

## 3.2 Drain C

This narrow (<2 m wide) drain (Figure 4) underwent water level reduction over the course of assessments, from an initial maximum depth of 0.21 m to completely dry in the upper Untreated reach, and to <0.15 m depth in the downstream Treated reach. Both banks were covered with tall grasses and pasture weeds.

Initial in-stream vegetation comprised filamentous green algae, water plantain (*Alisma plantago-aquatica*), water celery (*Apium nodiflorum*) and duckweed. Following diquat application in the Treated reach, some dieback of vegetation (particularly water plantain) could be seen by 28$^{th}$ November 2015, 15 days after application. However, comparison of SA and CAV between the Treated and Untreated reaches (Figure 5) were obscured by drying of the water course. No water flows could be measured and water depths were zero or minimal (Figure 5).

**Figure 4: Drain C showing the narrow, shallow channel and grassy batter.**

No reliable measurements of DO could be made in either the Treated or Untreated reaches due to lack of water (Figure 6). DO readings fluctuated widely and were at times negative.

Temperature ranges reflected the very shallow, stagnant and unshaded nature of the Treated reach (7.8 to 35 °C), and a very high range in the Untreated reach (3.5 to 50 °C), because the D-Opto logger was out of the water.

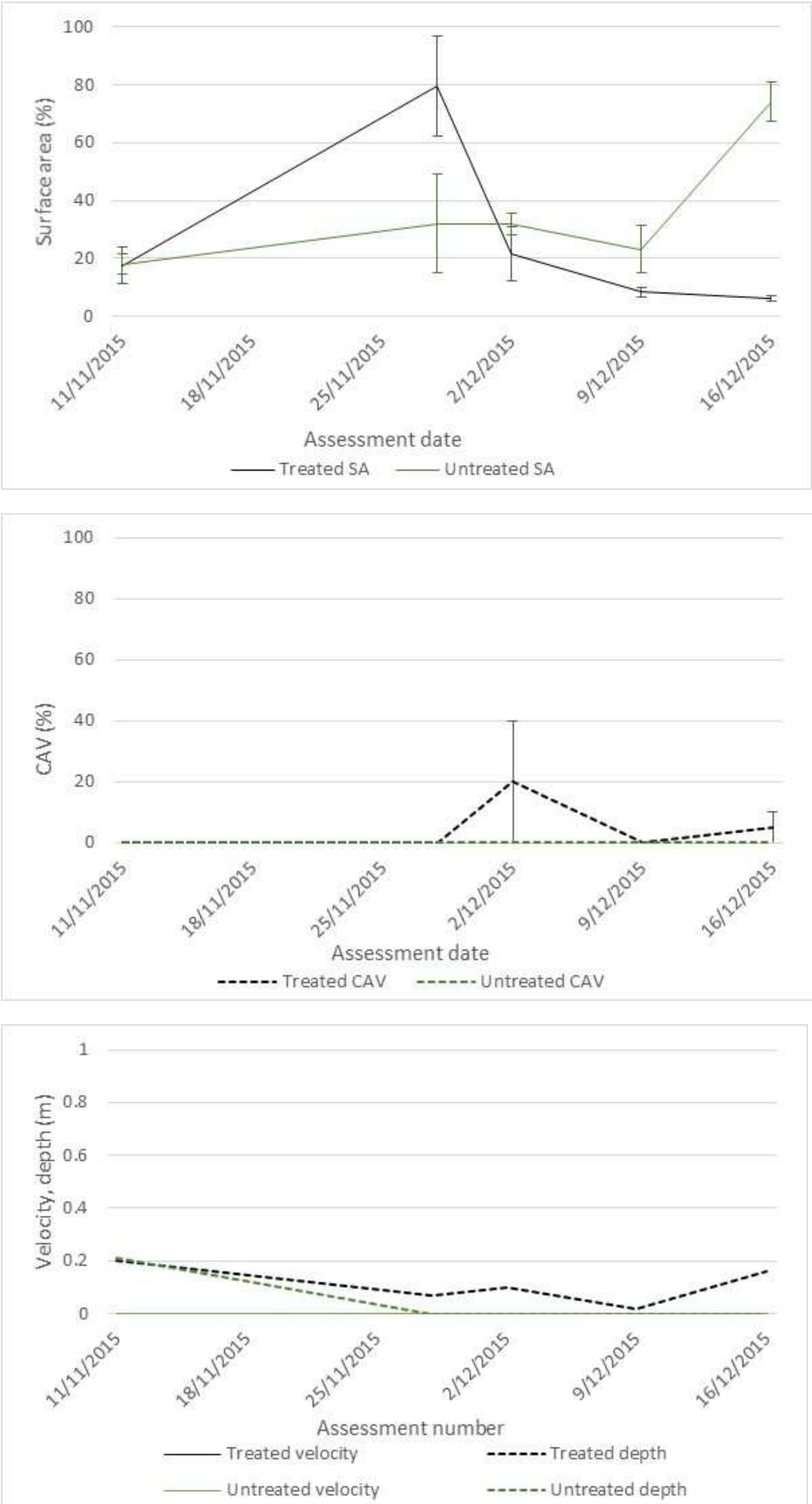



**Figure 5: Plots from consecutive assessments at Drain C.** Top, average SA (%), middle, average CAV (%) and bottom, average maximum water velocity (m/sec), and average maximum water depth (m). Error bars are ±1 SE, (n=5).

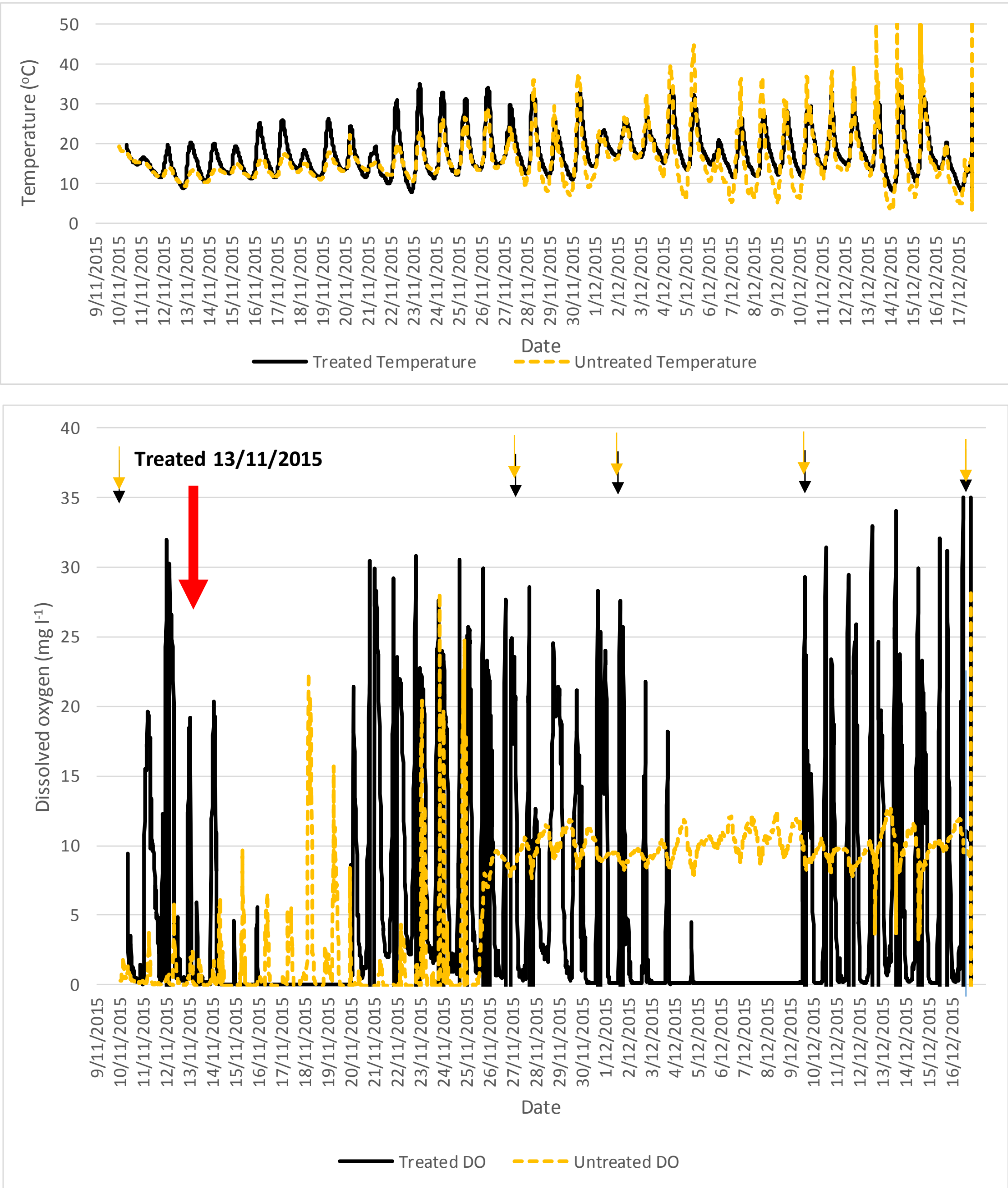



**Figure 6: Water temperature (top) and dissolved oxygen (bottom) for the Treated and Untreated reach at Drain C.** The timing of diquat treatment (red) and reach assessments (yellow and black) are shown as coloured arrows.

## 3.3 Kellys Drain (Drain N)

This watercourse was 2.8 m wide on average (all assessments) and up to 0.72 m deep. The batter was covered by pasture grasses and weeds, but the left bank of the Untreated reach (Figure 7) and both banks of the Treated reach had previously been sprayed by adjacent landowners.

In-stream vegetation was initially dominated by elodea (*Elodea canadensis*), lagarosiphon, pondweed (*Potamogeton cheesemanii*) and bentgrass (*Agrostis stolonifera*). Herbicide impacts were apparent on vegetation in the Treated reach by the 3rd December 2015, 20 days after diquat application, with elodea being particularly susceptible.

**Figure 7: Kellys Drain showing the narrow, deep channel and grassy batter that has been controlled on the left bank.**

Conversely, there was little overall biomass response to the diquat application in the Treated reach (Figure 8). SA measurements were similar between reaches at all assessments and although CAV decreased in the Treated reach relative (whereas CAV increased in the Untreated reach), this effect was minor and short lived (Figure 8). Maximum water velocity was similar and stable in both reaches. Although both reaches showed a decrease in maximum depth over the sequence of assessments, the drop was greater for the Treated reach (Figure 8).

Logged D-Opto data (Figure 9) showed that the water temperature in the Treated reach (12 to 18.5 °C) was similar to that in the Untreated reach (12 to 17.4 °C), while the diurnal DO range for the Treated reach was greater (5.4 to 12.4 mg $L^{-1}$), and with consistently higher peaks, than the Untreated reach (6.0 to 10 mg $L^{-1}$). Manual measurements (Table 2) indicated that the daytime range in DO (8-10 mg $L^{-1}$) of both reaches was similar.

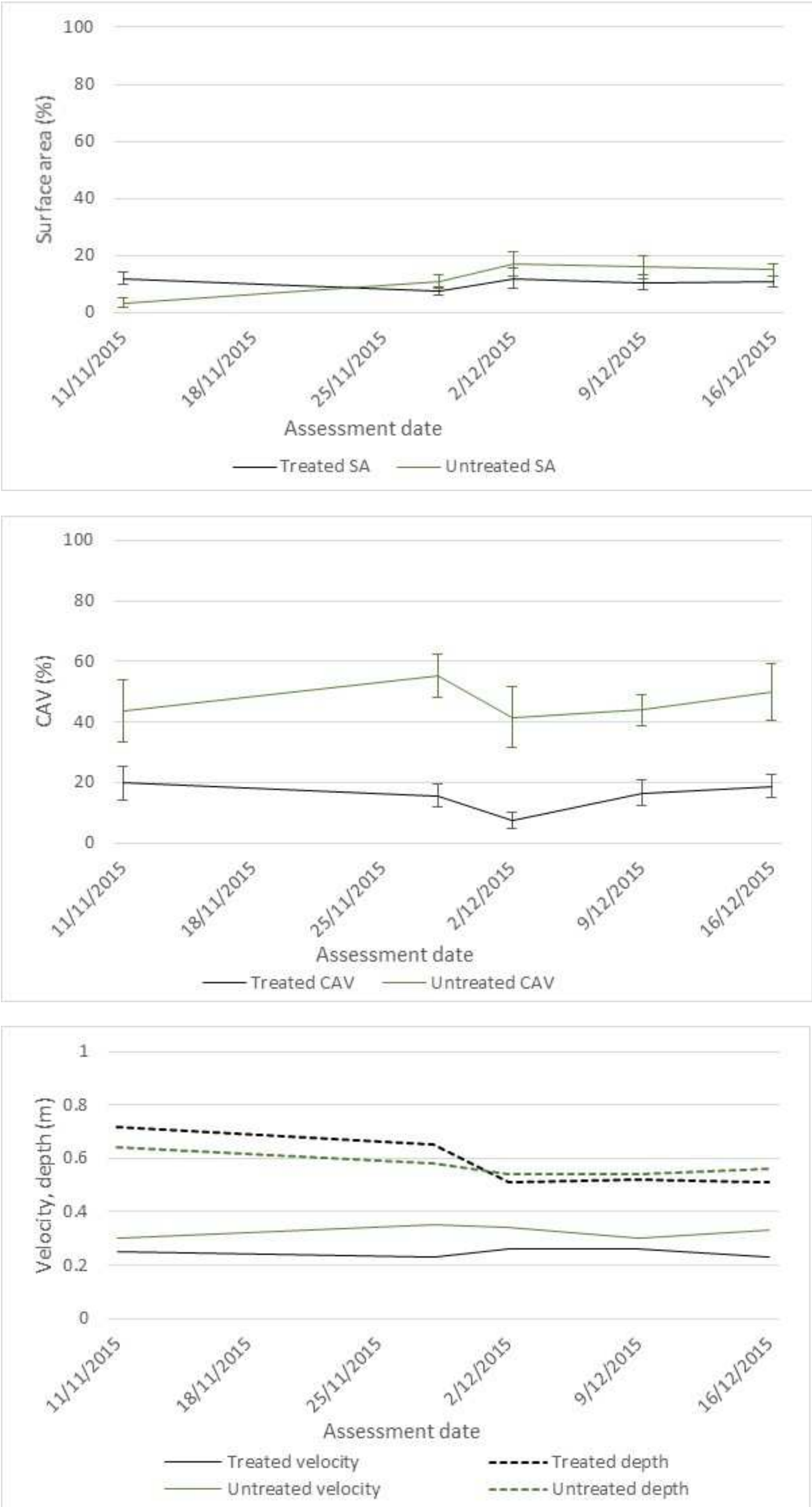
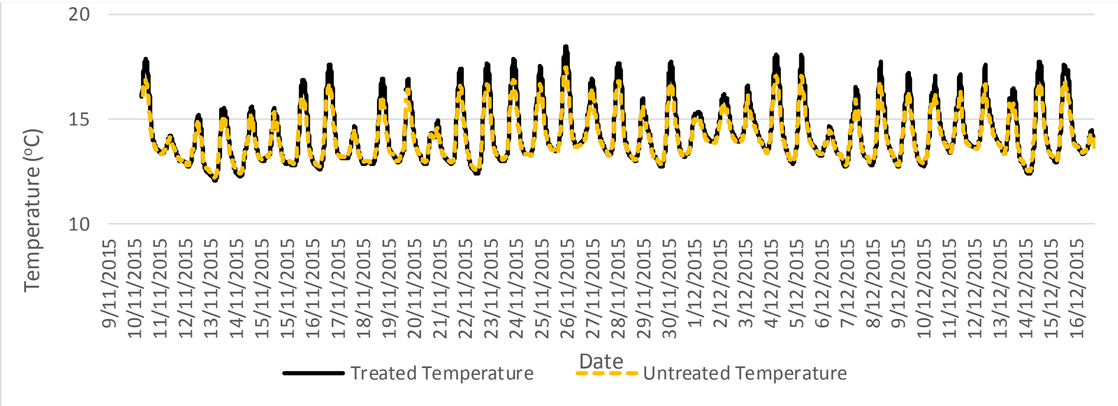



**Figure 8: Plots from consecutive assessments at Kellys Drain.** Top, average SA (%), middle, average CAV (%) and bottom, average maximum water velocity (m/sec) and average maximum depth (m). Error bars are ±1 SE, (n=5).



