Inland Waters

The influence of season and landscape on the water quality of ponds at multiple spatial scales

--Manuscript Draft--

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Abstract:	Understanding the spatial relationships between Land Use/Land Cover (LULC) and physicochemical water quality in pond ecosystems is vital to the conservation and management of ponds. This knowledge is especially critical to reconcile landscape planning and management with wildlife conservation, particularly in urban regions with rapid population growth. In this study, we measured i) seasonal differences in water quality and ii) the impact of the surrounding landscape at four spatial scales (10m, 100m, 500m and full catchment) on water quality of 50 ponds in the Auckland region, New Zealand. For each pond, seven physicochemical water quality variables and nine landscape properties (LULC and physical features of the pond) were measured in winter and summer. We found significantly higher measures of conductivity, total dissolved solids (TDS), percentage of dissolved oxygen (%DO), pH, salinity, and phosphates concentrations in summer. In contrast, ammoniacal nitrogen concentration was higher in winter. These findings are indicative of poorer water quality during summer. Multiple linear regression and redundancy analyzes showed that LULC and physical landscape features had different influences on the physiochemical variables across the different spatial scales and seasons. The landscape properties at all four spatial scales were good predictors of pond temperature, and %DO only in summer. Overall, variations in water quality were explained better by general landscape characteristics than by the LULC alone, at the catchment and 500m scale in winter and at the 100m scale in summer. This study highlights the importance of including different spatial scales, seasons, and landscape when quantifying land-water interactions.
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Response to Reviewers:	Reviewer one General comments: Comment 1: The manuscript: The influence of season and landscape on the water quality of ponds at multiple spatial scales presents new and valuable information about a set of ponds at Auckland NZ. The approach used by the authors examining the effects of various stressors on water quality is appreciated, and I think the results of the work are important, and this has great potential. Response 1: We thank the reviewer for their keen interest in our manuscript and positive views. Their meaningful and thorough comments and suggestions have been taken into consideration and have been applied where necessary to improve this paper. Comment 2: ..lack of enough information about the settings: the ponds and the area in terms of geomorphological hydrological settings. Furthermore, no mention of any (physical/geochemical) measurements in any of the ponds in the past. Is that the case? Response 2: We agree with the reviewer, and as suggested, we have revised it. We have included some information on the settings of the ponds, including geology and geography See in Study Area section (in red), page 5, lines 124-136. Comment 3: ..the discussion seems to take results from a set of ponds and expand the

inferences from the regional scale (Auckland ponds) to very general behavior of aquatic systems. The discussion of this aspect is not developed, and thus the reader is left with a feeling that this has no real base. This is also associated with citing other works from various places in the world. However, the authors do not discuss similarity or differences between their study and these other works.
Response 3: We thank Editor for their suggestion. We have now thoroughly gone through the discussion section to provide further discussion, particularly regarding comparing our results with previous studies and its implications.
Specific Comments:
Comment 4: Line 33: Sentence not clear
Response 4: The sentence has been revised and rephrased for clarity. See paragraph 3, page 1 lines 33-35 (in red).

Comment 5: Line 54: seems to me you turn too quickly- directly to Anthropogenic LULC. My understanding that the term LULC is general- and covers a wide variety of covers and uses, many may be natural, (e.g., open grassland vs. forest) and their effect on ponds is worth examining
Response 5: We agree with the reviewer. The sentence has been revised and background information provided as suggested. However, the term land use land cover was used because land cover applies to a larger area, while land use refers to human modifications of land for specific purposes. Because our study looked at use and cover, we decided to use both terms. See Introduction, paragraph 3, Section 3.4 (in red), page 11, lines 30-31.

Comment 6: Lines 62-67: If you include N-P in the pollutant group (which is ok), using the term direct toxicity to describe their effect on biota is a bit harsh
Response 5: We agree with the reviewer, and we have been revised as suggested. See Introduction, paragraph 3, page 3, lines 62-64 (in red).
Comment 6: Line 84: what do you mean by "…including catchment areas…"? Is not the catchment the only drainage into the system? Or do you infer complex deep hydrological transfer scenarios that transport water and solutes from other catchments?
Response 6: The reviewer is correct catchment areas are the drainage areas, and the sentence has been revised for clarity. See introduction, paragraph 4, page 1, lines 80-82 (in red).

