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Revisiting the Effect of Submarine Groundwater Discharge on Coral Abundance with New Statistical Models.

Abstract

This study re-visits a dataset from work done on Hawaii island's Hilo bayfront to examine the potential effects of submarine groundwater discharge (SGD) on the distribution of coral in the area. SGD originates as rainwater up-slope, and can travel underground until reaching the waterfront where it can emerge at the shore or as a point source some distance away underwater. Corals are affected by changes in temperature through effects such as bleaching in high temperatures, and are also affected by low salinity from flooding events, which can prove detrimental. SGD has the potential to affect coral through changes in salinity and temperature of surrounding water, the effect of which may be seen by examining their distribution in an area. This study uses random effects and zero inflation models to better fit the distribution of the response variables (coral presence/absence, and percent cover). Spatial clustering was also investigated to determine if the distribution of coral through the site was random or not. No influence of salinity or temperature to SGD was found, however clustering was found with coral appearing to become less prevalent at farther distances from the center. The causes for this clustering remain unknown, and could be further investigated.

Introduction

In the Fall of 2018, our team set out to the Hilo bay front on the island of Hawaii. The question at hand was, does submarine groundwater discharge influence the distribution of coral in the near shore environment?

Submarine groundwater discharge (SGD) begins on the island as rainwater. The water becomes trapped below ground and slowly makes its way downhill to the ocean. The lens of groundwater can extend offshore for some distance before emerging underwater as a below-surface freshwater spring that acts like a point source of fresh water (Peterson et al. 2009). The potential effects of SGD stem from how it changes the physical environment that the corals live in. The physical changes investigated here are temperature, and salinity.

Temperature

The temperature of the groundwater discharge has a median somewhere around 20C, whereas the surrounding ocean water may stay in the range of 23C (Johnson et al. 2008). Temperatures are a concern for corals. Temperatures that are too high, or too low will create a non-ideal environment for their survival. Bleaching due to high temperatures is the primary concern. Bleaching is the process whereby symbiotic microalgae that inhabits the coral polyps gets ejected at higher temperatures, reducing the polyps survival (Jokiel & Brown 2004).

Salinity

The groundwater has very little salinity, whereas salinity in this area has been measured around 34ppt. It has been reported that coral prefer salinity in the range of 25-42 ppt (Parsons et al. 2008). Historical flooding during intense rainstorms on Oahu caused die-offs of coral reported in Jokiel et al. (1993) as a response to decreased salinity that demonstrates its importance to coral.

Nutrients and Waves

Nutrient runoff from groundwater is another known element of SGD that has the potential to affect the coral distribution and abundance (Fabricius 2005). Nutrient content of the water was not investigated due to constraints on the research. Other factors known to affect coral distribution is the location and type of substrate and wave action at these locations. Corals prefer areas sheltered from waves as well as deeper areas below the wave action (Dollar 1981).

Light and Depth and other corals

While not investigated in this study, light transmission and quality is known to affect the distribution of corals. These patterns can be species specific, and lead to vertical zonation based on light quality (Mundy and Babcock 1998). In some corals, colonization of larvae has been shown to prefer dead coral substrates of the same species (Norström et al. 2006). The distribution habits of corals will become relevant later as the results are examined.

The interplay of these effects is difficult to predict at a given location, however for the purposes of this study, it was distilled to looking at only groundwater discharge, and the physical characteristics that would affect. The location chosen for this study was just offshore of Richardson’s Beach Park. SGD is known to be present along this shoreline in nearby locations (Carlson & Wiegner 2016). It gives easy access to the water by a sheltered cove.

The purpose of the data collection was to tie temperature and salinity measurements to coral abundance in an attempt to find a correlation in the sample area to submarine groundwater discharge (alternative). Even with improved methods, it’s possible that no such connection exists (null). No such connection was found in the first iteration of this study, however the statistical models used before may have been too limited to say definitively. This re-visit of the data employs new statistical models that take into account the distribution of the response variable data, as well as taking into account multi-day differences in temperature. Additionally, any clustering effects will be investigated to determine if the coral distribution and percent cover follow any kind of spatial pattern related to distance from the cluster. It may be that the coral is randomly distributed throughout the sample site (null), or it could follow some kind of non-random pattern (alternative).

