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The critical detection distance for passively tracking tagged fish using a fixed radio telemetry station in a small stream

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Abstract

Background: Fixed radio telemetry stations are used to study the movement ecology of fishes in streams and rivers. A common assumption of such studies is that detection efficiency remains constant through space and time. The objective of this study was to understand how site characteristics and tag distance can influence the detection efficiency of a fixed receiver when used for fisheries research in a small stream. Field tests included a fixed receiver station on Forty Mile Creek, in Banff National Park, AB, Canada that recorded signals from radio tags over specified distances (i.e., 0 m, 27 m, 53 m, 80 m) within the expected detection range from July to October, 2016. Model selection was used to test which parameters may influence detection efficiency.

Results: The fixed receiver was able to record an average of 89% of transmissions over the study period. Detection efficiency was greater or equal to 0.97 at tag distances of ≤ 53 m. Detection efficiency significantly declined by 36% to a rate of 0.62 for tags placed 80 m from the fixed receiver. Water temperature and water depth also reduced detection efficiency, but only at the critical threshold of 80 m from the tag. Interestingly, turbidity had no influence on detection efficiency in this study.

Conclusions: This study provided insights into the reliability of fixed receiver stations as a passive tracking technique in small streams. The abrupt change in detection efficiency observed in this study presumably occurs in other systems. Identifying critical detection distance thresholds would appear to be a useful strategy for avoiding false-negative results. It is recommended that researchers who conduct radio tracking studies with fixed arrays should consider the deployment of sentinel tags over the study to understand the system performance.

Keywords: Tag validation, Range testing, Transmitter, Radio telemetry, Sentinel tag, Fish

Background

Radio telemetry allows researchers to understand the habitat preferences and movement patterns of wild fishes in their natural environments. This equipment can be used to locate fishes using either passive or active tracking methods that provide versatility in monitoring options in the field [1, 2]. Manual tracking is an approach that requires researchers to physically locate each fish (e.g., by foot, boat, aircraft) with a radio tag over specified monitoring periods (i.e., not continuous; [3]), and are often limited by resources such as funding or manpower available to the research team [4]. An alternative approach, known as passive tracking, relies on fixed radio receiver stations that continuously monitor an area of interest over time. These stations can function without human intervention and can be placed in remote areas with minimal physical maintenance [5]. Fixed receiver stations are commonly used to estimate approach and passage efficiencies of fishes at man-made infrastructure

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(e.g., fishways), to estimate migration success, and to characterize the seasonal habitat use and movements patterns where continuous data collection is necessary to meet the study objectives [6, 7].

While detection efficiency (DE) has been addressed regarding PIT tags [7, 8] and acoustic telemetry systems [9, 10], there is limited information pertaining to the DE of fixed radio telemetry receivers used in fluvial environments. This is concerning given that changes in stream variables such as conductivity [11, 12] and water depth [13, 14] can influence detectability of radio tags in these systems. The purpose of this study is to provide an understanding of how environmental variables (i.e., specific conductivity, water temperature, water depth, and turbidity) and the distance separating the antenna and radio tags may influence the DE of a fixed radio receiver in a small montane stream. This information will help elucidate which abiotic variables should be considered by researchers who are designing passive tracking studies in similar systems and provide recommendations on how to incorporate environmental monitoring of tags in future telemetry-based research projects.

Methods

The field study was conducted on Forty Mile Creek (51° 12′ 10.12″ N, 115° 33′ 52.95″ W), which had an average wetted width of 8 m, situated within the montane ecoregion in Banff National Park, AB, Canada. Data were collected over a period of 84 days from July 16th to October 28th, 2016. Data were not collected for 12 days from July 23rd to August 3rd due to technical issues with the receiver station.