Comment 7: Line 92: "By studying small, isolated water bodies (ponds), it is possible to quantify the spatial variation and the primary environmental features across broad regional scales (Epele et al. 2018)." This sentence -although it has a ref. requires an explanation
Response 7: We have revised as suggested for clarity, and more explanation is provided. See introduction, paragraph 5, page 4, lines 93-94 (in red).

Comment 8: Lines 104-111: a) not targeting to differentiate between natural and Anthropogenic effects? b) probably target II and III should be switched in place…c)line 109- types7:typo
Response 8: We agree with the reviewer. Our target was not to differentiate between anthropogenic and natural effects - given the complex nature of these aquatic systems, differentiation would require a greater diversity of sites, something that is perhaps not possible given the direct and indirect impacts of human activities. Target II and III have now been switched. See introduction, paragraph 5, page 4, lines 107-109 (in red).

c)line 109- types7:typo corrected. See introduction, paragraph 5, page 4, lines 108 (in red).

Comment 9: Study area:
Some more detail about the ponds (range of surface areas, depths, volumes, biota parameters catchment, springs, rivers, geology etc') should be provided.
Thus(a) some more detail - and I refer to data already presented in Table 1 is required so the reader "gets acquainted" with this set of ponds. By the way- all ponds exist throughout the year (i.e., wet?), or some dry out?
(b) even if you set the reader to read details in table 1 - you should provide something here in the text
Response 9: We have now provided more background information in the text. See

study area, paragraph 1, page 5, lines 126-139 (in red).

Comment 10: Same goes for information relevant here collected by others (literature)- especially in the context of temporal (seasonal- annual) variance and where your measurement fall within this known variance. No previous data? Nobody monitored these ponds ever?
Response 10: We understand the relevance of this comment by the reviewer. Although there was more generic literature on pond water quality in the Auckland region, unfortunately, there is no existing data on the ponds used as part of our study.

Comment 11: Conductivity, TDS and salinity… Salinity? Did the authors measure salinity in a manner different than EC and TDS? Cl? Not mentioned here. Requires clarification.
Response 11: We agree with the reviewer. Conductivity, TDS and salinity are often interdependent but yes, we measured salinity in a manner different from EC. Details of Cl have been provided. See data collection, paragraph 2, page 6, lines 154-155 (in red).

Comment 12: Line 140: "The 10m and 100m and catchment scales were selected following Novikmec et al. (2016) and Declerck et al. (2006), where the importance of these scales on pond water quality were highlighted." As in line 92. Such a statement should be explained, the context of the Novikmec et al. (2016) and Declerck et al. (2006) research should be clarified. It is not sufficient to just use following X et al..
Response 12: We have provided further explanation is provided as suggested. See data collection paragraph 3, page 6, lines 116-117 (in red).

Comment 13: Line 181: pRDA: does that stand for partial RDA? The authors should use in such cases (e.g., partial RDA (pRDA)).
Response 13: We have revised as suggested. See data analysis paragraph 2, page 7, lines 208 (in red).

Comment 14: Line 235: "Nevertheless, variables like conductivity and TDS are mostly governed by the LULC at broader spatial scales like the catchment scale (Jayawardana et al. 2017; Olson and Hawkins 2017)."
a) I am not what the authors mean by this sentence. Is this a general statement about these parameters in ponds/ aquatic systems? (if so, is this the place or should such statement be in the Introduction?) How does it relate to the set of ponds and measurements in this current study? Is this what the authors see in their dataset? b) like other sentences /statement I have remarked on above: it is not sufficient to provide a statement such as this and a ref. Some explanation is required.
Response 14: We agree with the reviewer. The sentence has been moved to the introduction and revisions have been made in the discussion to emphasis our findings. We found TDS and conductivity to be governed by LULC at 500m scale in summer. See introduction, paragraph 2, page 5, lines 88-91 (in red) and discussion paragraph 2, page 10, lines 282 and 287288 (in red) .