Methods

The sample locations were chosen haphazardly within a defined region. Haphazard sampling was the only option due to technical and material constraints. A 1x1m quadrat was placed on the ground at each location, and a YSI 2030 with a sonde capable of measuring temperature, salinity, and dissolved oxygen was placed near the floor just above the quadrat. A depth measurement was taken simultaneously. A picture of the quadrat was taken with a Gopro Hero 4 camera. The quadrat location was recorded with a handheld GPS. The images were cropped and perspective transformed using GIMP. The transformed images were uploaded the service Coralnet, where the areas within the quadrat were classified by type of substrate and percentage cover of each type. Sampling took place over 2 days. Only live coral was counted.

Statistical Analysis

The previous statistical analysis focused on single linear regression with temperature and salinity as predictors and percentage coral cover as response variables. What was unnoticed however was the difference in temperature between Day 1 and Day 2 of sampling (Figure 1).

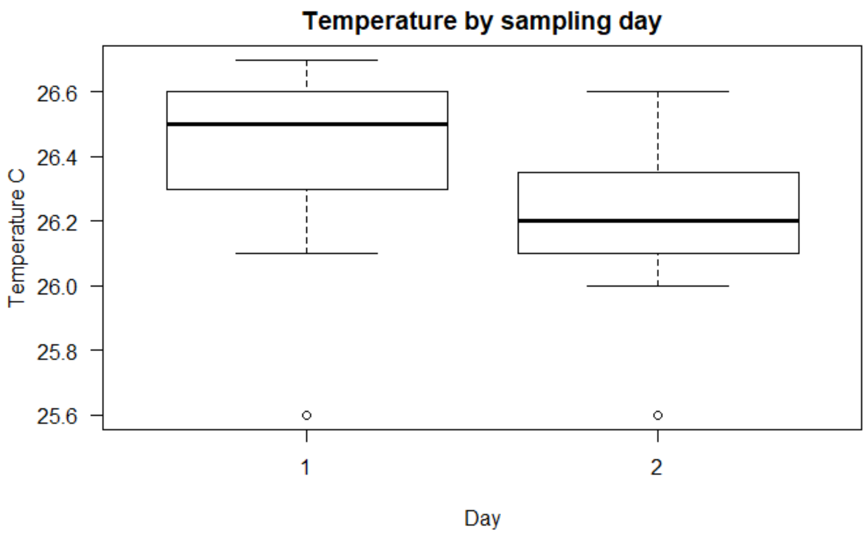

Figure 1: Temperature difference between sampling days 1 and 2.

The difference in temperature indicates that temperature should be regarded as a random explanatory factor, and the model used needs to reflect that. Additionally, the possibility of the clustering of coral wasn't examined. Also unaccounted for was the zero inflation of the coral cover percentage, which requires its own model.

Clustering

Clustering within the sampling area would indicate some favorable environmental factor is keeping the corals grouped together. The location of each quadrat and the percentage of coral cover in each one was calculated to a weighted average. The latitude and longitude were averaged separately, and the percent coral cover was taken as the weight. This gave a weighted center point of the coral cluster that served to calculate the distance in meters of all other quadrats from that center. Quadrats with more coral 'pull' the center farther than those with less. The *distm* function from the *geosphere* package was used for this (Figure 2). This distance from the new defined center to each quadrat was added as a column to the data set for each point (Figure 3).

```
library(geosphere)

y <- beach[,4]
weight <- beach[,10]
x <- beach[,5]
center <- c(weighted.mean(x, weight),weighted.mean(y, weight))

j <- nrow(beach)
l <- vector("numeric", j)
rownum=1
while(j>0){
  l[[rownum]] <- distm(center, c(beach[rownum,5], beach[rownum,4]), fun =
distHaversine)
  rownum=rownum+1
  j=j-1
}

beach$cdis  <- l
rm(j, rownum, y, x, weight, l)
```

Figure 2: Function to find the center of the coral clusters by calculating a weighted mean using the percent coral cover as the weight.