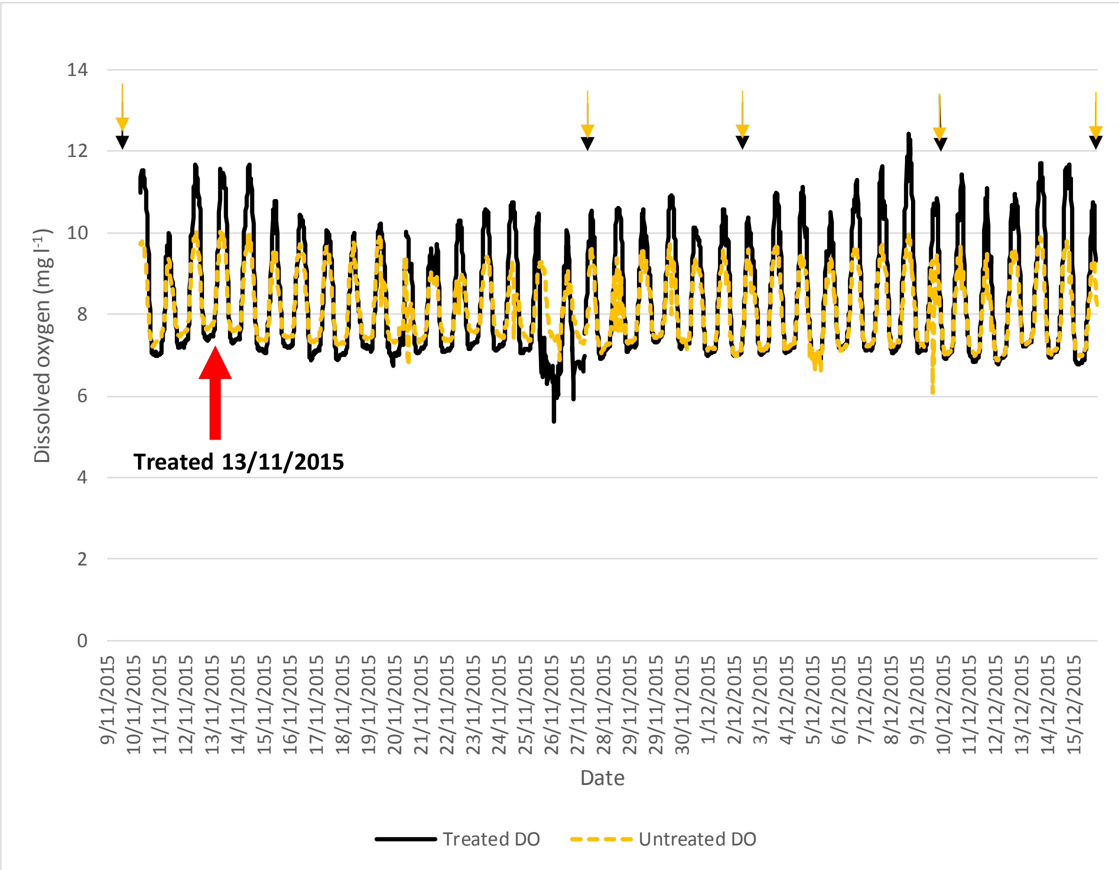




**Figure 9: Water temperature (top) and dissolved oxygen (bottom) for the Treated and Untreated reach at Kellys Drain.** The timing of diquat treatment (red) and reach assessments (yellow and black) are shown as coloured arrows.

**Table 2: Manual measurements of temperature and DO in the Treated and Untreated reach.** Data is a spot record for the date and time range that the watercourse was sampled.

| Date and time | Treated temperature | Treated DO mg $L^{-1}$ | Untreated temperature | Untreated DO mg $l^{-1}$ |
|---|---|---|---|---|
| 27/11/2015 7:15 | 14.0 | 8.0 | | |
| 27/11/2015 11:30 | | | 15.1 | 9.9 |
| 10/12/2015 9:45 to 10:00 | 13.8 | 9.6 | 14.1 | 9.6 |
| 16/12/2015 16:30 to 17:45 | 14.1 | 9.8 | 13.7 | 8.7 |

## 3.4 Murphys Creek

This large water course averaged 6.6 m in width (all assessments) and had a maximum depth of 0.85 m. The creek runs through residential suburbs and parks and the batter is modified by revetments or structures (Figure 10) and dominated by exotic planting or mown edges.

In-stream vegetation was initially dominated by lagarosiphon, bentgrass, watercress, pondweed, charophyte, duckweed and reed sweetgrass (*Glyceria* sp.). There was no notable die-off of vegetation in the Treated reach following diquat application, although lagarosiphon was reported as 'stressed' (discoloured and damaged) on the 9th December 2015, 26 days after diquat application.

**Figure 10: Murphys Creek showing access ways and creek-side structures typical of the watercourse.**

Following the diquat application of 13th November 2015, SA of the Treated reach appeared to be stable relative to large increases in SA of the Untreated reach (Figure 11). There was a relatively small decrease in CAV of the Treated reach relative to stable values in the Untreated reach (Figure 11). Velocities and depth in both reaches tended to decrease over time, although the Treated reach showed a larger overall drop in water level.

Initially the range in water temperature in the Untreated reach was smaller than in the Treated reach, but by the end of the logged period it slightly exceeded (12.5 to 15.0 °C) the range in the Treated reach (12.8 to 14.9 °C). DO in the Untreated reach (Figure 12) also initially had a lower range than in the Treated reach, but developed higher diurnal maxima over time (up to 12.7 mg $L^{-1}$) than the Treated reach (up to 9.6 mg $L^{-1}$). DO minima in the Treated reach generally remained slightly lower than in the Untreated reach.

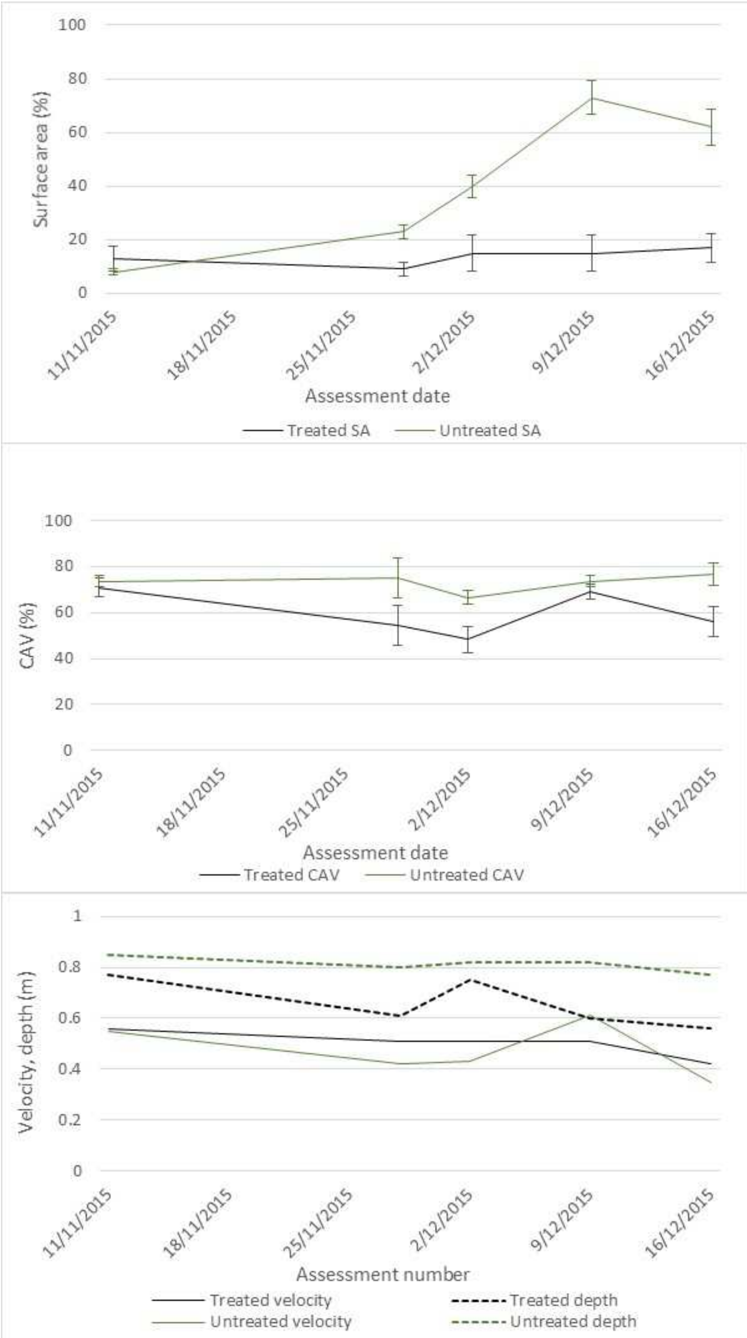
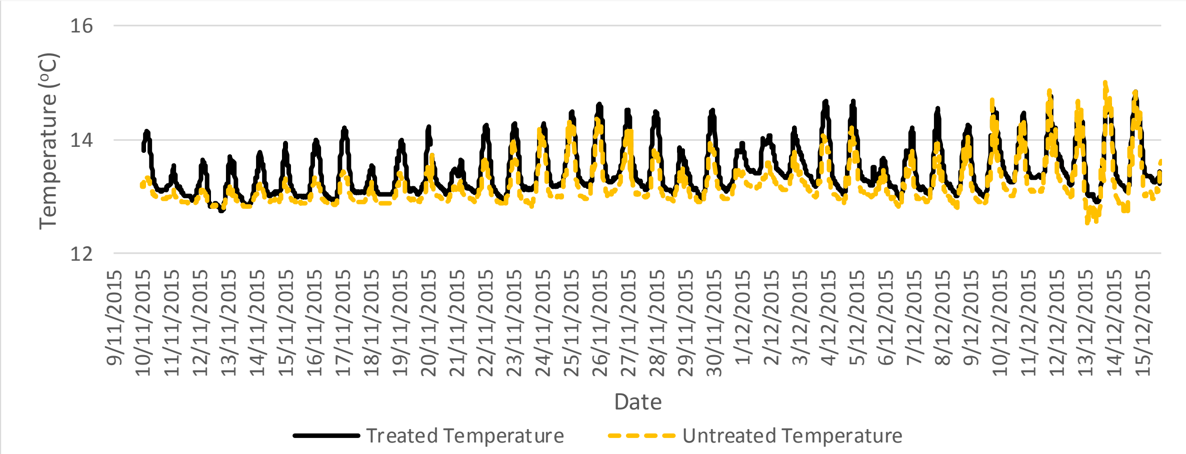



**Figure 11: Plots from consecutive assessments at Murphys Creek.** Top, average SA (%), middle, average CAV (%) and bottom, average maximum water velocity (m/sec) and average maximum depth (m). Error bars are ±1 SE, (n=5).



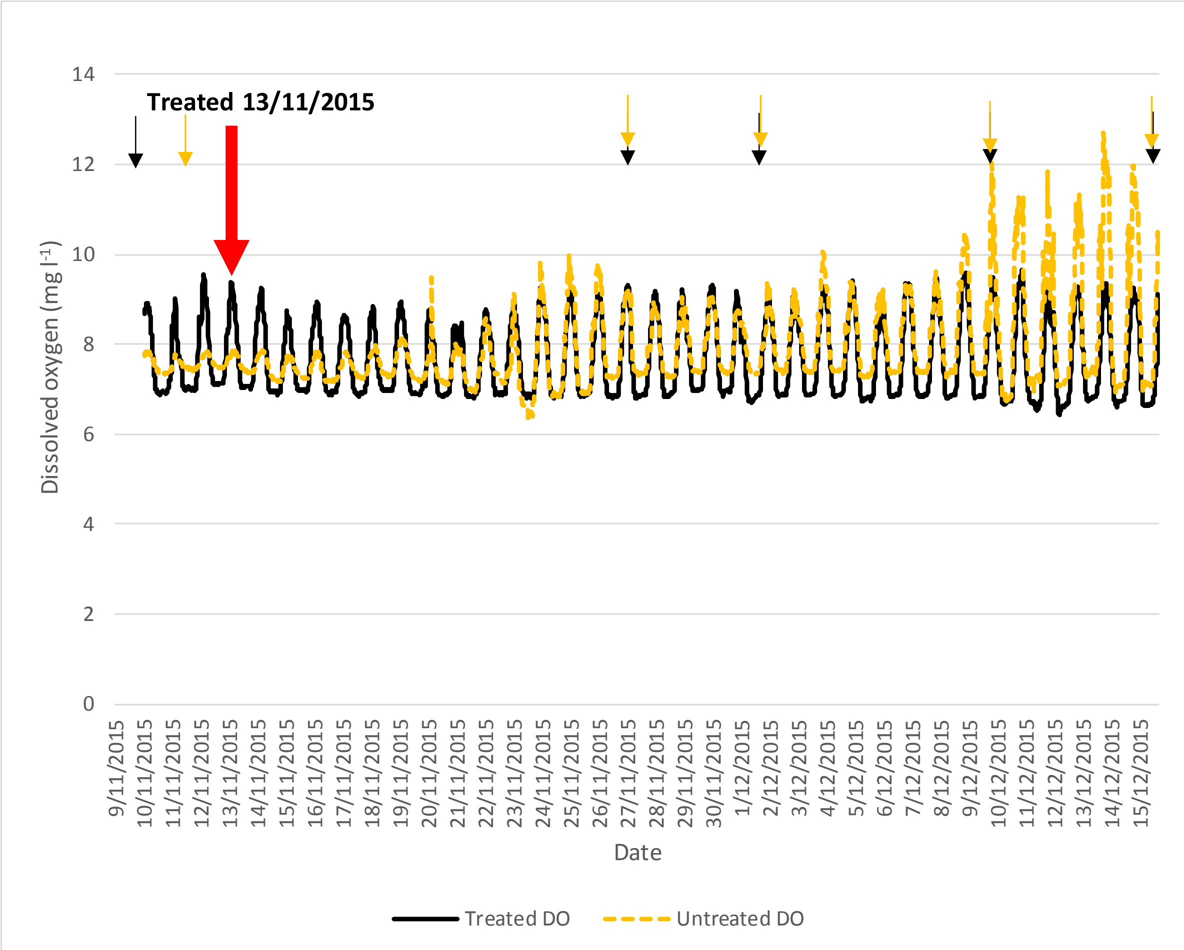




**Figure 12: Water temperature (top) and dissolved oxygen (bottom) for the Treated and Untreated reach at Murphys Creek.** The timing of diquat treatment (red) and reach assessments (yellow and black) are shown as coloured arrows.

**Table 3: Manual measurements of temperature and DO in the Treated and Untreated reach.** Data is a spot record for the date and time range that the watercourse was sampled.

| Date and time | Treated temperature | Treated DO mg $L^{-1}$ | Untreated temperature | Untreated DO mg $L^{-1}$ |
|---|---|---|---|---|
| 10/11/2015 11:05 | 14.0 | 9.6 | | |
| 12/11/2015 16:45 | | | 13.0 | 8.6 |
| 27/11/2015 17:30-17:45 | 14.1 | 8.8 | 13.4 | 8.5 |
| 10/12/2015 11:30-11:45 | 14.3 | 9.7 | 14.0 | 9.5 |
| 16/12/2015 10:45-11:00 | 13.5 | 9.0 | 13.3 | 8.7 |

## 3.5 Cravens Creek

This waterway averaged 4.2 m width and 0.73 m depth. The right batter bank was dominated by a complete cover of grasses to 0.46 m in average height (Figure 13), whereas the left bank had been controlled by land owners and comprised occasional grasses to ≤0.25 m height.