Comment 15: Line 239: "The correlations we detected among the TDS, conductivity and salinity indicates that these variables are interdependent (Tyagi et al. 2020)."
a) I am not sure what the authors mean here. "The correlations we detected among…" and then parameters: what is correlated with what? Variables are independent? So, what is not-correlated with what? I wonder (following Data analysis section) if the authors meant that correlation between each of these parameters was examined. If so I think the phrase correlation we detected" is a bit misleading.
b) Tyagi et al. 2020. Why is this cited? Are the results in the current similar to Tyagi? Or similar method? And if either is true, why is it important? Not clear
Response 15: We agree with the reviewer. The sentence is misleading and the findings are covered elsewhere, and has now been deleted.

Comment 16: Line 242: opposing effect? Is opposing the right word here?
Do the authors mean that during some seasons N-P concentrations are lowered? If so, other seasons are associated with higher concentrations. Seasonality is a repeating circular feature… Consider rephrasing the entire sentence.
Response 16: The sentence has been revised for clarity. See discussion paragraph 3, page 10, lines 282 and 289-292 (in red).

Comment 17: Line 248: "The high concentration of ammoniacal nitrogen…" what about NO3? This should be mentioned and discussed here with reference to ammonium. "…observed in our study in winter. 249 may be due to this leaching process…", this is ok, but again what about NO3?
Response 17: We agree with the reviewer. Our findings for nitrates have been provided. See discussion paragraph 3, page 10, lines 302 -305 (in red).

Comment 18: Line 250: "Contrary to ammoniacal nitrogen, we found that levels of phosphates were higher in summer. As the authors suggested a mechanism for ammonium, it would be beneficial to suggest something here regarding elevation of phosphates…
Responses 18: We agree with the reviewer we have added a suggestion for elevated phospahtes in paragraph 3, page 10, lines 294-302.

Comment 19: Line 251: Citing research from other locations is good- however do the authors claim that in aquatic systems worldwide summer is always associated with high P levels? - associated with high P loads? If other research cases are cited- it is advisable to develop a discussion comparing the situation in the current research area/ set vs. those studies. For example, Carpenter et al. 2018 discuss P loads from agricultural fields (by the way - doing so for extreme precipitation). The authors should discuss here how similar/ dis-similar the situation in the set of ponds is in comparison with these other study areas.
Responses 19: We agree with the reviewer and have expanded the discussion to included similarities and dissimilarities with other studies. See discussion paragraph 3, page 10, lines 282 and 292-302 (in red).

Comment 20: a) The authors are directed to a statement they cite from Novikmec et al. 2016 (see line 269). This statement should be used in an introduction part of the discussion…
b) following (a), the use here of the term "corroborates" and in other places similar terms on the same line (e.g., supports in line 266), is not adequate, unless the authors claim that their observations from Auckland ponds and other case studies in various aquatic systems point to a general trend (e.g., that P always rises in summer, see remark on line 251). And even if that is the case, caution should be preferred…So: I suggest using more terms like "our results are similar to"…
Responses 20: We agree with the reviewer. The sentence has been revised for clarity. Sentence moved Suggestions accepted and edits made. See discussion paragraph 4, page 10, lines 306-307 (in red).

Comment 21: Line 254: "After accounting for the effect of physical features, our results show that LULC at the catchment scale and the 500m significantly determine the water quality of ponds in winter.
a) The sentence is not clear enough. Do the authors mean that 500m and larger scales (i.e., catchment) are also significant (i.e., that smaller scales are important, but also larger scales)?
Or do the authors mean that only the larger scales are significant.
b) what is the meaning of the beginning of the sentence: "After accounting for the effect of physical features…?"
Response 21: We have revised to make this clearer; yes, only larger scales are significant. See discussion paragraph 4, page 10, lines 318-322 (in red).