A fixed receiver station was set up to continuously monitor radio tags (Sigma-Eight Inc., Markham, ON; Model PSC-I-80, 1.5 V, 150 mHz; tag: 2.5 cm [length] × 1.0 cm [width]; 4.2 g [mass], antenna: 28 cm [length]). The station included one 3-element yagi antenna (AF Antronics, Urbana, IL) directed at 90° to its fixed position on a tree. The antenna was placed parallel to the downstream flow and at a height of 4 m relative to the 100 year flood line of the stream. This antenna was connected to a VHF wireless radio receiver (Lotek SRX 800, Newmarket, ON, Canada) which was secured in a waterproof storage box (Greenlee®) and powered by a solar panel system (Make: Samlex Solar, Model: SSP-150-KIT). Tags were placed at four incremental downstream distances (0 m, 27 m, 53 m, 80 m). This ensured that we captured all distances within the longitudinal detection range (≤ 80 m) of the receiver based on preliminary field tests. The receiver equipment was programmed with a gain of 60 decibels (dbi) for the entire study duration. This gain was chosen because it is strong enough to detect tags within a reasonable distance, while also being sensitive enough to not

detect erroneous signal noise from radio interference. There were 5 tags anchored to the stream substrate in a plastic casing at each of the four distances for the study duration ($n = 20$ total). The radio tags were programmed to be offset from one another to ensure collisions did not occur for the specified number of signals per hour, which included a minimum of 5 signals to a maximum of 8 signals on an hourly basis. The minimum hourly transmission rate was used to evaluate DE in this study. Tag programming was tested in a controlled environment over a 48 h period before deployment to ensure that signal collisions were not occurring. Weekly checks were conducted to ensure all tags were properly emitting their expected signals, to make certain there were no disturbances to the tag antennas or anchored position, and to offload data from the receiver.

A water level logger (model U20L, Onset Hobo Inc.) was used to collect water depth (to the nearest cm) and water temperature (to the nearest 0.5 °C). Specific conductivity (μS/cm) and turbidity (NTU) were measured using a multiparameter water quality meter (600 OMS V2 Optical Monitoring Sonde; YSI®) at 30 min intervals. These instruments were placed 100 m upstream of the study site for logistical reasons. Daily averages were calculated for all stream parameters.

DE was measured as the proportion of expected signals that were detected by the fixed receiver for each tag during each day of the study period. For example, if zero signals from an individual tag were detected on a given day, a score of 0.0 was generated. Whereas, if all signals from an individual tag were detected on a given day, a score of 1.0 was generated. DE was linked with daily averages for water temperature, water depth, conductivity, turbidity, tag distance (i.e., location; 4 levels) of each tag ID for each sampling day. Prior to model formation, the covariates were evaluated for multicollinearity with pair plots and the Pearson correlation coefficient (r), as well as by measuring variance inflation (VIF > 3; [15, 16]). Non-linear relationships of covariates with DE were assessed using scatterplots of the raw data. Temporal autocorrelation was diagnosed by examining an autocorrelation function (ACF) plot of the model residuals and evaluating the estimated correlation parameter (alpha) after fitting a Generalized Estimating Equation (GEE) model.

Within the R statistical environment (version 3.4.3; [17]), a mixed model with a binomial distribution was applied to the DE response by applying a GEE model using the 'geeglm' function (geepack package; [18]) to determine which fixed terms and interactions were influential. Given that each tag was repeatedly sampled daily throughout the study period, the model included a random effect for tag ID. An "AR1" correlation structure was also included in the fitted models to account

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for the temporal dependency between sequential daily observations. Hypothesis testing was used to select for the best fitted model by comparing nested models to the full model with the Wald test. First, a model with all fixed terms was fit to the dependent variable. Each fixed term was then dropped in turn and compared with the full model using the Wald test, which evaluates the Chi-square statistic based on the given degrees of freedom to compute a *p*-value. Interactions were also tested by adding each two-way interaction individually and evaluating whether it improved the model using the Wald test. Fixed terms and interactions that were not significant ($p > 0.05$) were dropped from the final fitted model.