Initial in-stream vegetation comprised bentgrass, *Isolepis* sp. and watercress, with some patches of floating duckweed and azolla (Figure 13). Herbicide symptoms were apparent on vegetation of the Treated reach from six days after treatment (2$^{nd}$ November 2016).

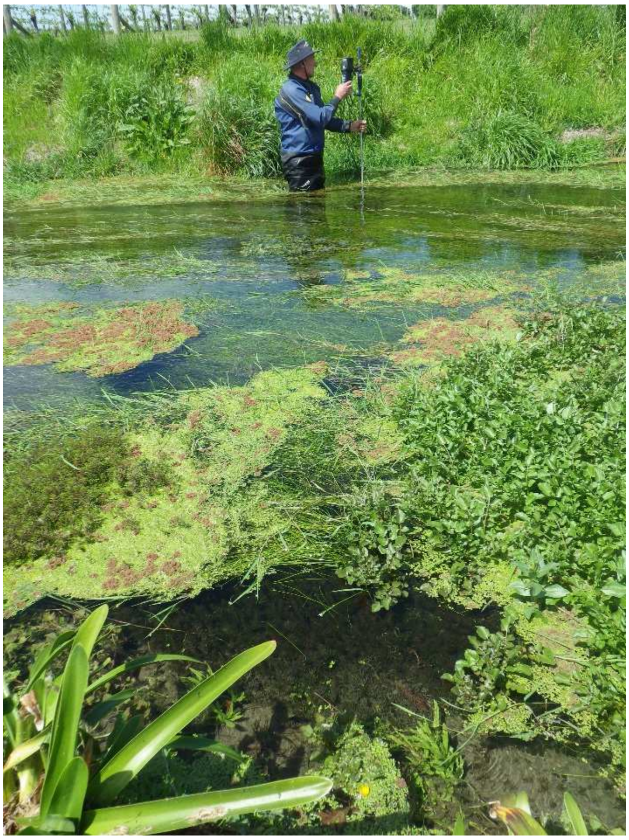


**Figure 13: Cravens Creek showing the grassy batter on the true right and in-stream vegetation before herbicide treatment.**

SA and CAV did not respond strongly to herbicide treatment (Figure 14). SA of both reaches decreased after 10$^{th}$ November 2017, possibly in response to a small fresh, and by the final assessment were lower than pre-spray assessment. By contrast, the CAV decreased more in the treated reach. Velocities remained similar, but the depth of both reaches increased over the assessment period (Figure 14).

Diurnal DO fluctuations were greater in the Treated reach than the Untreated reach (Figure 15). The lowest DO measurement in the Treated reach (Figure 15) occurred c. two days following the Kaikoura earthquake (time interval 45:30 post-earthquake). This was preceded by a temperature spike (time interval 39:00 post-earthquake) that does not relate to air temperatures at the time (Appendix B2). The Untreated reach had a similar response to the earthquake c. 1 hour earlier, although the lowest recorded DO levels here occurred prior to the earthquake (7$^{th}$ & 10$^{th}$ November 2016).

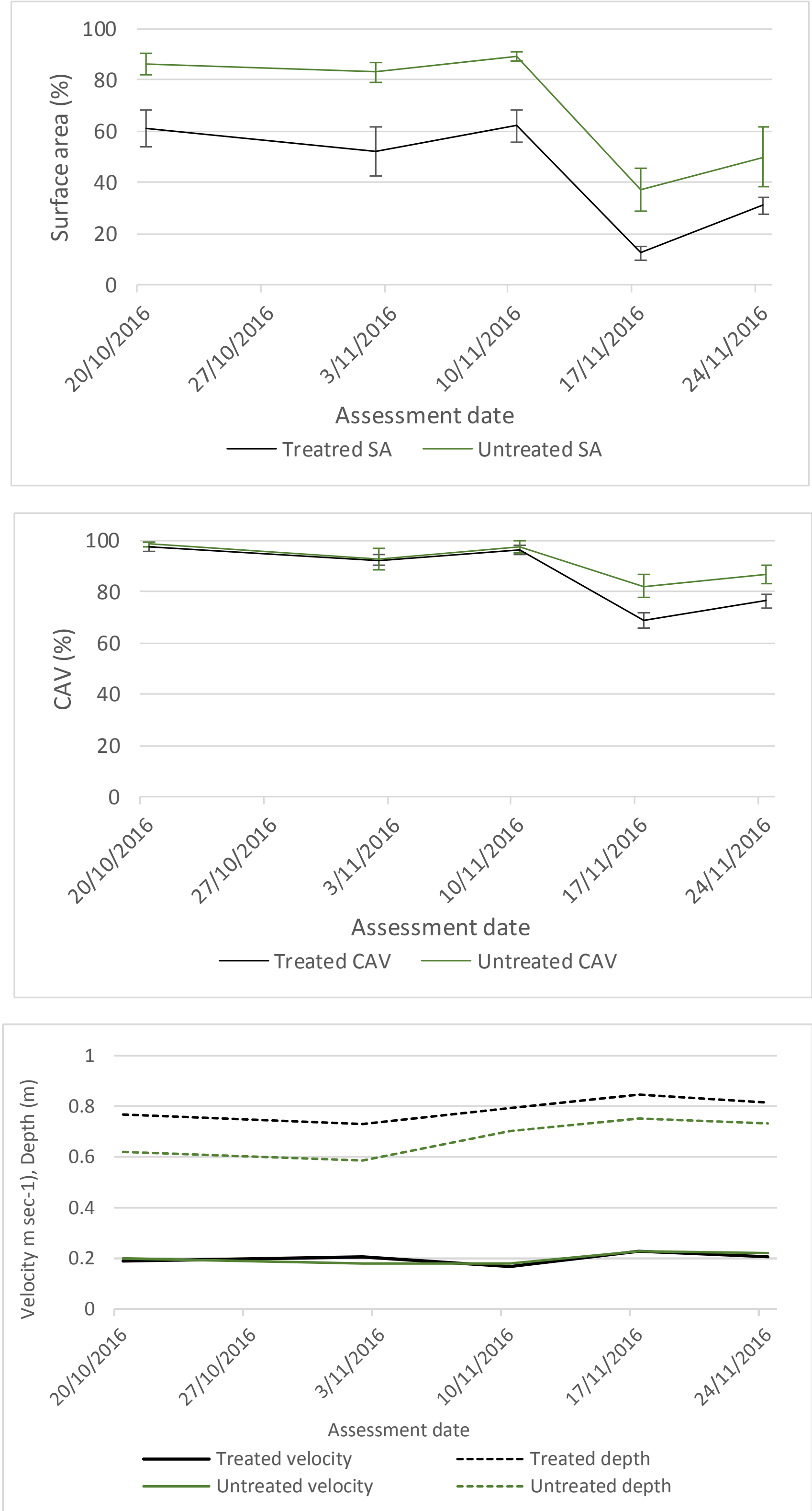



**Figure 14:** **Plots from consecutive assessments at Cravens Creek.** Top, average SA (%), middle, average CAV (%) and bottom, average maximum water velocity (m/sec) and average maximum depth (m). Error bars are ±1 SE, (n=5).

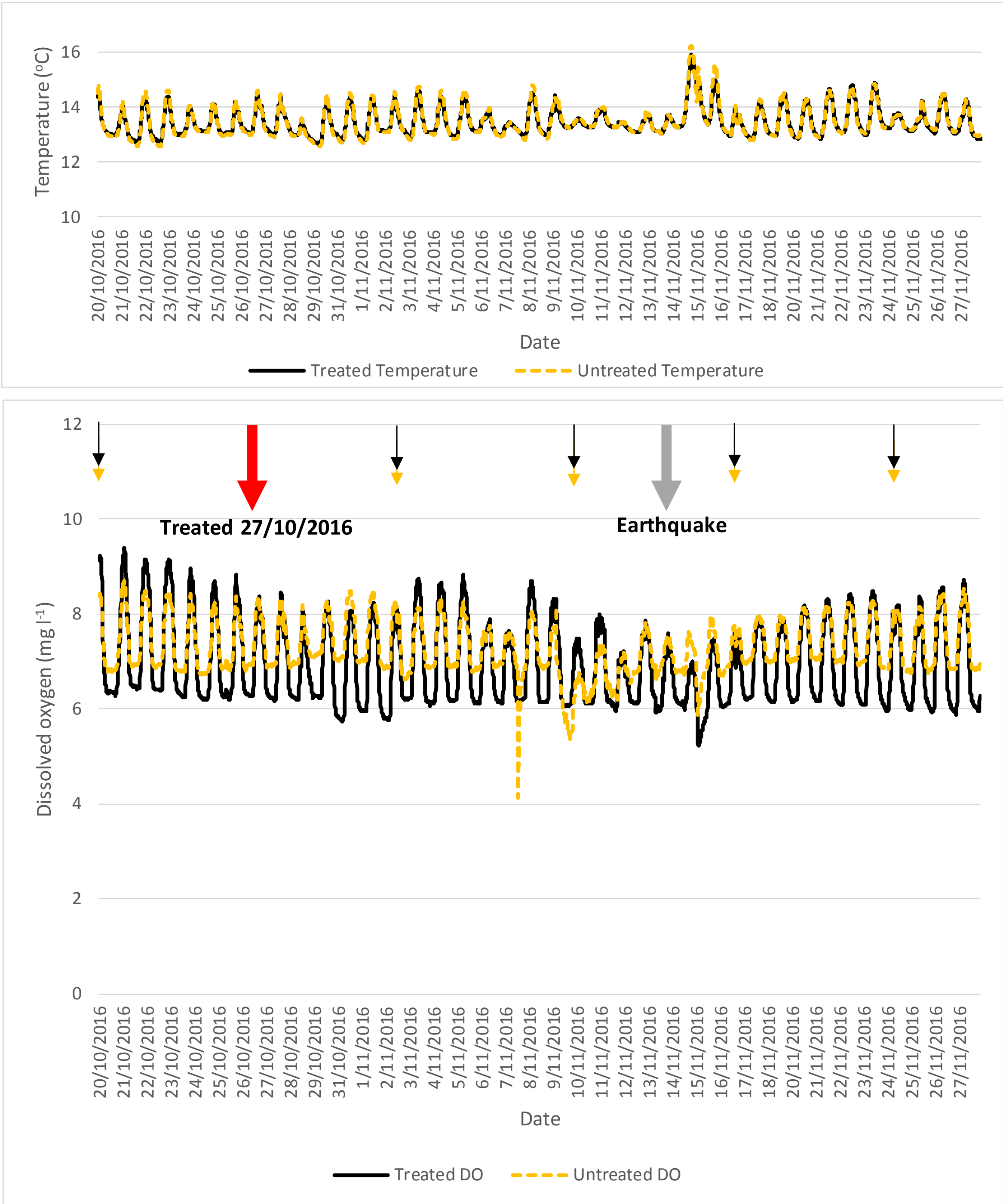



**Figure 15: Water temperature (top) and dissolved oxygen (bottom) for the Treated and Untreated reach at Cravens Creek.** The timing of diquat treatment (red), earthquake (grey) and reach assessments (yellow and black) are shown as coloured arrows.

**Table 4: Manual measurements of temperature and DO in the Treated and Untreated reach.** Data is a spot record for the date and time range that the watercourse was sampled.

| Date and time | Treated temperature | Treated DO mg $L^{-1}$ | Untreated temperature | Untreated DO mg $L^{-1}$ |
|---|---|---|---|---|
| 20/10/2016 12:15-12:30 | 14.4 | 9.5 | 14.8 | 8.5 |
| 2/11/2016 16:00-16:30 | 14.0 | 8.4 | 14.0 | 7.6 |
| 9/11/2016 14:00-14:15 | 14.1 | 8.3 | 14.4 | 7.4 |
| 28/11/2016 10:45-11:15 | 13.7 | 8.6 | 13.8 | 8.0 |

## 3.6 Drain Q

A narrow incised drain, Drain Q averaged 1.2 m width and 0.22 m depth. The batter banks of the Untreated reach comprised weeds and grasses which had been controlled in places, while the Treated reach was lined with *Agapanthus praecox* with patches of dead grasses and weeds in places.

Before herbicide (glyphosate) application the dominant vegetation within the drainage channel was *Nitella* sp. aff. *cristata* (submerged) and duckweed (floating), with marginal vegetation sprawling into the water. Herbicide symptoms were apparent along the edges of the treated reach by 14 days after treatment (10$^{th}$ November 2016).

**Figure 16: The narrow incised channel of Drain Q.**

The Treated reach showed a modest reduction in SA, while the Untreated reach remained similar throughout the assessments (Figure 17). Both reaches underwent a slight reduction and recovery in CAV, whilst velocity and depth showed little change through the assessments (Figure 17).

The diurnal range of DO in the Treated reach was generally higher than the Untreated reach, with the only time the daily DO minima of the Treated reach was less than the Untreated reach occurring immediately after the Kaikoura earthquake. DO dropped to <3.4 mg $L^{-1}$ in the Treated reach over 00:15 and 00:30 on 14$^{th}$ November 2016. Another DO sag was evident after about 2 days (time interval 47:00 post-earthquake) in both reaches. This was preceded by a temperature spike (time interval 41:15 post-earthquake) in both reaches that does not relate to air temperatures at the time (Appendix B2).