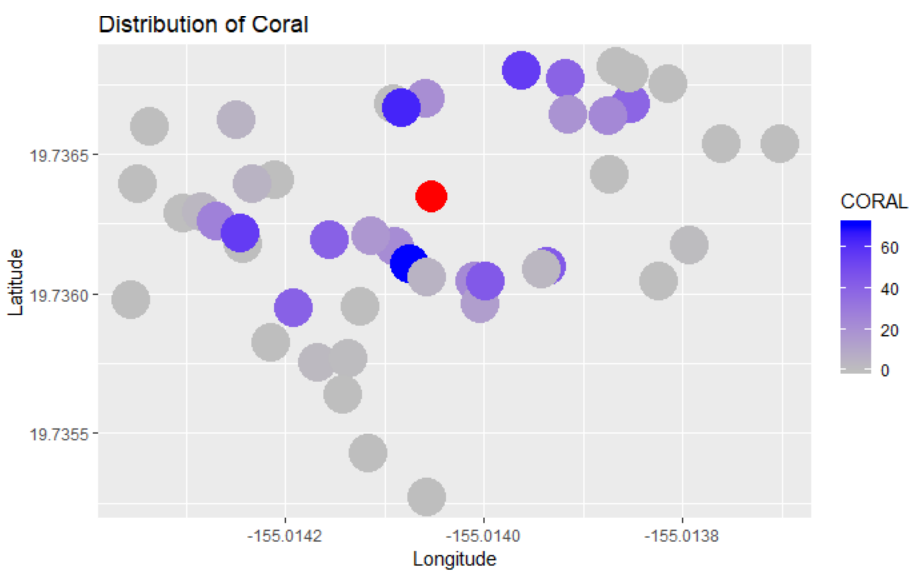

Figure 3: Clustering of the coral distribution at Richardson's Beach Park showing the percent cover within each quadrat and its location. Red dot is the weighted center.

Explanatory Variables and Models

In this model, the explanatory variables are taken to be, temperature (random slope and intercept), salinity, and distance from the center. The percentage coral cover was taken to be the response variable initially, however the model was highly overdispersed (c-hat of 27.4), possibly on account of a high abundance of zero values (zero inflation). The response variable was then changed to the presence or absence of coral, and the model family changed to binomial. The model is a random effects model accessed by the glmer function from the lme4 package (Figure 3). Temperature was taken to be the random slope and intercept based on the day of sampling.

```
library(lme4)

fm1 <- glmer(PRES ~ SAL + cdis + TEMP + (TEMP | Day), data=beach, na.action =
"na.fail", family=binomial)
```

Figure 4: Random effects model with binomial distribution

To address the percent coral cover properly as a response variable, the regression function zeroinfl from the pscl package was used. This regression is designed to handle zero inflated count data, which this data-set resembles in the high number of zero values in the coral cover percentage (Figure 4) (Figure 5).

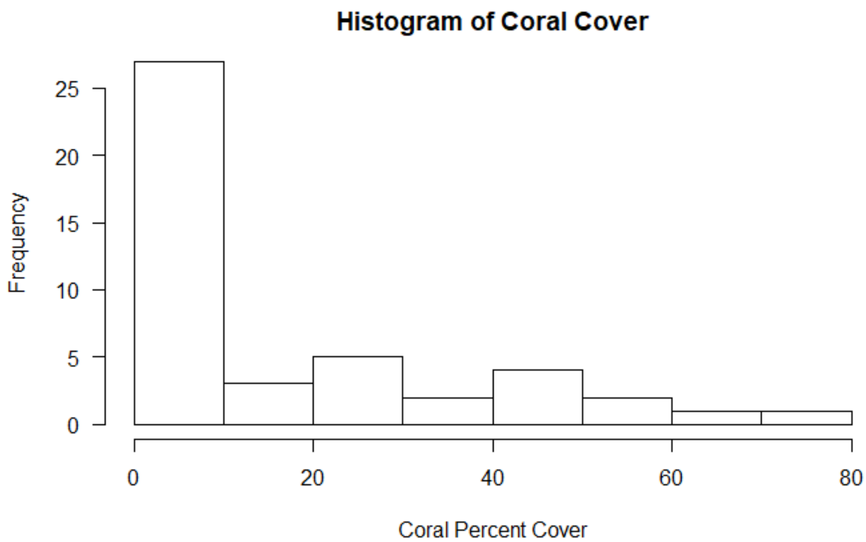

Figure 5: Histogram of coral percent cover showing high zero inflation.

```
library(pscl)

summary(m1 <- zeroinfl(CORAL ~ SAL + cdis + TEMP| 1 , data = beach))
```