The assumptions of normality and homogeneity of variance of the residual error were visually examined for the fitted models. We checked for collinearity between predictor variables and found that specific conductivity and water temperature were negatively correlated. Upon further visual inspection, it was decided that specific conductivity would be dropped from the model given that temperature appeared to have a clear relationship with DE based on distance (Fig. 1), which was not seen with conductivity over the time period studied here. In addition, specific conductivity had a small range in values over the study period (11% change between min and max values), whereas water temperature showed a wider

range in values in terms of high and low temperatures (64% change between min and max values) for which predictions could be made.

An analysis of variance (ANOVA) was conducted to compare DE at the 4 different levels of tag distance to the receiver to determine the distance where tag signals were more or less likely to be detected. We recognized that post hoc comparisons could not be generated with a GEE model, therefore, a repeated measures ANOVA (to account for dependency in the observations from each tag) was applied to compare tag distance (i.e., a 4-level nominal variable) relative to DE. This was followed by an investigation of the pairwise comparisons between tag distances using Tukey's post hoc Honestly Significant Difference (HSD) from the 'multcomp' package [16]. The threshold for model significance was evaluated at $p < 0.05$.

Results

Over the course of the study, DE of the fixed receiver was calculated at an average rate of 0.89 (i.e., 89% of signals were detected by the fixed receiver) based on 187,801 signals across all tag distances. Hypothesis testing demonstrated that water temperature, water depth, and tag distance influenced DE. Furthermore, a two-way interaction for water temperature and tag distance was also found to be important for influencing DE (Table 1).
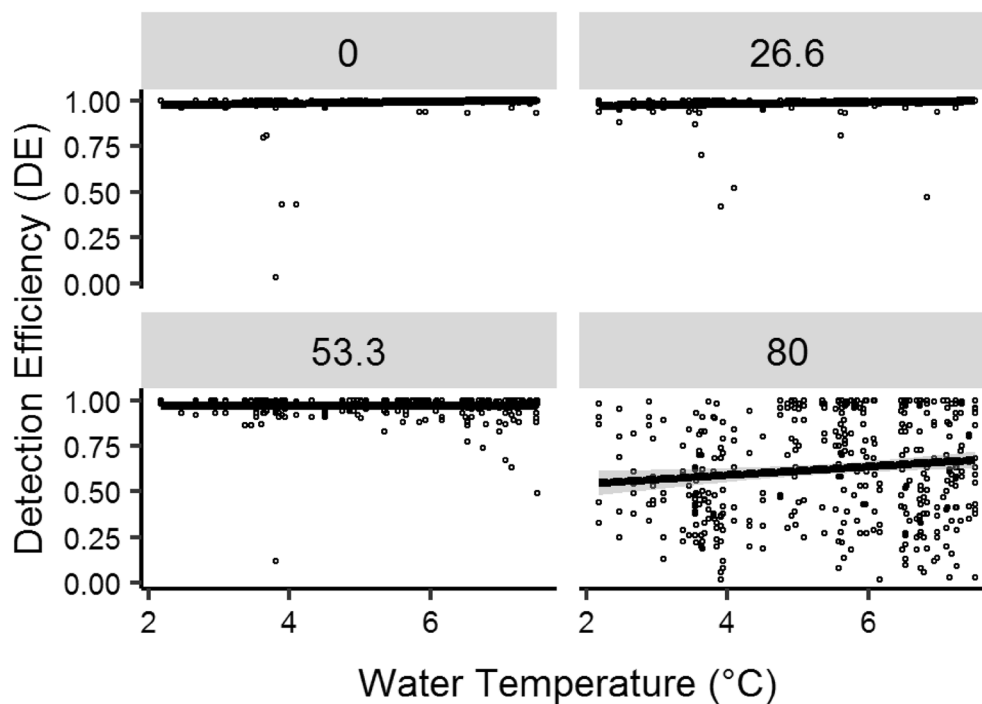
Fig. 1 Detection efficiency (DE) as a function of water temperature (°C) at different tag distances (m) using radio tags (Sigma-Eight Inc., 3 V, 84 dB, 150 MHz) in a small montane stream. The scatterplot provides the linear regression line (black line) and 95% confidence interval (shaded area), which is not the model output of the GEE; it is simply plotted for visualization purposes