Comment 22: Line 271: change to "…contrary to original hypothesis."
Response 22: Changed. See discussion paragraph 4, page 10, lines 326 (in red).
Comment 23: Line 278: these sentences belong to an introduction to the discussion that should be added.
Response 23: we are not clear of what the reviewer meant. The sentence has been maintained because it explains the unexplained variance in our models see page 11, lines 337-340 .

REVIEWER 2
We thank the reviewer for their keen interest in our manuscript and positive views. Their meaningful and thorough comments and suggestions have been taken into

consideration and have been applied where appropriate improve this paper.

Comment 1: Please add the statistical method applied that you used to draw your conclusions
Response 1: We have added more details, and a correction has been made with regards to the analysis. Please see data analysis section line 189, 204, 207-210, 212 (in blue)

Comment 2: I suggest writing "… between the ratio of land use and land cover (LULC) and …."
Response 2: We agree with the reviewer. This has now been better explained. Please see reviewer 1, response 5.

Comment 3: L18: delete "where there is a need"
Response 3: We agree with the reviewer. The "where there is a need" has been deleted. Sentence moved See abstract, page 2, lines 18 (in blue).

Comment 4: L20: how do you assess 50 ponds? I suggest writing: In this study, we measured i) seasonal differences in water quality and ii) the impact of the surrounding landscape at multiple spatial scales (10m, 100m, 500m and full catchment) on water quality of 50 ponds in the Auckland region, New Zealand
Response 4: We agree with the reviewer. The sentence has been revised for clarity. Sentence moved See abstract, page 2, lines 19-22 (in blue).

Comment 5: L22: please write "at four spatial scales" instead of "multiple"
Response 5: The sentence has been revised. Sentence moved See abstract, page 2, lines 21 (in blue).

Comment 6: L23: please write: For each pond,
Response 6: The sentence has been revised. See abstract, page 2, lines 21 (in blue).

Comment 7: L26: please write total dissolved solids (TDS), percentage of oxygen saturation (% DO),… and phosphates concentrations in summer
Response 7: These corrections have been made. See abstract, page 2, lines 25-27 (in blue).
Comment 8: L30: "different pattern" is difficult to understand, please rephrase.
Response 8: We have rephrased. See abstract, page 2, lines 30-32 (in blue).

Comment 9: L32: please write: "only in summer"
Response 9: Done. See abstract, page 2, lines 33 (in blue).

Comment 10: L33: please write: "Overall, variations in water quality are better explained by general landscape characteristics than by LULC alone at the catchment …"
Response 10: The sentence has been revised. See abstract, page 2, lines 33 (in blue).

Comment 11: L38: delete the point
Response 11: Done

Introduction
Comment 12: L42: please write land use/land cover (LULC)
Response 12: Done. See introduction, page 2, lines 42-43 (in blue).

Comment 13: L46: please write: "influencing freshwater ecosystem state"
Response 13: Done. See introduction, page 2, lines 46 (in blue)

Comment 14: L46: please write: "However, the effect of other stressors, including…"
Response 14: Done. See introduction, page 3, lines 46-48 (in blue).

Comment 15: L60: please write: "Anthropogenic activities occurring in catchments, are associated
directly or indirectly with major inputs of nonpoint pollutants such as nitrogen and phosphorus into ponds (Tu 2011; Nielsen et al. 2012; Nobre et al. 2020)."
Response 15: Corrected. See introduction, page 3, lines 60-60 (in blue).

Comment 16: L69: what do you want to express with "Rapid urbanization with LULC"? please, prephrase
Response 16: We agree the sentence has now been rephrased. See introduction, page 3, lines 66-67 (in blue).

Comment 17: L73: just write: "known to affect freshwater quality and impact biodiversity…"
Response 17: The sentence has been revised as suggested. See introduction, page 3, lines 70-71 (in blue).