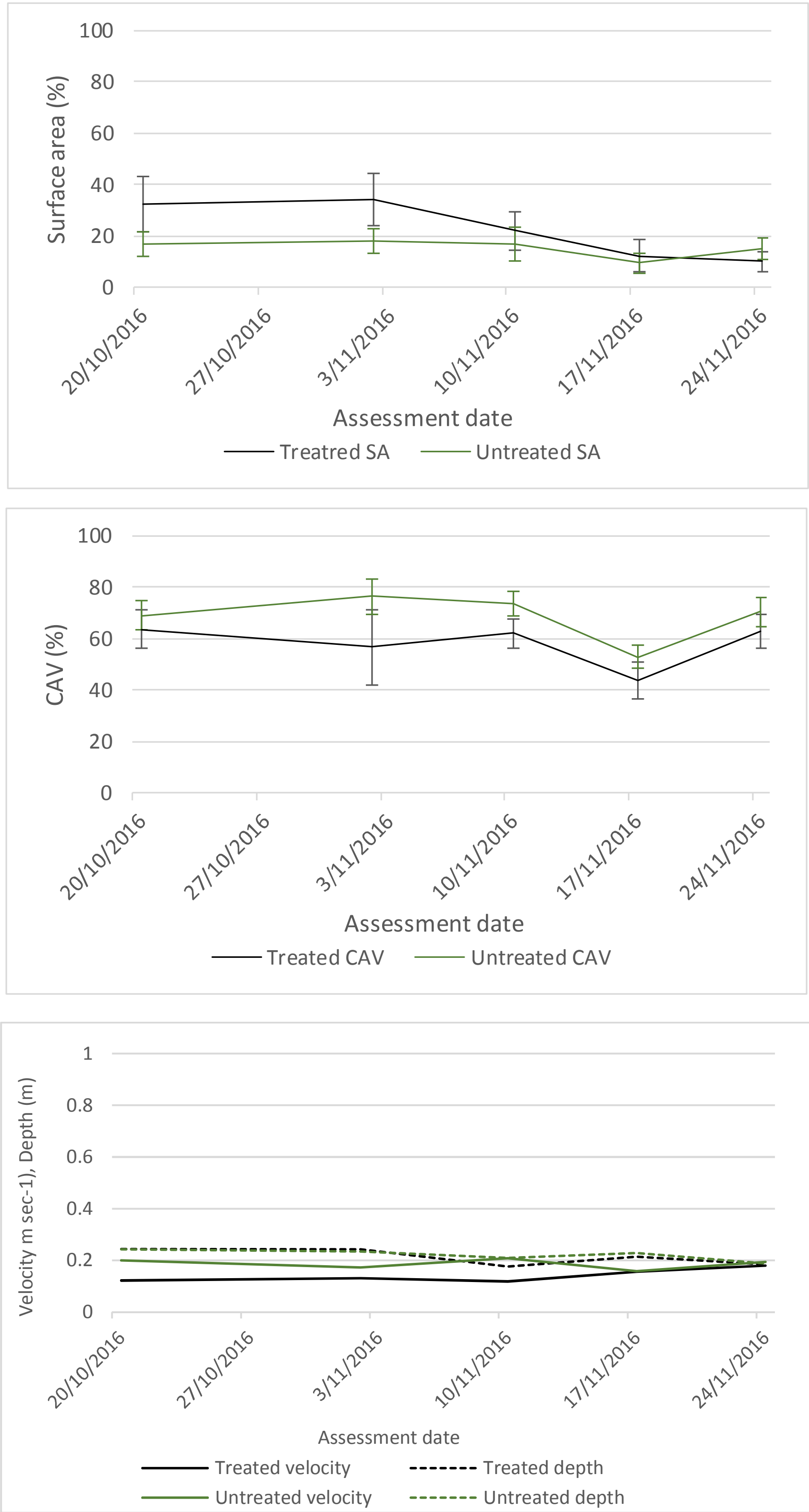
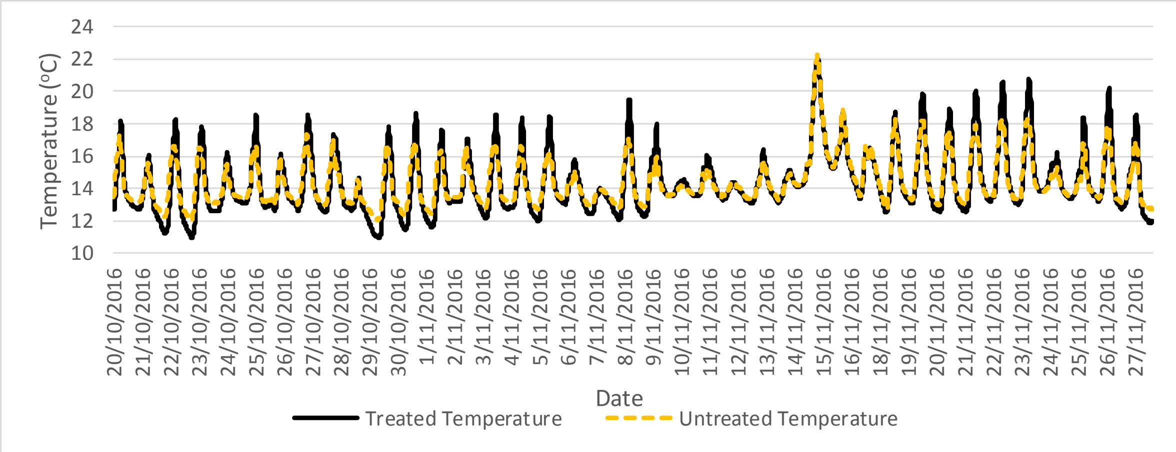



**Figure 17: Plots from consecutive assessments at Drain Q.** Top average SA (%), middle, average CAV (%) and bottom, average maximum water velocity (m/sec) and average maximum depth (m). Error bars are ±1 SE, (n=5).



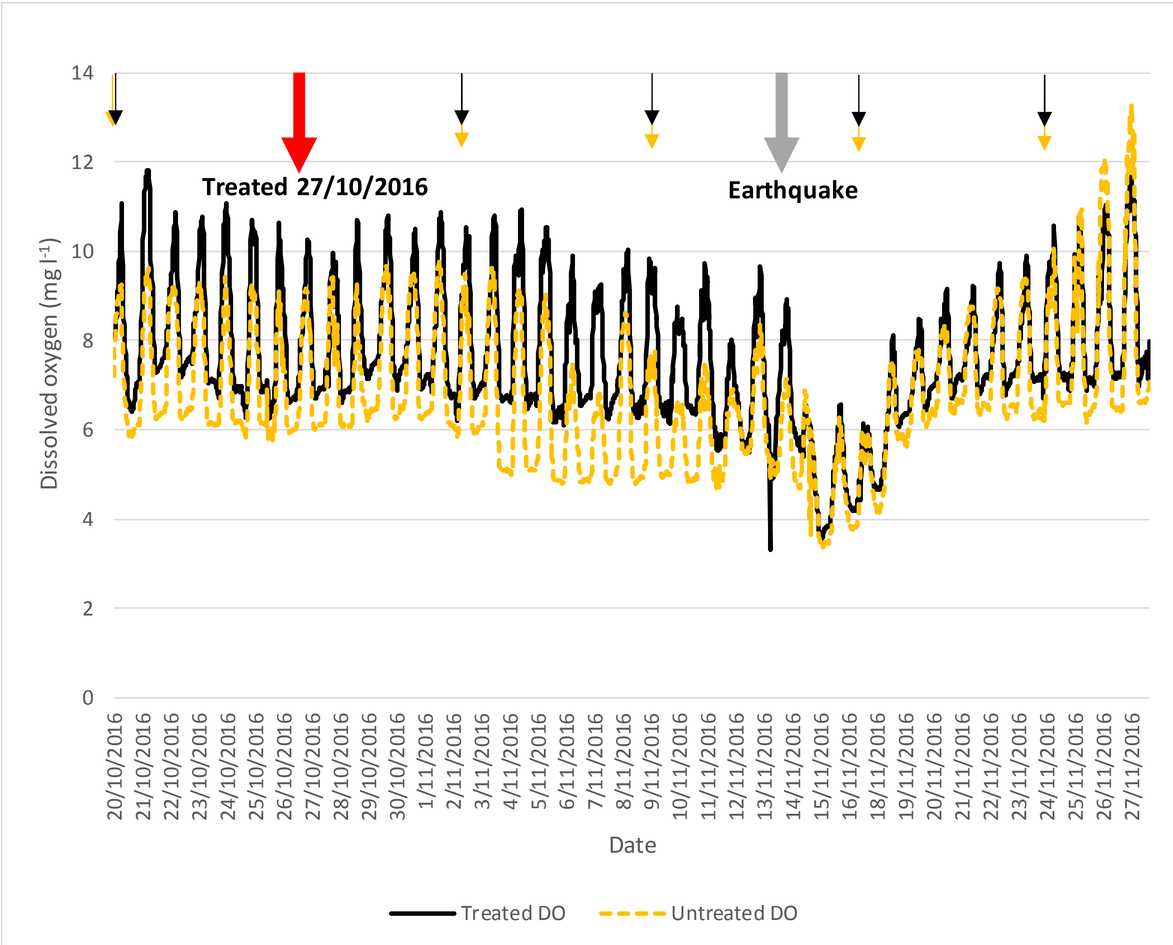




**Figure 18: Water temperature (top) and dissolved oxygen (bottom) for the Treated and Untreated reach at Drain Q.** The timing of glyphosate treatment (red, earthquake (grey) and reach assessments (yellow and black) are shown as coloured arrows.

**Table 5: Manual measurements of temperature and DO in the Treated and Untreated reach.** Data is a spot record for the date and time range that the watercourse was sampled.

| Date and time | Treated temperature | Treated DO mg L-1 | Untreated temperature | Untreated DO mg L-1 |
|---|---|---|---|---|
| 20/10/2016 8:30-9:15 | 12.7 | 8.2 | 13.4 | 7.6 |
| 2/11/2016 11:30-11:45 | 15.0 | 9.5 | 15.6 | 8.8 |
| 9/11/2016 14:45-15:00 | 16.6 | 9.4 | 15.3 | 7.7 |
| 28/11/2016 11:00-11:30 | 14.6 | 9.6 | 16.2 | 12.6 |

## 3.7 Fairhall Co-op Drain

The average width of Fairhall Co-op drain was 2.9 m and depth was 0.47 m. Both batter banks had high covers of tall grass (average 0.6 m). In-channel vegetation comprised water speedwell (*Veronica anagallis-aquatica*), monkey musk (*Erythranthe guttata*), water buttercup (*Ranunculus trichophyllus*), watercress, duckweed and grass from the batter. Bank vegetation of the Treated reach was observed to be dying by 14 days after treatment (10th November 2016).

**Figure 19: Abundant instream vegetation at Fairhall Co-op.**

Both the Treated and Untreated reaches had similar patterns for SA and CAV, with a slight reduction over the assessment period (Figure 20). Velocities decreased a little in both reaches, whilst depth increased more in the Untreated reach (Figure 20).

Most of the time DO was similar between the reaches or diurnal fluctuations were greater in the Untreated reach (Figure 21). A major DO depression was evident in both reaches before the Kaikoura earthquake. This was more pronounced in the Treated reach where DO dropped under 4 mg $L^{-1}$ in the early morning of the 12th November 2016 (Figure 21). Signals were again visible in the DO measurements for both reaches at approximately two days following the Kaikoura earthquake (time interval 44:15 to 44:30 post-earthquake) and a temperature spike was also evident (time interval 39:00 to 39:15 post-earthquake).

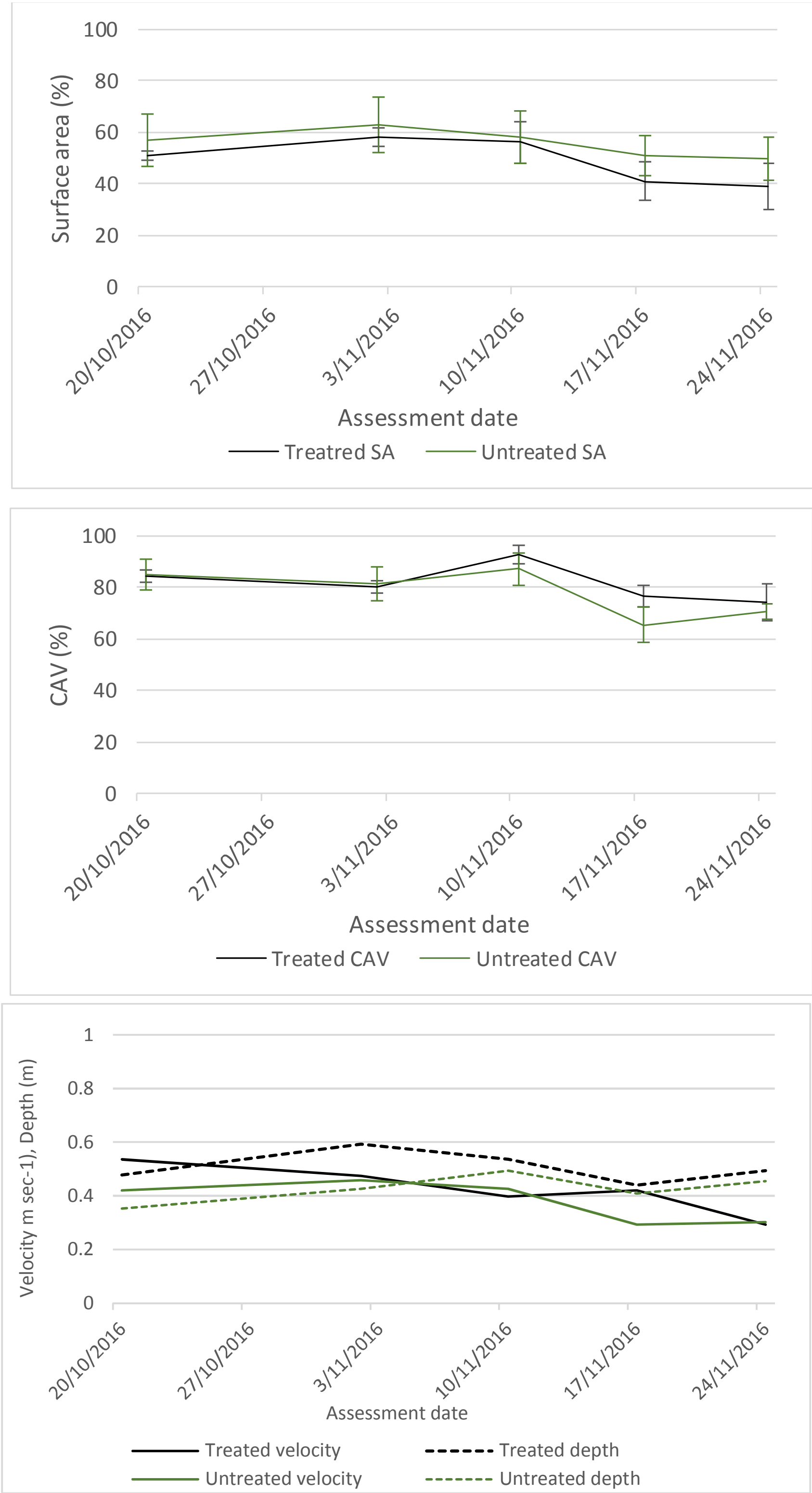



**Figure 20: Plots from consecutive assessments at Fairhall Co-op.** Top, average SA (%), middle, average CAV (%) and bottom, average maximum water velocity (m/sec) and average maximum depth (m). Error bars are ±1 SE, (n=5).

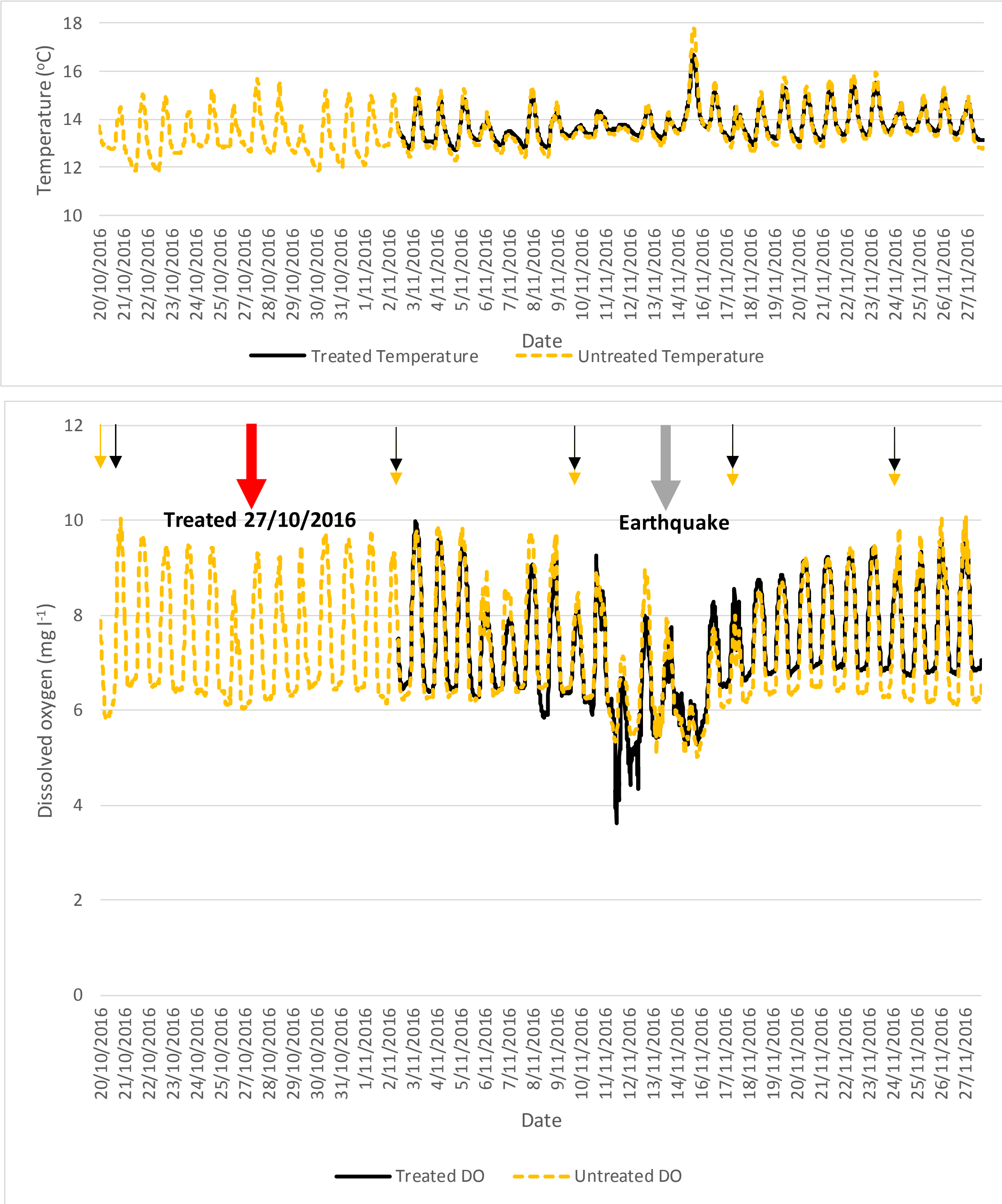



**Figure 21: Water temperature (top) and dissolved oxygen (bottom) for the Treated and Untreated reach at Fairhall Co-op.** The timing of glyphosate treatment (red), earthquake (grey) and reach assessments (yellow and black) are shown as coloured arrows.