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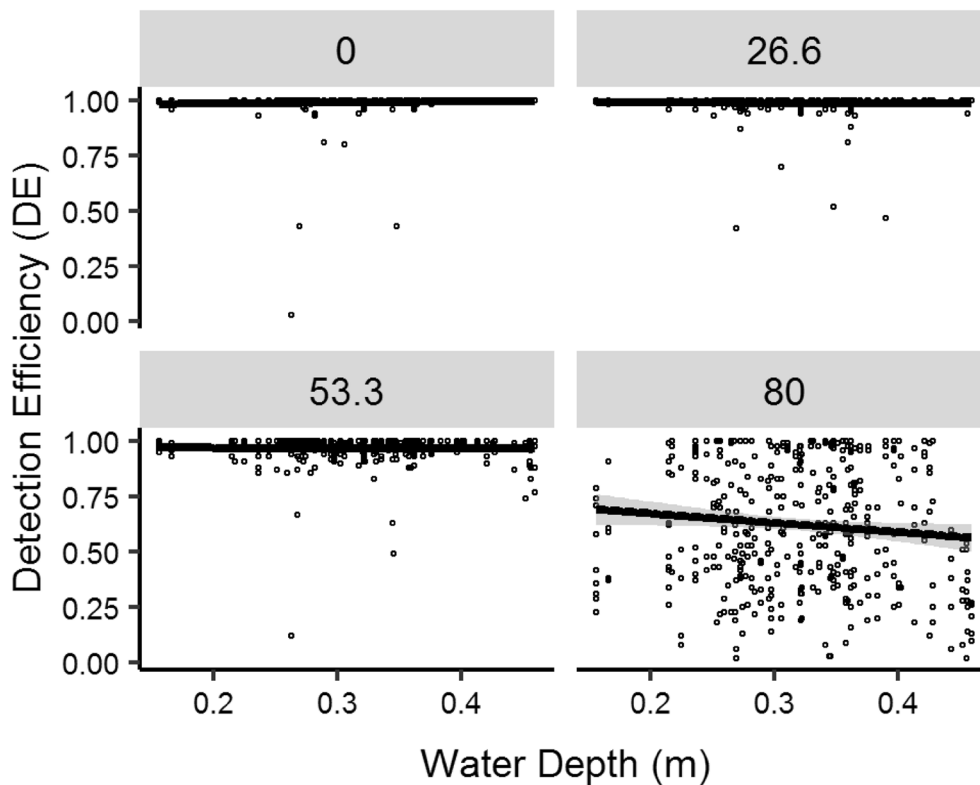
Fig. 2 Detection efficiency (DE) as a function of water depth (m) at different tag distances (m) using radio tags (Sigma-Eight Inc., 3 V, 84 dB, 150 MHz) in a small montane stream. The scatterplot provides the linear regression line (black line) and 95% confidence interval (shaded area), which is not the model output of the GEE; it is simply plotted for visualization purposes

Turbidity was not an important variable and was dropped from the fitted model. The model outcome demonstrated that water temperature (range = 2.1–7.5 °C) had a positive influence on DE ($\chi^2 = 9.75$; $p = 0.002$) with a greater effect occurring at the 80 m tag distance as shown by the two-way interaction term ($\chi^2 = 62$, $p < 0.0001$; Fig. 1). Lower rates of DE occurred when water depth increased ($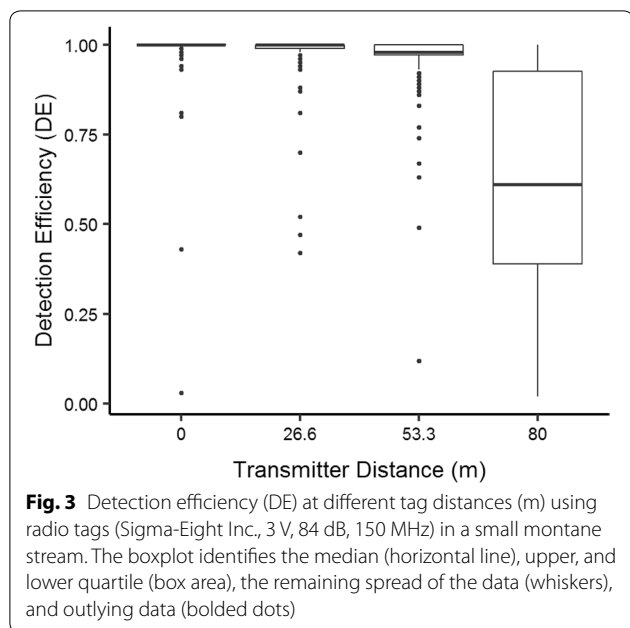\chi^2 = 8.5$, $p = 0.004$) and this relationship was more pronounced at the 80 m tag distance, when these variables are plotted for visualization purposes (Fig. 2).