Figure 6: Zero inflation model accounting for high abundance of zero counts

Results

Random Effects Model

Running the random factors model shows the variance of the intercept (1562) exceeds the standard deviation of the intercept (39.5), which indicates that the different temperatures on different days is different enough to affect the model. Of the fixed effects, the only coefficient that has a p-value approaching the threshold to reject the null at p=0.0639 was distance from the center, and which had a negative coefficient indicating that coral was less likely to be present at greater distances from the defined center of the cluster (Table 1)(Figure 6). Coefficient of distance was (0.963 80% CI 0.928—0.985). For salinity and temperature, we again accept the null that they do not significantly affect the percent coral cover (p > 0.1).

Table 1: Transformed (exp) coefficients for the random effects model.

		10 %	90 %
(Intercept)	0.0009006125	1.102784e-20	7.355050e+13
Distance (m)	0.9626664372	9.280035e-01	9.859743e-01
Temp C	1.4567437996	5.731104e-01	5.626367e+01
Salinity	0.9716950972	3.551140e-01	1.856267e+00

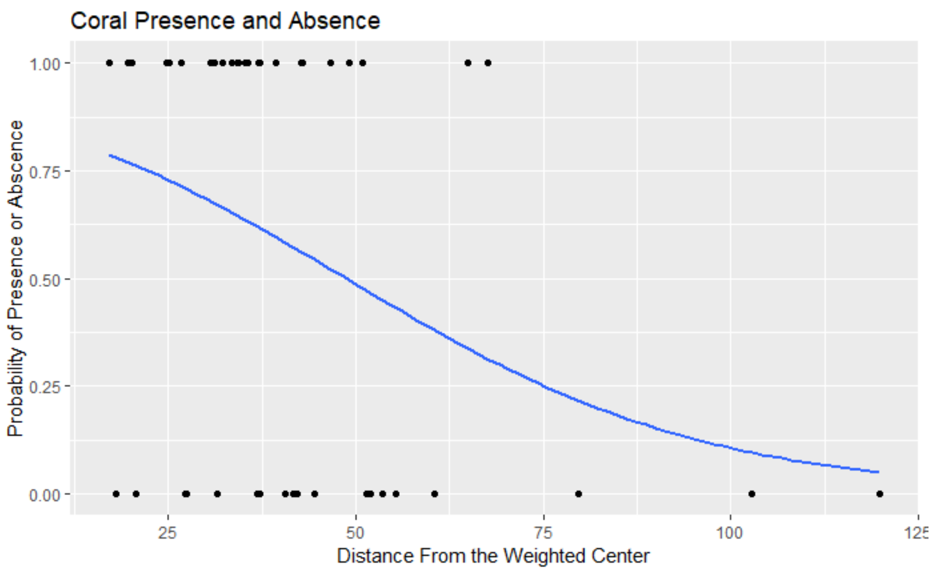

Figure 7: Scatterplot with binomial family smooth curve showing the probability of finding coral at different distances in meters from the center. 1=present, 0=absent

Table 2: Non-transformed coefficients for random effects model.

		10 %	90 %
(Intercept)	-7.01243542	-45.95386419	31.9289934
Distance(m)	-0.03804831	-0.07471982	-0.0141250
Temp C	0.37620367	-0.55667686	4.0300490
Salinity	-0.02871321	-1.03531643	0.6185674

Zero Inflation Model

The zero inflation model showed that the coral percent cover was significantly correlated to distance from the center of the cluster (p-value 0.024), where we can reject the null. The coefficients remained negative with an 80% confidence interval (Table 3).

Table 3: Zero inflation model raw coefficients.

	10 %	90 %
count_(Intercept)	4.32739147	17.21739509
Salinity	-0.00280162	0.24977129
Distance (m)	-0.01215221	-0.00331359
Temp C	-0.77111246	-0.09002675
zero_(Intercept)	-0.70045074	0.07313581

The transformed coefficient for distance (0.992) showed a variation between 0.988 and 0.996 (80%CI), meaning that the percent coral cover decreases by this percent for each additional meter away from the center of the cluster according to the model (Table 4) (Figure 7). We accept the null for the effect of salinity and temperature on coral percent cover (both $p > 0.1$).