Comment 18: L83: just write "according to season"
Response 18: Done. See introduction, page 3, line 79 (in blue).

Comment 19: L100: please write: "effects operate, and predicting"
Response 19: Done. See introduction, page 4, line 100 (in blue).

Comment 20: L106: please write: "quality in a pond ecosystem"
Response 20: Done. See introduction, page 4, lines 104 (in blue).

Comment 21: L109: either delete "7" or move it to the right place
Response 21: 7 has been deleted. See introduction, page 4, lines 109 (in red).

Comment 22: L111: please give background information why you expect that summer water quality will be poorer than winter one; finally, explain your expectations in more detail (for iii; iv is easier to understand)
Response 22: Additional explanation has been added. High evaporation/ low precipitation rate during summer will lead the lower water quality. See introduction, page 4, lines 110-111 (in blue).

Methods
Comment 23: L486+487: just write: "Summary of…"
Response 23: We agree with the reviewer. The title has been revised. See page 18, lines 559-560 (in blue).

Comment 24: L490: please write: "Map of …. the location of ….
Response 24: Done. See page 18, lines 563 (in blue).

Comment 25: L491: please write: "Variance explained ……. models for a) summer and b) winter."
Response 25: the figure has now been deleted as suggested by reviewer in comment 43

Comment 26: Table 2: what is t?
Response 26: We have added the definition for t (t-value). See table 2 (in blue).

Comment 27: Table 3: please report first the results of the full RDA and then that of the partial RDA; adjusted R2 values < 0 should not be reported at all
Response 27: The values of the tables (R2, adjusted R2 and p-values for each model and season has been added to the graphical output of the model. See Figure 2 and 3, lines 564-567 (in blue).

Comment 28: Figure 1: the legend of figure 1 is more detail rich than that of the legend per se
Response 28: We think the details in the title are necessary for interpreting the data.

Comment 29: Figure 2: the legend of figure 2 is more detail rich than that of the legend per se and I can not read what is written on figure 2
Response 29: As suggested,The figure has been removed and replaced with RDA plots for summer as suggested in comment 43 by the reviewer. See figure 2 and figure 3, page 18, line 564-567 (in blue)

Comment 30: L146: I suggest deleting the whole sentence "Table 1 summarizes and provides a description of the landscape …. " and to write "The LULC were

	1categorized as grass, forest or urban (Table 1; impervious surface). Response 30: Changed as suggested. See data collection, page 6, lines 170-171 (in blue). Comment 31: L151: spatial analyst Response 31: Done. page 6, lines 175 (in blue). Comment 32: L178: please write redundancy analysis (RDA) Response 19: Done. See introduction, page 4, lines 100 (in blue). Comment 32: L181: please write "partial RDA (p-RDA)" Response 32: Done. See data anlalysis, page 7, lines 204 (in blue). Comment 33: L181: I do not understand why plural for pRDA when you only tested the importance of LULC? Is this just a typo or did you forget to write something? Furthermore, please consider that a partial RDA seeks to remove the effect of one or more explanatory variables on a set of response variables prior to a standard RDA. You could adopt this writing to better explain what a pRDA does Response 33: This was a typo and has been corrected, page 7, lines 208 (in red) and 209-210 (in blue). Comment 34: L184: for correct R citation you have to state the R version you used and cite it (e.g. R version 4.0.2; R core team 2020) Response 34: Corrected. See data analysis, page 7, lines 211-212 (in blue). Results Comment 35: L189-190: something is wrong here: Table 2 reports the t-tests but writing about distances relates to PERMANOVA; thus, please rephrase Response 35: This was an error. The sentence has been corrected and information has been added about the t-test. See results, page 8, lines 215-219 (in blue). Comment 36: L194: I suggest writing "correlation of LULC at multiple spatial scales with water quality variables" because correlation is not causation Response 36: The sentence has been revised as suggested. See results, page 8, lines 223 (in blue). Comment 37: L197: one) too much Response 37: Deleted Comment 38: L198: just write: "Urban cover was also positively correlated to %DO (ρ = -0.4, $p < 0.05$)." Supplementary table 1: by doing so many corelations you are running in the multiple comparison problem (taken from Wikipedi: In statistics, the multiple comparisons, multiplicity or multiple testing problem occurs when one considers a set of statistical inferences simultaneously[1] or infers a subset of parameters selected based on the observed values.[2] In certain fields it is known as the look-elsewhere effect. The more inferences are made, the more likely erroneous inferences become. Several statistical techniques have been developed to address that problem, typically by requiring a stricter significance threshold for individual comparisons, so as to compensate for the number of inferences being made. Thus, you should correct the p-values for multiple testing (Bonferroni or Holm correction) and this will make small correlations with large p-values even bigger and non-significant; I do not think that this invalidates your conclusions because correlations found are already weak. In any case, correct the p-values for multiple testing (you have 4*3*9*2 correlations) Response 38: The section and table have been revised after applying Bonfonerri corrections to the p-value as suggested by reviewer. See results, page 8, lines 225-230 (in blue). Comment 39: L203: just write "relationships between…" Response 39: Revised. See results, page 8, lines 232 (in blue).