**Table 6: Manual measurements of temperature and DO in the Treated and Untreated reach.** Data is a spot record for the date and time range that the watercourse was sampled.

| Date and time | Treated temperature | Treated DO mg $L^{-1}$ | Untreated temperature | Untreated DO mg $L^{-1}$ |
|---|---|---|---|---|
| 20/10/2017 16:45 | | | 13.8 | 8.2 |
| 21/10/2017 8:50 | 13.0 | 7.5 | | |
| 2/11/2016 17:00-17:15 | 13.8 | 7.9 | 13.8 | 8.0 |
| 9/11/2016 13:00-13:15 | 14.0 | 9.0 | 14.1 | 8.9 |
| 28/11/2016 13:00-13:15 | 14.9 | 9.7 | 15.1 | 10.4 |

## 3.8 Woolley & Jones Drain

On average this small watercourse was 1.5 m wide and 0.21 m deep. The lower batter comprised dead grasses. Dominant in-channel vegetation comprised duckweed, azolla, watercress, water plantain, *Nitella* sp. aff. *cristata* and grasses from the batter. Herbicide symptoms were evident in bankside vegetation by 14 days after treatment (10$^{th}$ November 2016).

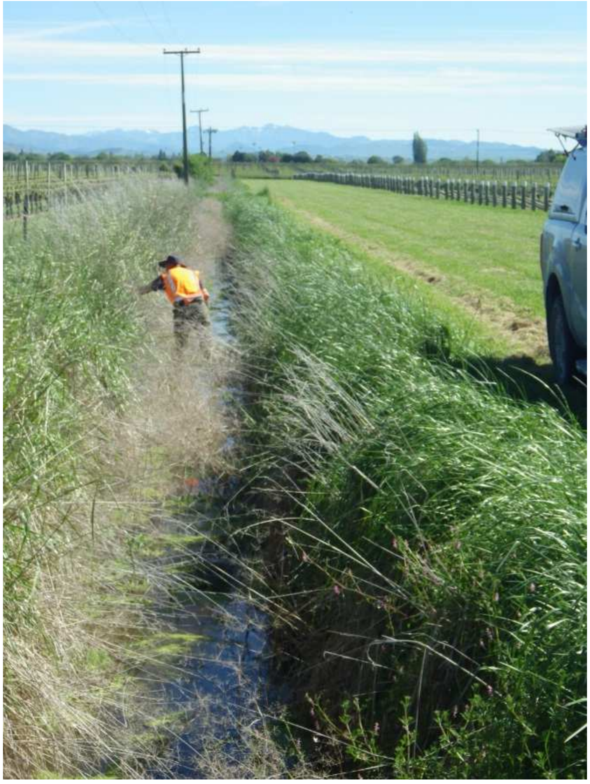


**Figure 22: Drainage channel at Woolley & Jones.**

Average SA and CAV decreased slightly in both reaches, with variability increasing over the assessment period (Figure 23). Velocity increased in both reaches, returning to near-original values by the end of the assessments. Depth increased slightly more for the Treated reach but this watercourse remained shallow (<0.35 m, Figure 23).

This watercourse was subject to large diurnal DO fluctuations with low minima (<5 mg $L^{-1}$), especially in the Untreated reach, which at times became anoxic. Manual measurements confirmed lower DO concentrations in the Untreated Reach (Table 7).

A temporary DO reduction was seen in both reaches within two days of the Kaikoura earthquake (time interval 45:45 to 46:45 post-earthquake), with this event causing the lowest DO record for the Treated reach. Again, a temperature spike was seen in both reaches before the post-earthquake DO minima (time interval 41:00 to 41:15 post-earthquake).

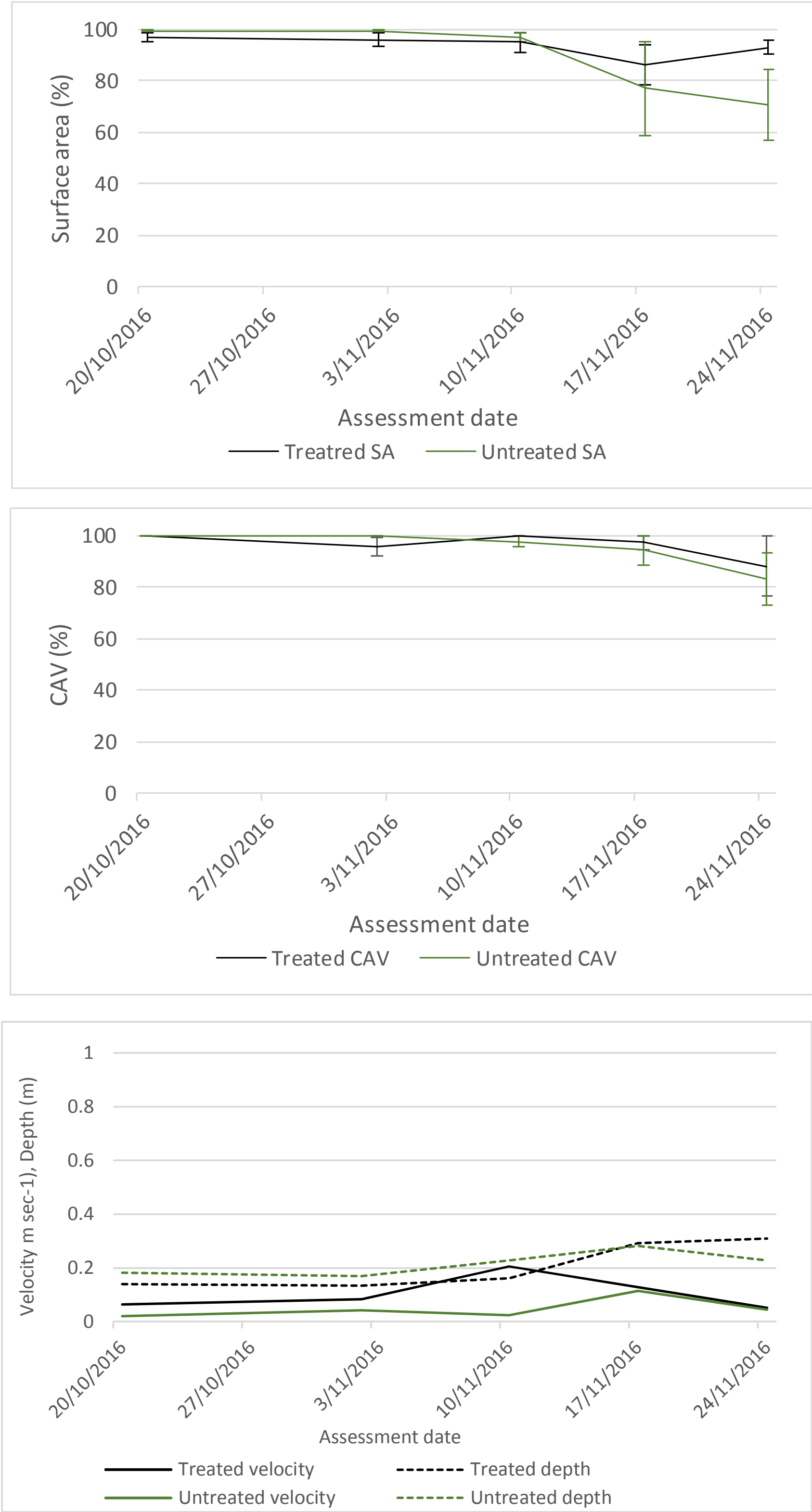



**Figure 23: Plots from consecutive assessments at Woolley & Jones.** Top, average SA (%), middle, average CAV (%) and bottom, average maximum water velocity (m/sec) and average maximum depth (m). Error bars are ±1 SE, (n=5).

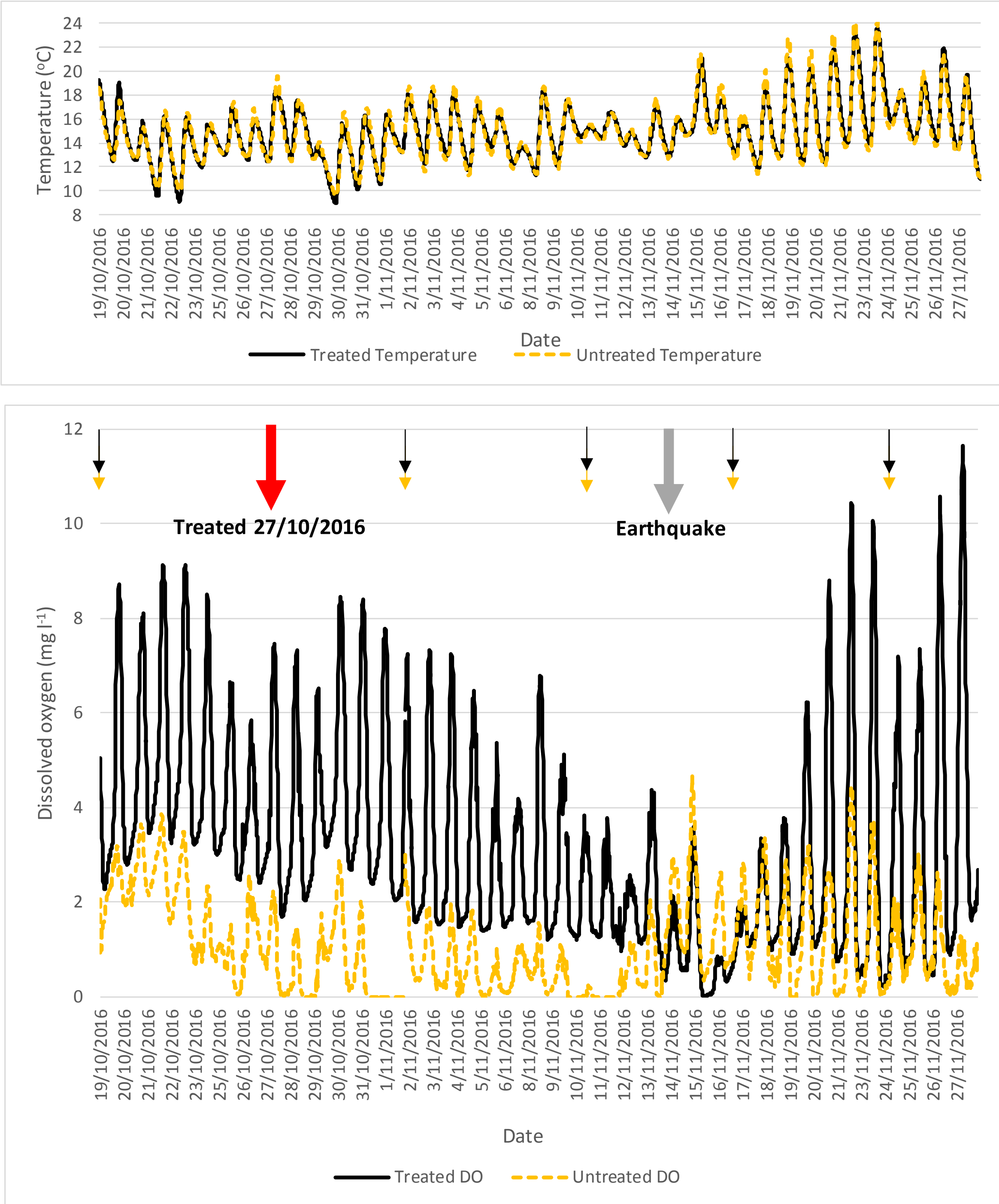



**Figure 24: Water temperature (top) and dissolved oxygen (bottom) for the Treated and Untreated reach at Woolley & Jones.** The timing of glyphosate treatment (red), earthquake (grey) and reach assessments (yellow and black) are shown as coloured arrows.

**Table 7: Manual measurements of temperature and DO in the Treated and Untreated reach.** Data is a spot record for the date and time range that the watercourse was sampled.

| Date and time | Treated temperature | Treated DO mg L-1 | Untreated temperature | Untreated DO mg L-1 |
|---|---|---|---|---|
| 19/10/2016 16:45-16:55 | 19.4 | 5.4 | 19.5 | 2.3 |
| 2/11/2016 10:15-11:00 | 15.7 | 6.4 | 14.2 | 2.2 |
| 9/11/2016 16:45-17:15 | 17.4 | | 17.3 | |
| 28/11/2016 2:15-12:30 | 15.7 | 10.6 | 15.7 | 4.8 |

# 4 Analysis of dissolved oxygen concentrations

DO measurements were obtained for the stipulated consent monitoring period from 10 days after diquat treatment for a period of three weeks post-treatment. However, reliable readings were not possible for Drain C under the conditions that prevailed during the 2015 assessment period (dry or stagnant conditions). Measurements prior to herbicide application (pre-impact) were seen as beneficial, but loss of initial data for both reaches of Caseys Creek and for the Treated reach of Fairhall Co-op prevented use of pre-impact data in these analyses.

The results of the RMANOVA for the three sites in 2015 (Table 8) did not identify any significant effect of diquat treatment on daily DO minima over the three-week consent monitoring period, and although the analysis suggested DO minima changed with time, there was no significant time*treatment interaction (Table 8). This shows that no consistent pattern of lower DO or decreasing DO was identified for the Treated reaches where herbicide was applied.

Similarly, the RMANOVA for the four sites in 2016 (Table 9) showed that herbicide treatment had no effect on DO minima, although a change with time was detected. This significant variation in DO minima through time was associated with the Kaikoura earthquake, with measurements from 15$^{th}$ November (and some from the 16$^{th}$ November) differing from all measurements from 19$^{th}$ of November 2016 onwards.

**Table 8: Results of RMANOVA on daily DO minima in 2015.** "Treatment" is Treated vs Untreated reaches of three replicate watercourses and "time" is the three-week consent monitoring period.

| Effect | SS | df | MS | F | p |
|---|---|---|---|---|---|
| Treatment | 1.570 | 1 | 1.570 | 0.062 | 0.816 |
| Time | 3.369 | 20 | 0.168 | 1.936 | 0.020 |
| Time*Treatment | 1.591 | 20 | 0.080 | 0.914 | 0.571 |

**Table 9: Results of RMANOVA on daily DO minima in 2016.** "Treatment" is Treated vs Untreated reaches of four replicate watercourses and "time" is the three-week consent monitoring period.

| Effect | SS | df | MS | F | p |
|---|---|---|---|---|---|
| Treatment | 3.05 | 1 | 3.054 | 0. 018 | 0.898 |
| Time | 30.83 | 21 | 1.468 | 3.573 | 0.000 |
| Time*Treatment | 5.43 | 21 | 0.258 | 0. 629 | 0.891 |

According to the draft National Objectives Framework attributes for DO in rivers and streams (Davies-Colley et al. 2013), there is a risk of significant degradation of ecosystem health when the 7-day mean value drops below 6.5 mg $L^{-1}$, the 7-day mean minimum drops below 5 mg $L^{-1}$ or the 1-day minimum drops below 4 mg $L^{-1}$. We note however that these guidelines were proposed for *'Summer monitoring data for discrete specified periods'* but the exact timing is not specified in this document.