Over 97% of the signals were detected at 0 m, 26 m, and 53 m, whereas only 62% were detected at the 80 m distance and with greater variability (Fig. 3). The repeated measures ANOVA demonstrated that there was a significant effect from tag distance on the DE outcome ($F_{3,16} = 31.3$, $p < 0.0001$). The Tukey's post hoc

Table 1 Summary of the outcomes of the Wald Test for each model term that was dropped and compared to the full model developed using a Generalized Estimation Equation (GEE) for detection efficiency (DE)

Model response	Model covariate	Range	DF	χ^2	*p*-value
Detection efficiency (DE)	Turbidity (NTU)	0.5–8.6	1	3.4	0.07
	Tag distance (m)	0–80	3	144	*<0.0001*
	Water depth (m)	0.13–0.47	1	8.5	*0.004*
	Water temperature (°C)	2.2–7.5	1	9.75	*0.002*
	Distance-temperature	NA	3	62	*< 0.0001*
	Distance-depth	NA	3	7.7	0.05

An AR1 covariance term for temporal autocorrelation and tag ID was included as a random effect in the GEE. The 'Location' term is a categorical variable with 4 levels, where 0 m was used as the baseline level in the fitted model. Significant *p*-values of model terms are italicized. This is simply used to provide an understanding of hypothesis testing rather than the fit of our final model

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Fig. 3 Detection efficiency (DE) at different tag distances (m) using radio tags (Sigma-Eight Inc., 3 V, 84 dB, 150 MHz) in a small montane stream. The boxplot identifies the median (horizontal line), upper, and lower quartile (box area), the remaining spread of the data (whiskers), and outlying data (bolded dots)

HSD pairwise comparisons showed that DE was similar between 0 m, 26.6 m, and 53.3 m (Table 2). However, DE was significantly lower at 80 m when compared to the other three levels (Table 2), which is also apparent when visually examined (Fig. 3).

Discussion

Radio signals are transmitted through a medium (e.g., water and air) as a form of wireless communication with a receiver. The characteristics within the medium can reflect, refract, or diffract these signals resulting in signal attenuation or total propagation loss [19]. Here, we investigated how stream variables and tag distance can affect DE of a fixed receiver station used for fisheries research. As expected, the results show that tags beyond the distance threshold from the receiver have a lower likelihood of being detected (i.e., located at 80 m) than those within < 53 m for this study. In addition, signals that traveled over greater distances to the fixed receiver

station (i.e., 80 m) were more likely to be influenced by water temperature and water depth, while signals transmitted within a closer proximity to the receiver (i.e., ≤ 53 m) were consistently detected.

Radio telemetry validation studies have focused on active tracking, with specific interest in both conductivity and water depth for large river systems. For example, previous research has found that detection distance was reduced with an increase in water depth [12, 14] and conductivity [12, 13]. However, this trend was not seen at very low conductivities (i.e., 60–90 μS/cm) in one of the aforementioned studies [12]. With that said, these examples are likely not representative of the natural fluctuations within small-scale stream systems (e.g., seasonal vertical water depth change of < 2 m) and used low frequency tags in the range of 48–49 mHz, which is appropriate for deep and highly conductive systems not studied here (i.e., we used 150 mHz tags; [20]).