	Comment 40: L205-208: please rewrite both sentences following this structure: the LULC and physical parameters at the 10m, 100m and catchment scale significantly explained the variation …. Response 40: The sentences have been revised as suggested. See results, page 8, lines 234-238 (in blue). Comment 41: L213: start with a new paragraph because this is a new type of analysis I missed the results o the multiple linear regression and guess that they are hidden in L205-2013; In any case, please provide a table for MLR with the detailed results because this would be easier to understand (it would show p-values, coefficients, predictors and dependent variables) Response 41: Revised as suggested. The results of the MLR are provided in Table 3. Information of the significant predictors of the best models have been given. The table shows p-values and adjusted p-values. Details of the best models and best predictors are provided in the results pages 240-253 and Table 3, page 18, lines 560-562 (in blue) Comment 42: L213-2015: please provide more details on your results of the RDA and the pRDA (e.g. 100m scale had highest R2) Response 42: We agree with the reviewer. More details have been provided (e.g. The model at the 10m scale had the highest variance (R2 = 0.34) in summer, while the model at catchment area scale had the highest variance (R2 = 0.26) in winter. See page 9, lines 254-263 (in blue). Comment 43: Parts of Table 3 are equivalent to Figure 3 and I suggest deleting the present Figure 3 and present a new one: The RDA output (it is quite strange to perform the RDA without showing the graphical output); generally for the RDA, variability explained by the whole model and by the first two axes is reported; in summary, please provide more details on your RDA (figure and text); by the way, was your RDA like this: your physicochemical variables dependent on LULC? If yes, please describe this in more detail in the method section, if no, describe in more detail what you did. Response 43: We agree with the reviewer. The first figure 3 in the first manuscript submitted has been deleted and replaced with the graphical output of the RDA. Figures 2 (for summer) and figure 3 (for winter). See page 18, lines 564-567 (in blue). More details of RDA has been provided. See data analysis, page 7 line 208 (in blue) and results, page 9, lines 254-263 (in blue) Discussion Comment 44: L221: delete (Response 44: Deleted. See discussion, page 9, lines 269 (in blue). Comment 45: L222: "The spatial variations of the key variables we chose to measure can be related to temporal heterogeneity in catchment characteristics" -> this is a fully enigmatic sentence to me: which spatial variables? Please name them; do you mean seasonal heterogeneity because related to summer versus winter? Please, be more specific Response 45: The sentence has been revised for clarity. See discussion, page 9, lines 270-271 (in blue). Comment 46: L224: spatial characteristics in pond? What is the spatial characteristic of a pond? I guess you mean the consideration of different spatial scales of the catchment; in any case, please rephrase to provide a clearer understanding Response 46: Rephrased to be clearer. See discussion, page 9, lines 272-273 (in blue). Comment 47: L227: during summer Response 47: Corrected. See discussion, page 9, line 274 (in blue). Comment 48: L229: what about photosynthesis as contributor to high pH? Response 48: We agree with the reviewer. Yes photosynthesis influences pH. The sentence has been revised to include how photosynthesis influence pH. Discussion, page 9, lines 275-277 (in blue). Comment 49: L227: "leads to increased degradation of organic substances"; please

provide more background information on this by naming the underlying processes (photobleaching? microbial degradation?)
Response 49: More background has been included e.g. photoxidation, photobleaching. See discussion, page 9 and 10, lines 276-277 (in blue).