In 2015 the only site that did not meet the critical threshold for ecosystem health (Table 10) was the Untreated reach of Caseys Creek. At this site the increasing divergence in DO values over time between the Treated and Untreated reaches, together with increasing measures of vegetation biomass (as SA and CAV) suggest vegetation development contributed to the lower DO status of this reach (as recognised by Davies-Colley et al. 2013) or that the spring source for the upstream reach was increasingly de-oxygenated over time, yet was oxygenated and stable in the Treated reach.

In 2016 Woolley & Jones remained below the critical thresholds for ecosystem health (Table 10) at all times. In Drain Q the period of time encompassing the Kaikoura earthquake (week 2) was below critical thresholds for ecosystem health for all reaches, but the Untreated reach also failed to achieve some DO thresholds during week 1, as did the Treated reach of Fairhall Co-op.

**Table 10: Comparison of key DO statistics for the sites over the three week consent monitoring period that relate to DO concentration thresholds (mg $L^{-1}$) identified by Davies-Colley et al. 2013**. Values not meeting the guidelines for ecological health identified in red.

| Site | Week | Treated 7-day average | Untreated 7-day average | Treated 7-day mean minimum | Untreated 7-day mean minimum | Treated 1 -day minimum | Untreated 1-day minimum |
|---|---|---|---|---|---|---|---|
| Kellys Drain (2015) | 1 | 8.1 | 8.1 | 6.6 | 7.2 | 5.4 | 6.9 |
| | 2 | 8.4 | 8.1 | 7.0 | 7.0 | 7.0 | 6.9 |
| | 3 | 8.5 | 8.0 | 6.9 | 6.9 | 6.8 | 6.1 |
| Caseys Creek (2015) | 1 | 7.7 | **5.8** | 5.8 | 5.0 | 5.6 | 4.7 |
| | 2 | 7.7 | **5.7** | 5.7 | **4.7** | 5.1 | 4.5 |
| | 3 | 7.7 | **5.1** | 5.8 | **4.1** | 5.7 | **3.7** |
| Murphys Creek (2015) | 1 | 7.7 | 7.8 | 6.8 | 6.9 | 6.8 | 6.4 |
| | 2 | 7.7 | 8.0 | 6.8 | 7.3 | 6.7 | 7.3 |
| | 3 | 7.7 | 8.4 | 6.7 | 7.1 | 6.4 | 6.7 |
| Cravens Creek (2016) | 1 | 6.8 | 6.8 | 6.1 | 5.7 | 6.0 | 4.1 |
| | 2 | 6.7 | 7.2 | 5.9 | 6.6 | 5.2 | 5.9 |
| | 3 | 7.0 | 7.4 | 6.0 | 6.9 | 5.9 | 6.8 |
| Drain Q (2016) | 1 | 7.4 | **5.8** | 6.1 | **4.8** | 5.5 | 4.6 |
| | 2 | **6.0** | **5.6** | **4.4** | **4.3** | **3.3** | **3.3** |
| | 3 | 8.0 | 7.6 | 6.8 | 6.2 | 6.7 | 6.2 |
| Fairhall Co-op (2016) | 1 | 6.9 | 7.2 | 5.8 | 6.1 | **3.6** | 5.3 |
| | 2 | 6.8 | 6.6 | 5.8 | 5.6 | 4.3 | 5.0 |
| | 3 | 7.8 | 7.5 | 6.8 | 6.3 | 6.7 | 6.2 |
| Woolley & Jones* (2016) | 1 | **2.4** | **0.3** | **1.3** | **0.0** | **0.9** | **0.0** |
| | 2 | **1.4** | **1.4** | **0.5** | **0.2** | **0.0** | **0.0** |
| | 3 | **3.1** | **1.2** | **0.5** | **0.1** | **0.2** | **0.0** |

*Slightly negative readings (up to -0.021) were transformed to 0 value for calculations.

The NPS-FM (2014) provides grades for DO in rivers below point source discharges. Grades A to C represent increasing levels of DO stress and grade D falls below the national bottom line, or minimum acceptable state proposed for rivers. We note, however, that the 1-day minimum for the NPS-FM is stipulated as the lowest measurement across the whole summer period (1 November to 30th April), much longer than the three-week consent monitoring period of this report. Grades for Kellys Drain, Murphys Creek and Cravens Creek were above the national bottom line (Table 11). Caseys Creek displayed D grades in the Untreated reach. Drain Q showed a D grade across all reaches during week 2 when the Kaikoura earthquake occurred. Outside of week 2, the Untreated reach of Drain Q and Treated reach of Fairhall Co-op also had D grades. Woolley & Jones was below the national bottom line for the three-week consent monitoring period.

**Table 11: Watercourse grades based on the Attribute State for DO in rivers below point source provided by the National Policy Statement for Freshwater.** D grade (red text) falls below the national bottom line.

| Site | Week | Treated 7-day mean minimum | Untreated 7-day mean minimum | Treated 1 -day minimum | Untreated 1-day minimum |
|---|---|---|---|---|---|
| Kellys Drain (2015) | 1 | C | B | B | B |
| | 2 | B | B | B | B |
| | 3 | C | C | B | B |
| Caseys Creek (2015) | 1 | C | C | B | C |
| | 2 | C | D | B | C |
| | 3 | C | D | B | D |
| Murphys Creek (2015) | 1 | C | C | B | B |
| | 2 | C | B | B | B |
| | 3 | C | B | B | B |
| Cravens Creek (2016) | 1 | C | C | B | C |
| | 2 | C | C | B | B |
| | 3 | C | C | B | B |
| Drain Q (2016) | 1 | C | D | B | C |
| | 2 | D | D | D | D |
| | 3 | C | C | B | B |
| Fairhall Co-op (2016) | 1 | C | C | D | B |
| | 2 | C | C | C | B |
| | 3 | C | C | B | B |
| Woolley & Jones (2016) | 1 | D | D | D | D |
| | 2 | D | D | D | D |
| | 3 | D | D | D | D |

# 5 Discussion

DO levels in freshwater are controlled by a complex array of factors that include (Davies-Colley et al. 2013):

- Photosynthetic release of oxygen by plants and algae.
- Plant respiration that consumes oxygen.
- Microbial processing of organic matter that consumes oxygen.
- Temperature that controls rate of decay and oxygen solubility (and thereby reaeration rates).
- Reaeration as influenced by water depth, flow and mixing.
- Obstruction of the water surface (e.g., by excessive vegetation) preventing aeration.
- DO status of water inputs (e.g., groundwater).
- Biological oxygen demand of point source inputs.

Management of excessive vegetation using herbicides could result in a range of DO outcomes in treated watercourses. In-stream vegetation control using herbicides may result in a temporary increase in contributed organic matter and biological oxygen demand. But conversely, management intervention to control instream vegetation can increase average DO conditions by reducing plant respiration.

Monitoring of the eight Wairau Plains watercourses stipulated by Condition 19 of consent no. U070702 did not reveal any consistent, statistically significant impacts on DO following application of diquat or glyphosate. Previous investigations following herbicide applications to the watercourses of the Wairau Plains have also failed to identify any impacts on DO levels (Young et al. 2004, Wells and Smith 2006).

The period of monitoring in this investigation (28 to 33+ days) was sufficient for vegetation to display symptoms of herbicide application. We noted that change in SA and CAV was more apparent with in-stream treatments (diquat), than treatments of overhanging/emergent vegetation (glyphosate), possibly due to faster clearance of affected submerged vegetation by increased water velocity. In the case of Caseys Creek, herbicide application resulted in a substantial decrease in vegetation abundance (as measured using SA and CAV), and in Cravens Creek slight reductions were apparent. In Murphys Creek, diquat appeared to have a 'biostatic' effect, impairing growth substantially relative to the Untreated reach, possibly due to herbicide damage in active growing points, requiring the plant to reallocate growth resources to dormant buds. Herbicide impacts on abundance (as SA and CAV) were not pronounced in the remaining five watercourses.

The design of this investigation included Untreated reaches of each watercourse as a 'control', which we believe provides advantages over the approach followed in previous investigations (Young et al. 2004, Greer 2014), where separate watercourses were chosen as the 'control'. The earlier approach was less able to distinguish the effects of herbicide treatment from inherent differences in watercourse characteristics. We regarded complications arising from choosing separate watercourses as controls were greater than the risk of encountering widely differing conditions between the selected reaches within each spring-fed watercourse.

We do not believe that the scale of monitoring, based on a 100 m treated reach above our 'impact' instruments, limited our detection of herbicide impacts on DO. A D-Opto logger deployed in Murphys

Creek by MDC approximately 0.5 km downstream of our treated reach (but still within the extended treated area) was unable to detect downstream impact on DO concentrations. MDC data (not shown) showing an average DO of 8.7 mg $l^{-1}$ and minimum of 7.6 mg $l^{-1}$ over the three-week consent monitoring period.

Although none of the Treated reaches showed significant reductions in DO levels following herbicide application, DO concentrations in four watercourses did fall below suggested critical thresholds for ecosystem health (Davies-Colley et al. 2013, NPS-FM 2014). Fairhall Co-op failed to meet a 1-day minimum of 4 mg $l^{-1}$ DO (national bottom line) in the Treated reach during one monitoring week. Woolley & Jones did not attain any of the guideline DO levels or either national bottom line during the three week monitoring period. In Drain Q the guideline DO thresholds and the national bottom line were not met in either reach during the week of the Kaikoura earthquake. The Untreated reach of Drain Q also fell below 7-day mean value of 6.5 mg $l^{-1}$ and the 7-day mean minimum of 5 mg $l^{-1}$ (national bottom line) during week 1 of the consent monitoring period. The Untreated reach of Caseys Creek also failed to meet the 7-day mean value of 6.5 mg $l^{-1}$, or the 7-day mean minimum of 5 mg $l^{-1}$ (national bottom line) at times. In the case of Caseys Creek, it is possible that the contribution from spring water inflow, or the DO status of groundwater inflow, changed in the untreated reach over time. Depleted DO is a feature of spring-fed watercourses in the Wairau Plains (Young et al. 2002).

The 2016 monitoring of four waterways captured the influence of the major Kaikoura earthquake on temperature and DO. Within two days of the event there was a spike in water temperature. Correlations (data not shown) showed water temperatures at this time were much higher in Cravens and Fairhall Co-op than could be explained by corresponding air temperature, although the pattern was not so clear for Woolley & Jones (air temperature logger for Drain Q could not be relocated). Both statistical analyses of DO and comparisons with ecological thresholds for DO identified a time signal associated with the earthquake, whereas changes arising from herbicide application were not apparent.

Excessive vegetation biomass in watercourses can increase flow resistance and water levels within a waterway to the point that hydraulic capacity is reduced (Wilcock et al. 1999; Luhar et al. 2008; Jones et al. 2012). Increased water depth from flow resistance also limits gaseous diffusion (Wilcock et al. 1999). Therefore clogging of watercourses by vegetation can limit reaeration by water flows and exacerbate diurnal extremes in DO driven by photosynthetic and respiration processes. Vegetation control by herbicides in the watercourses of the Wairau Plains is aimed at lowering water levels and improving hydraulic efficiency and drainage. Therefore, ongoing vegetation management in these systems is likely to improve rates of reaeration by preventing accumulation of large amounts of plant material instream often associated with elevated water levels and lower velocity.

Another feature of the watercourses in the Wairau Plains is their generally low and constant temperature regime, dependent on watercourse size and how well connected they are to the Wairau aquifer (Young et al. 2002). Air temperature patterns were similar within each set of sites (Appendix B-1 & 2). Murphys and Cravens Creek were the coolest watercourses (average c. 13.5 °C) and varied little (2.5-3.6 °C) during the full monitoring period. Fairhall Co-op averaged 13.7 °C, but varied over 6 °C. Kellys Drain and Drain Q had a similar average temperature of 14.3-14.4 °C, but Drain Q had a larger range (11.1 °C) than Kellys Drain (6.5 °C). The warmest watercourses, at an average of 15-15.5°C, were Caseys Creek which varied by 8.2 °C and Woolley & Jones which ranged over 14.7°C. Lower rates of decay under cool water conditions in these systems (average 13 to 15 °C) may also reduce DO impacts following herbicide treatments in these systems.

From these results we conclude that the risk of deoxygenation of watercourses on the Wairau Plains following herbicide application is likely to be low. Ecological impacts following herbicide application would be most likely where a very high in-stream plant biomass exists, DO status is already reduced, flows are low, a large standing water volume exists, and where high temperatures are likely to promote rapid decay of vegetation.

# 6 Acknowledgements

Many thanks to Craig Depree (NIWA) for advice on the monitoring approach and to Samantha Parkes and John Nagels (NIWA) for calibrating the D-Opto loggers and clarification on deployment and downloading data. We are grateful to Roger Fitzgerald and Steve Bezar (MDC) who took the time to orientate NIWA staff on site.

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# Appendix A Site identification and maps

**Table A1: List of sites stipulated in condition 19.** Information is drawn from Appendix D of the MDC code of practise for aquatic herbicide application (2008).

| Assessment year | Watercourse name | No* | Description† | Length (m) |
|---|---|---|---|---|
| 2016 | Kellys | 78 | 'Drain N' 5 Vickerman St to Kellys outlet through Sadds (sample reach upstream of Drain O outlet) | c. 936 |
| 2016 | Drain C | 86 | Sample reach is above outlet to Drain A | 1005 |
| 2016 | Caseys A | 106 | Sample reach in lower end | 2535 |
| 2016 | Murphys Creek | 109 | Where accessible | 2090 |
| 2017 | Drain Q | 80 | Roses | 744 |
| 2017 | Fairhall Co-op | 116 | Below Bells Road | 2255 |
| 2017 | Woolley and Jones | 32 | | 2412 |
| 2017 | Cravens Creek | 52 | | 1370 |

*Appendix D (MDC 2008).

†MDC (2008) augmented by R. Fitzgerald, MDC, pers comm. 8/07/2015.