One study that explores detectability through tracking error at the same frequency and conductivity range used here [22] found that conductivity influenced lateral tracking error (across the stream) and not longitudinal tracking error (downstream or upstream). However, active tracking studies are not able to account for the likelihood that a tag is detected constantly over time given their finite time during search periods. Our study not only found that distance influenced the overall detectability of tags at 80 m (62%), but it also revealed that both water depth and temperature influenced DE in this range based on longitudinal distance. The reduction in DE at a farther distance (80 m) provides a lesson to fisheries researchers that detection distance should be of utmost importance in study design to ensure that the possibility of false negatives, otherwise known as type-II errors, are avoided.

Prior to this study, there were few aquatic radio tag detection validation studies that considered temperature. Previous work in this area has mostly been associated with terrestrial applications in tropical climates where significant changes in atmospheric conditions (i.e., humidity and temperature) can occur daily. For example,

Table 2 Post hoc pairwise comparisons of repeated measures ANOVA using Tukey's HSD for detection efficiency (DE) measured at 4 different distances (0 m, 26.6 m, 53.3 m, and 80 m)

Model response	Pairwise comparison	Estimate	Std. error	*z*-value	*p*-value
Detection efficiency (DE)	26.6–0	− 0.003	0.045	− 0.3	1.00
	53.3–0	− 0.022	0.045	− 2.14	0.961
	80–0	− 0.367	0.045	− 35.46	*< 0.0001*
	53.3–26.6	− 0.019	0.045	− 1.84	0.975
	80–26.6	− 0.364	0.045	− 35.16	*< 0.0001*
	80–53.3	− 0.345	0.045	− 33.32	*< 0.0001*

Significant differences in the response variable between distance comparisons are italicized

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an increase in air temperature alongside a decrease in humidity during the daytime has favored high radio signal strength whereas the opposite was seen under humid conditions (i.e., morning and evening; [21]). The reason for low DE at reduced temperatures in this study could be due to battery performance [22]. Although these tags were deployed within their operating capacity of − 30 °C to 60 °C, a decrease in temperature results in an increase in internal battery resistance which could ultimately reduce the battery capacity. As such, it would be reasonable to assume that at lower operating temperatures the battery operating power would be reduced leading to changes in signal attenuation or total propagation loss. In addition, it is possible that frazzle ice was present during the low temperatures which could have also influenced the detectability of the tags.

From an engineering perspective, the lower DE at a greater distance could also be related to a number of engineering parameters including the strength of the transmitter (i.e., battery voltage, battery size, antenna length, and antenna pattern), propagation loss in water (i.e., temperature and frequency), interference and reflections in water (i.e., closeness of transmitter to rocks etc.), refraction loss which varies non-linearly with angle, peaks at Brewster angle, dispersion loss, multipath loss, transmission line losses, the overall receiver sensitivity, and ambient noise levels, which show the complexity of the issue [23]. To our knowledge, this is the first documented study to consider turbidity and its possible influence on radio signal transmissions. Although turbidity did not influence DE in the range considered here, it may affect DE across a broader range of values.

Conclusion
In this study, we showed the importance of monitoring environmental variables, while also acknowledging engineering-related factors that could influence DE when using fixed receiver arrays. Further research is needed over longer study durations and greater ranges of environmental variables as well as accounting for the engineering parameters mentioned previously. In recognition of this, the findings from this case report should not be directly applied to future studies, but rather they should be used as a guide for researchers who want to assess DE in future studies. This study also emphasized the importance of identifying the critical distance threshold for which DE declines to avoid false-negative results. We recommend that researchers include a dedicated tag validation station (described here) on a concurrent basis with their main telemetry-based research projects so that they can identify the variables and distances at which false-negative detections could be prevalent, allowing them to interpret their results accordingly. Once researchers identify the critical distance threshold, they may wish to consider excluding data collected at that distance and beyond for some types of study questions.

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