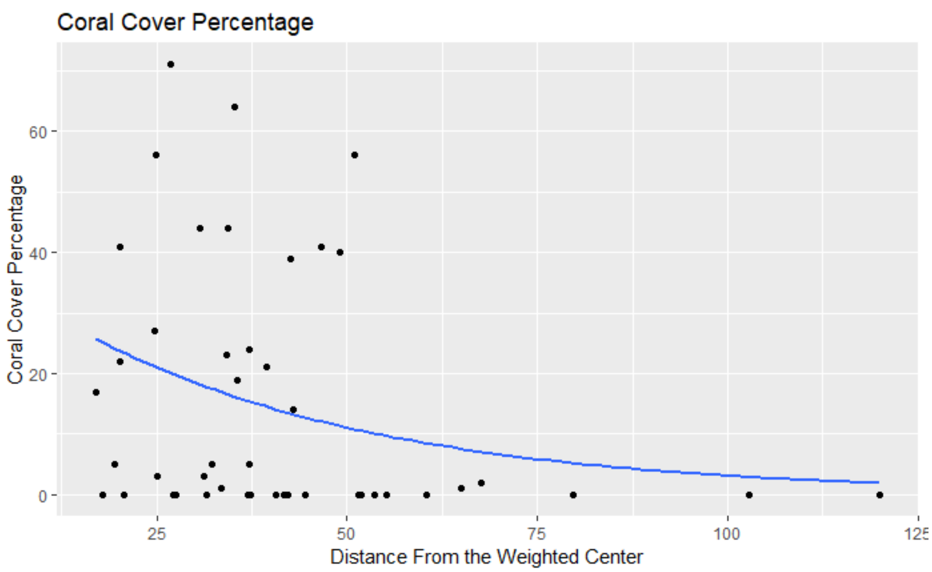

Figure 8: Scatterplot with coral cover percentage at varying distances in meters from the center with poisson family smooth curve.

Table 4: Exponent transformed coefficients for the zero inflated model.

	10 %	90 %
count_(Intercept)	75.7464417	3.002062e+07
Salinity	0.9972023	1.283732e+00
Distance m	0.9879213	9.966919e-01
Temp C	0.4624983	9.139067e-01
zero_(Intercept)	0.4963615	1.075877e+00

Conclusion

As with the last analysis, the results from this study showed no significant correlations between temperature, salinity, and either presence/absence or coral percent coverage. The only explanatory variable that approached significance for either model was the distance of quadrats from the weighted center. This indicates that coral was more likely to be found nearer to the center, and was not likely to be randomly distributed throughout the sampling area. The exact cause of this clustering is hard to predict. If coral coverage in the area were related to salinity or temperature changes from a point source of SGD, this would have been reflected with temperature and salinity measurements; it was not. There is some issue with the zero inflated statistical model in that it does not account for the variable temperatures over the multiple sampling days. The random effects model cannot account for overdispersion by usage of a quasipoisson family, and was thus unusable with the distance explanatory variable.

While clustering did exist, it isn't indicated that it was caused by SGD. One possibility is that the clustering was based on other unmeasured factors like the substrate type or light level (Mundy and Babcock 1998), and wave action (Dollar 1981). In this particular area, one part of the sampling area was protected from waves by a rocky outcrop, while another part was not. The area consisted of part sand and part lava with coral mixed in. The human presence there was observed to be high. Being a public access to the water, it is possible that human disturbance with activities such as spear fishing and snorkeling also contribute to the distribution of living coral heads in the area. The usage of an area by humans and affects on coral in this near shore area of Hawaii island could be a research avenue.

This study (and future studies like it) would have benefitted from inclusion of wave action and substrate types as predictive factors in the coral distribution. As a response variable, the recruitment of new coral polyps should be included as distribution alone may be insufficient (Norström et al. 2006). Given some sources suggest that nutrient content has effects on coral, a way to measure nutrient content of the water may be advisable for response variables. Surveying multiple sites, and sampling a broader area among those sites may be advisable as is implementing a real random sampling technique as opposed to haphazard.

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