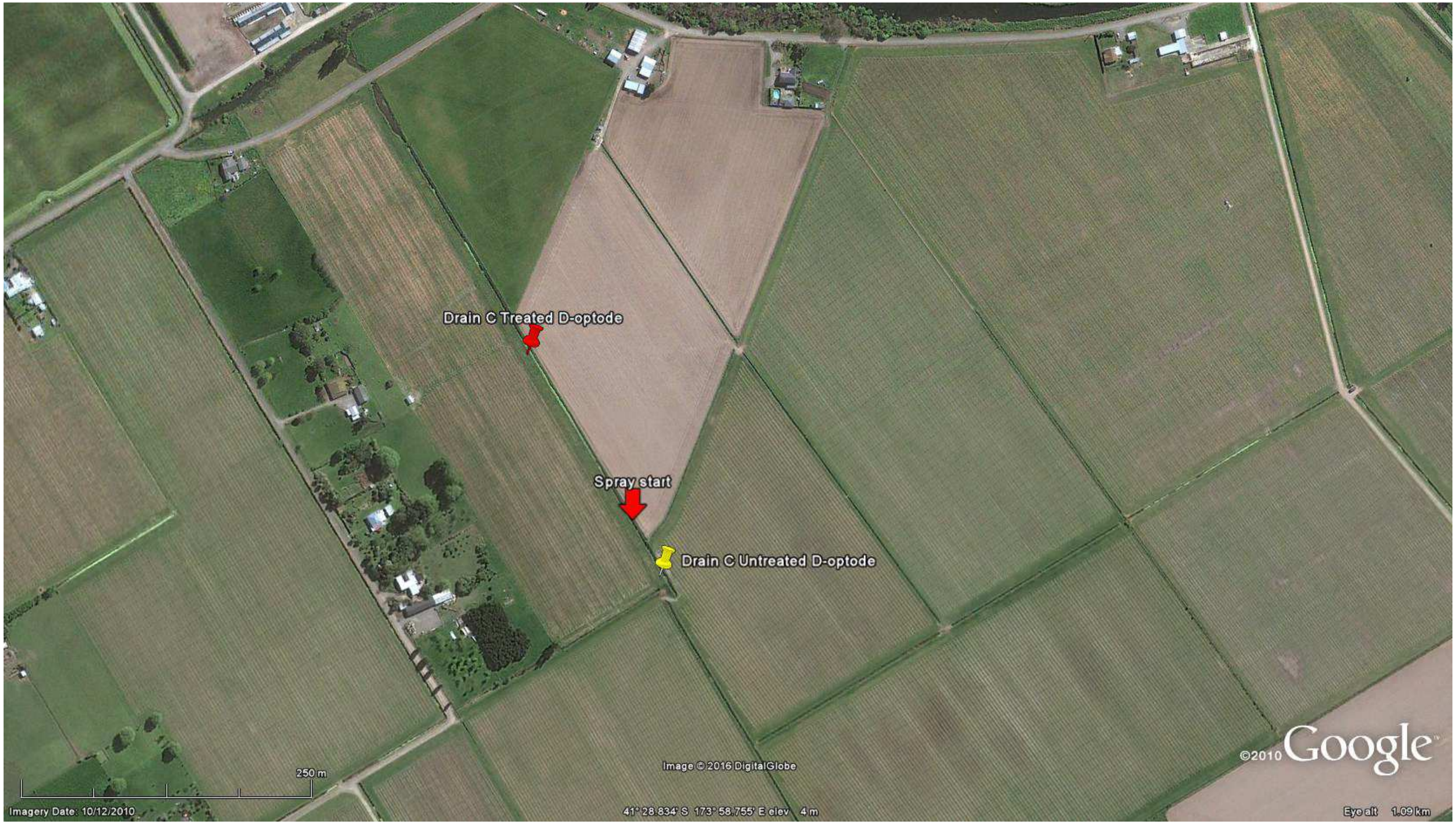


**Figure A1: Drain C showing the start point for herbicide application and locations of the D-Opto loggers measuring DO and water temperature in the untreated reach (yellow marker) and treated reach (red marker).**

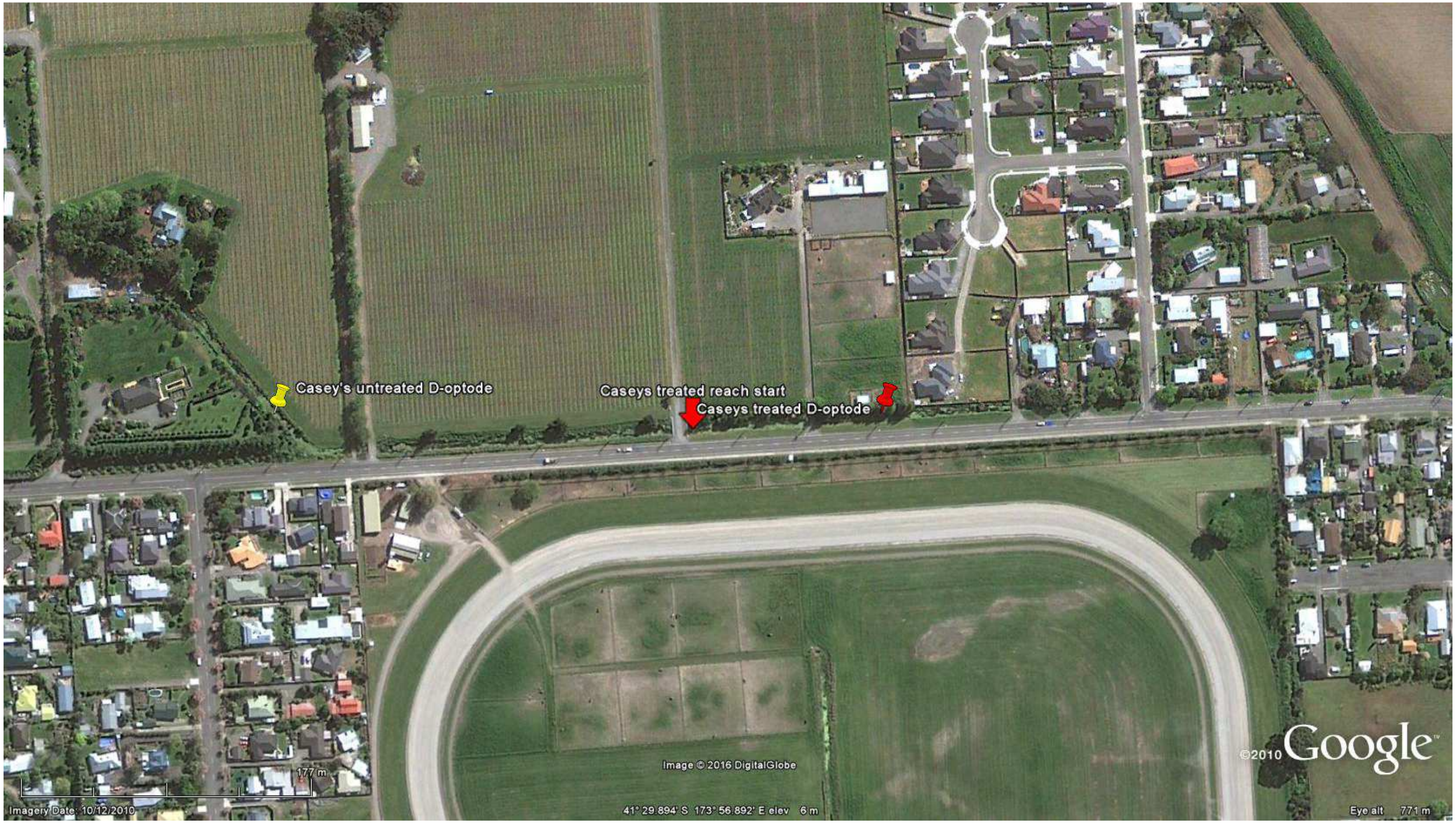


**Figure A2: Casey's Drain showing the start point for herbicide application and locations of the D-Opto loggers measuring DO and water temperature in the untreated reach (yellow marker) and treated reach (red marker).**

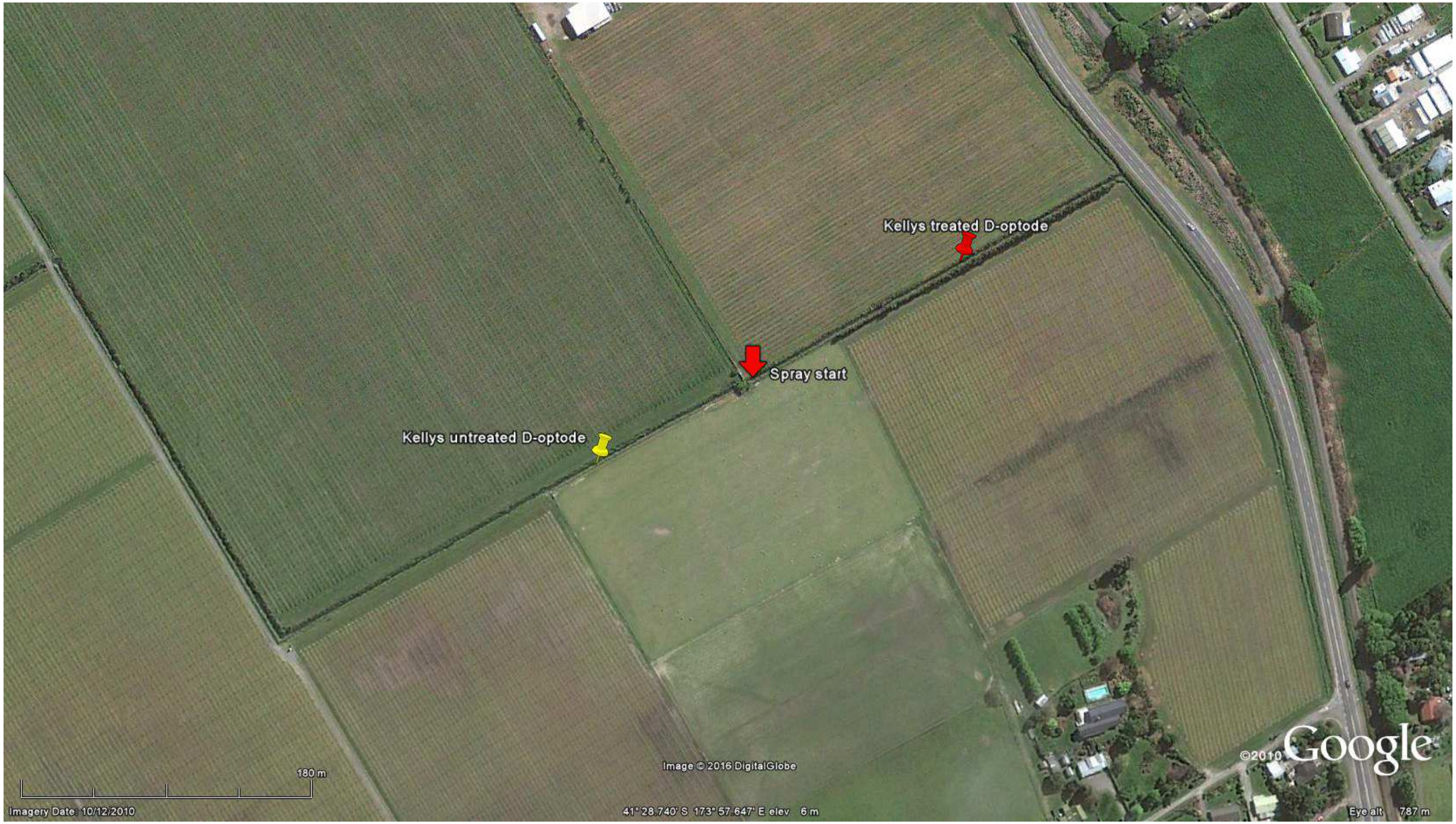


**Figure A3: Kellys Drain showing the start point for herbicide application and locations of the D-Opto loggers measuring DO and water temperature in the untreated reach (yellow marker) and treated reach (red marker).**

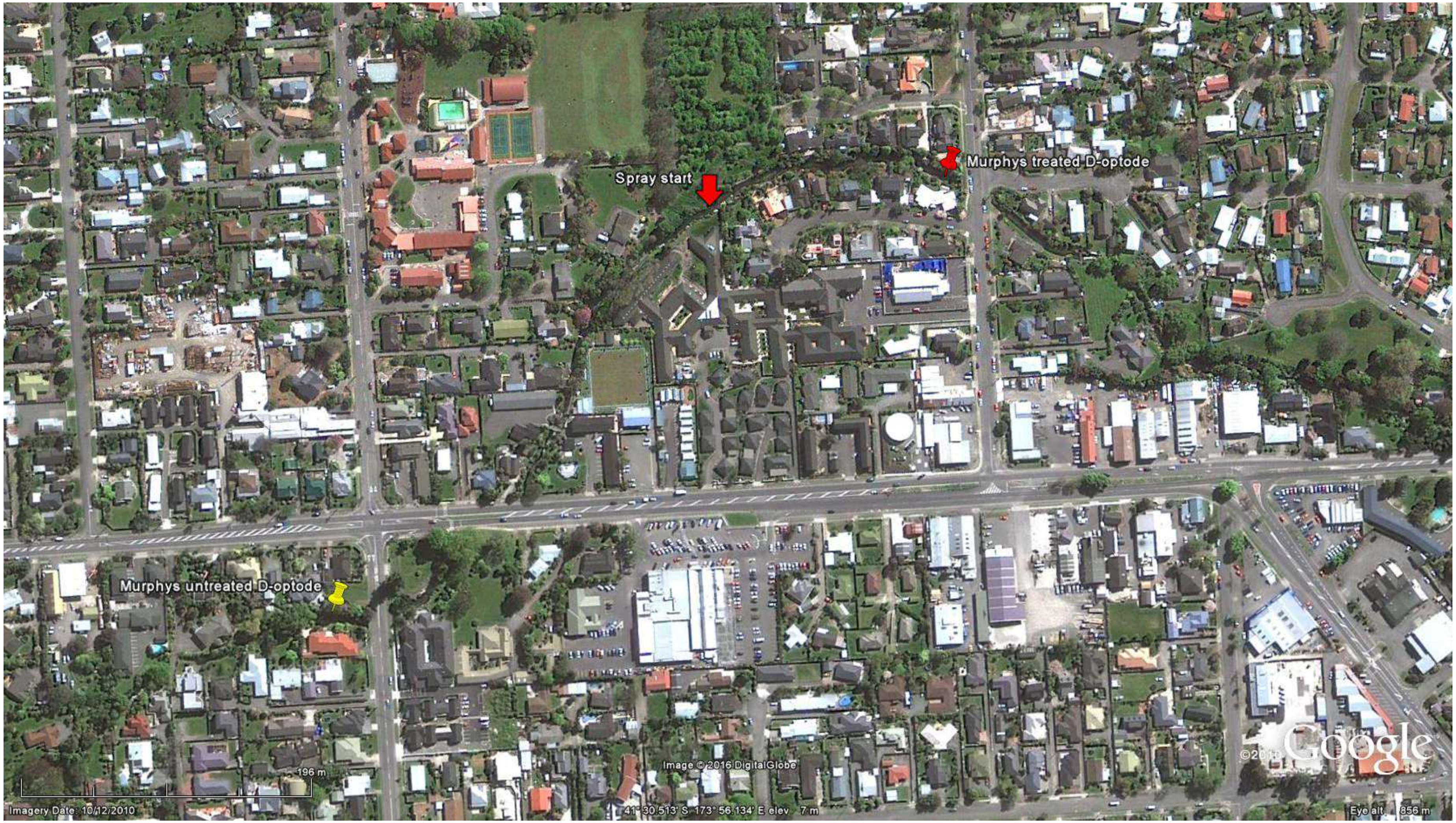


**Figure A4: Murphys Drain showing the start point for herbicide application and locations of the D-Opto loggers measuring DO and water temperature in the untreated reach (yellow marker) and treated reach (red marker).**

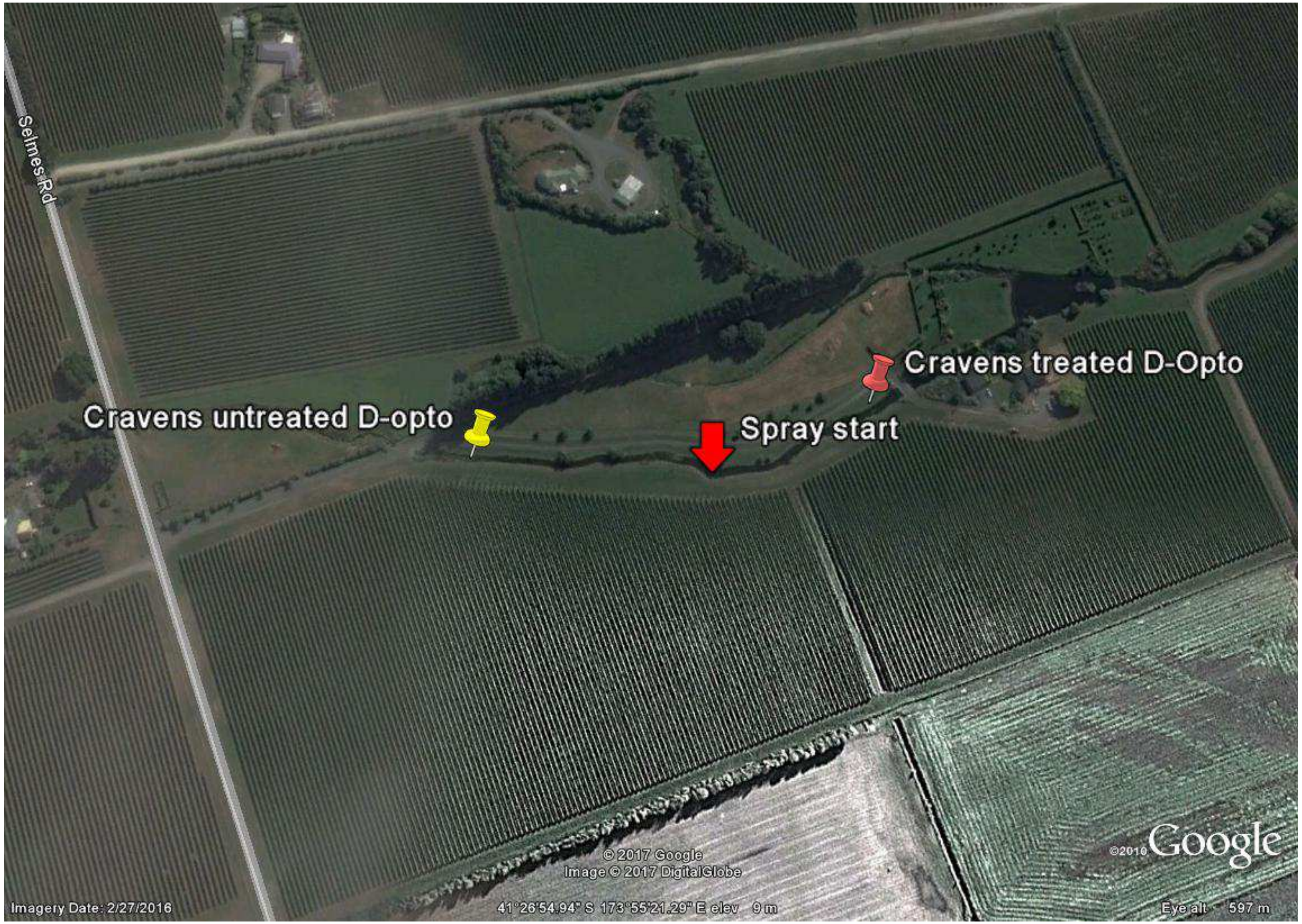


**Figure A5: Cravens Creek showing the start point for herbicide application and locations of the D-Opto loggers measuring DO and water temperature in the untreated reach (yellow marker) and treated reach (red marker).**


**Figure A6: Drain Q showing the start point for herbicide application and locations of the D-Opto loggers measuring DO and water temperature in the untreated reach (yellow marker) and treated reach (red marker).**

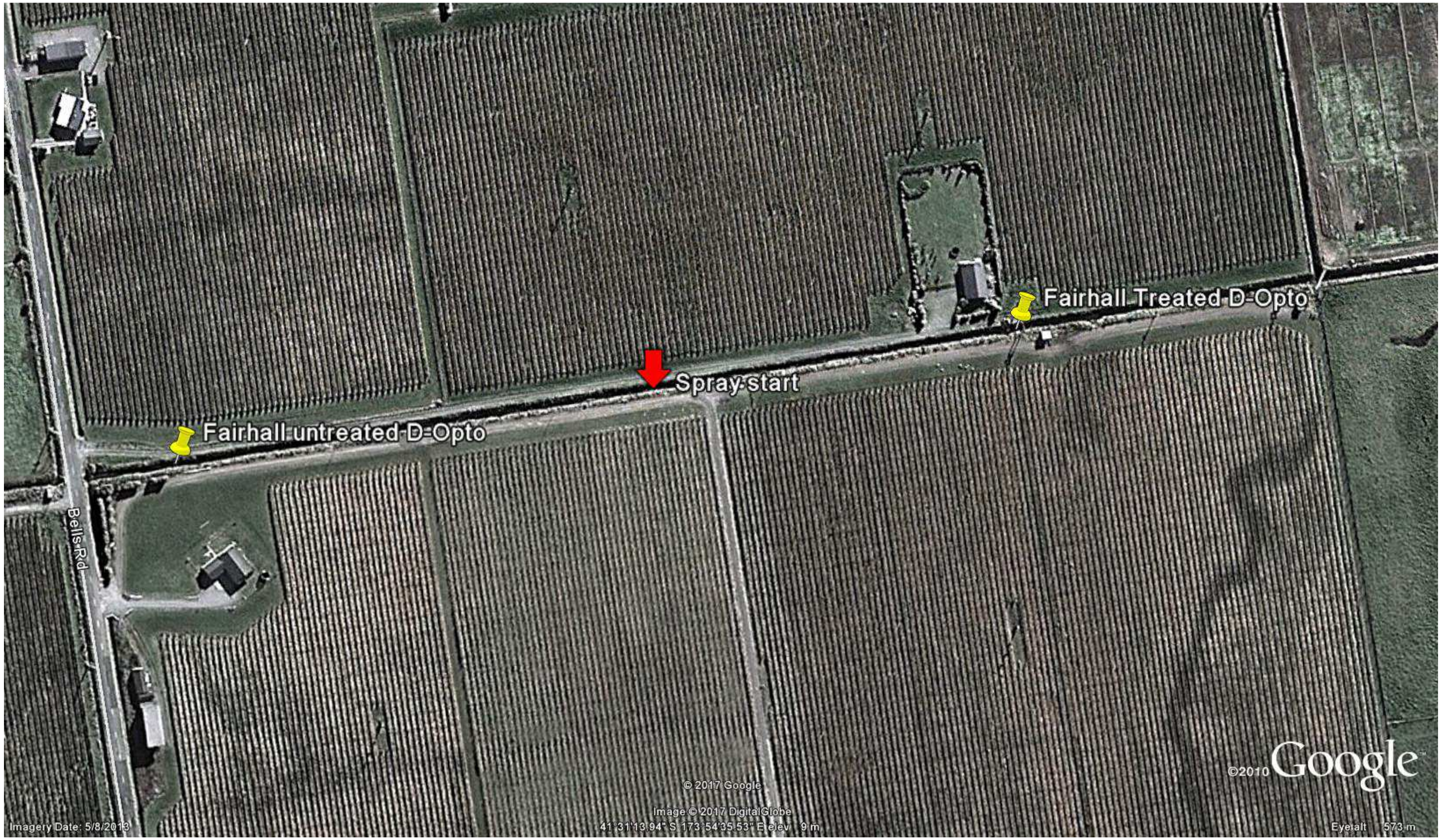


**Figure A7: Fairhall Co-op showing the start point for herbicide application and locations of the D-Opto loggers measuring DO and water temperature in the untreated reach (yellow marker) and treated reach (red marker).**


**Figure A8: Woolley & Jones showing the start point for herbicide application and locations of the D-Opto loggers measuring DO and water temperature in the untreated reach (yellow marker) and treated reach (red marker).**

# Appendix B Air temperature data

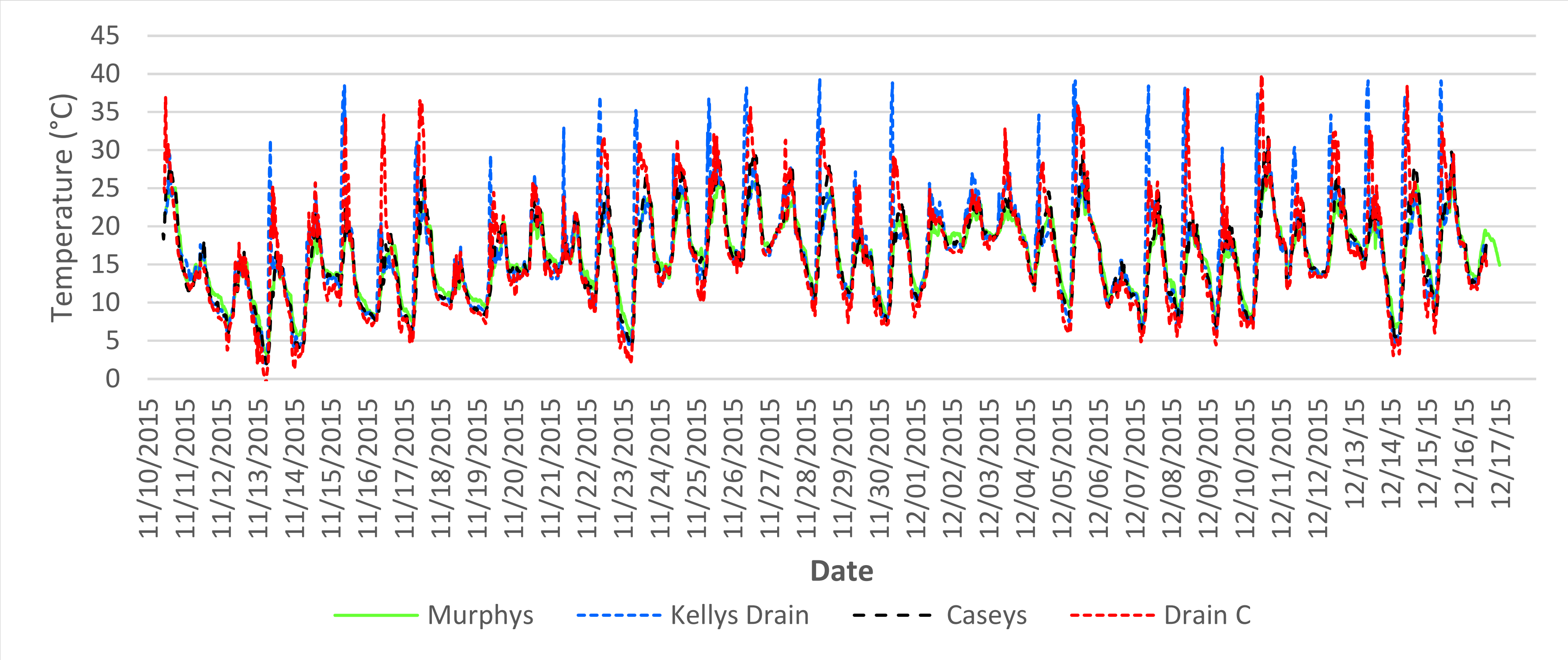


**Figure B-1: Logged air temperature (°C) for the four watercourses over the 2015 investigation period.**

**Table B-1: Manual records of air temperature for four watercourses over the 2015 investigation period.**

| Date | Watercourse | Time (DST) | Air temperature |
|---|---|---|---|
| 27/11/2015 | Kellys | 11:30 | 21.9 |
| 28/11/2015 | Caseys | 12:15 | 23.2 |
| 27/11/2015 | Murphys | 17:45 | 22.3 |
| 28/11/2015 | Drain C | 12:45 | 23.4 |
| 10/12/2015 | Caseys | 10:45 | 26.4 |
| 10/12/2015 | Kellys | 9:45 | 19.8 |
| 16/12/2015 | Murphys | 10:30 | 13.8 |
| 16/12/2015 | Kellys | 15:30 | 10.9 |

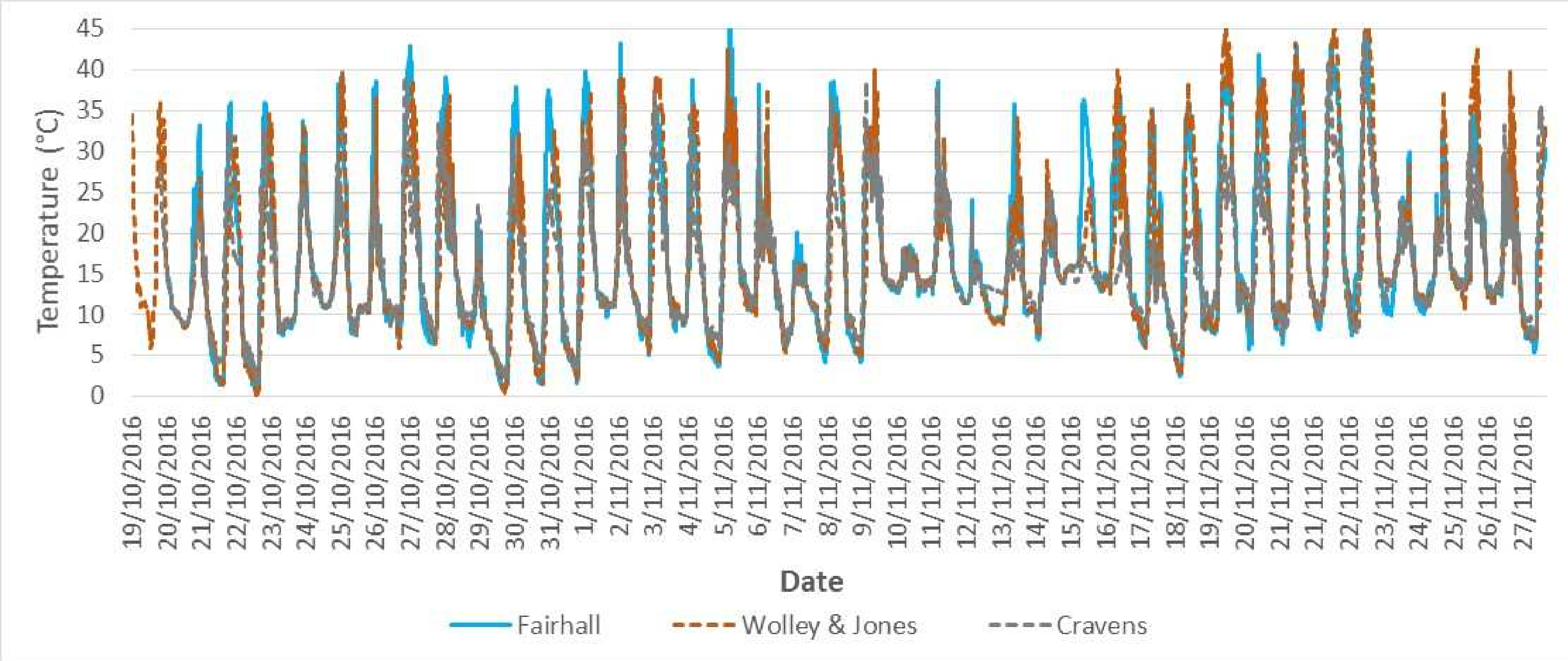


**Figure B-2: Logged air temperature (°C) for the three watercourses over the 2016 investigation period.** NB. Hobo air temperature logger for Drain Q could not be located.

**Table B-2: Manual records of air temperature for four watercourses over the 2016 investigation period.**

| Date | Watercourse | Time (DST) | Air temperature |
|---|---|---|---|
| 19/10/2016 | Woolley & Jones | 16:45 | 25.7 |
| 20/10/2016 | Drain Q | 8:30 | 14.1 |
| 20/10/2016 | Cravens | 12:15 | 17.4 |
| 20/10/2016 | Fairhall co-op | 16:45 | 14.9 |
| 2/11/2016 | Woolley & Jones | 10:15 | 19.9 |
| 2/11/2016 | Drain Q | 11:45 | 17.2 |
| 2/11/2016 | Cravens | 16:30 | 16.2 |
| 2/11/2016 | Fairhall Co-op | 17:00 | 15.3 |
| 9/11/2016 | Fairhall Co-op | 13:15 | 22.1 |
| 9/11/2016 | Cravens | 14:15 | 25.7 |
| 9/11/2016 | Woolley & Jones | 17:15 | 17.7 |
| 28/11/2016 | Cravens | 10:45 | 18.8 |
| 28/11/2016 | Fairhall Co-op | 13:15 | 21 |