Comment 51: L239-241 are about the correlation analysis that is more or less not significant and should accordingly be discussed; furthermore, where can I see that TDS, conductivity and salinity indicates that these variables are interdependent?
Response 51: We apologise for the confusion. The sentence is misleading and the findings are covered elsewhere, and has now been deleted. The data was not analysed to reflect this in the results.

Comment 52: L254: because these results are not based on experiments but on data analysis, please write results indicated (please remember that when referring to your study to use past tense and when referring to the studies of others you use present tense)
Response 52: Corrected here page 11, lines 318-319 (in red), and throughout the MS

Comment 53: L254-256: I am not convinced that your results indicated that LULC significantly determined water quality because in the multiple regression analysis the R2 is missing (or at least I did not find it); while I think the discussion you present is reasonable, it is not well founded on your main results (RDA, MLR) that are not well presented
Response 53: Details of MLR models and RDA has been provided, the R2 has been provided in Table 3 for the MLR and in figure 2 & 3 for the RDA. The predictors of the best models has also been stated. See table 3, figure 2 and 3 and results 'Relationships between the physical, LULC and physicochemical variables at multiple scales' and page 11, lines 240-263 (in blue) and page 18, lines 560-567.

Comment 54: L271: change "my" to "our"
Response 54: Corrected. See discussion, page 11, lines 326 (in blue).

Comment 55: L278: regarding unaccounted factors, what about algal blooms, cyanobacteria, trophic state, fish presence…that can all affect water chemistry? The fact that you try to explain water chemistry by an extrinsic factor (out of the lake) is interesting but you should not neglect the in-lake biology
Response 55: Although the factors mentioned can and do effect water chemistry, they were beyond the scope of our study. We have now mentioned fish presence and algal biomass in our discussion as potential factors for further investigation. See discussion, page 11, lines 338-339 (in blue).

Comment 56: L286-292: can be integrated with 274-275
Response 56: We do not agree with the reviewer. The sentences in these two sections provide information relevant to other parts of the discussion, for example, lines, 349-352 would loose context.

Comment 57: L293-307: these correlation-based result has to be re-considered under the light of multiple testing
Response 57: We have added a correction factor for multiple testing, and the section has been revised. See discussion, page 12, lines 353-366 (in blue).

Comment 58: L297: where is this result? Supplementary Table 1 is the Spearman's rank correlations between physicochemical variables and LULC but not between the physicochemical variables
Response 58: We agree with the reviewer. There was an error in the sentence. The sentence has been removed. Yes supplementary Table 1 is the Spearman's rank correlations between physicochemical variables and LULC but not between the physicochemical variables.

The influence of season and landscape on the water quality of ponds at multiple spatial scales

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The influence of season and landscape on the water quality of ponds at multiple spatial scales

Understanding the spatial relationships between Land Use/Land Cover (LULC) and physicochemical water quality in pond ecosystems is vital to the conservation and management of ponds. This knowledge is especially critical to reconcile landscape planning and management with wildlife conservation, particularly in urban regions with rapid population growth. In this study, we measured i) seasonal differences in water quality and ii) the impact of the surrounding landscape at four spatial scales (10m, 100m, 500m and full catchment) on water quality of 50 ponds in the Auckland region, New Zealand. For each pond, seven physicochemical water quality variables and nine landscape properties (LULC and physical features of the pond) were measured in winter and summer. We found significantly higher measures of conductivity, total dissolved solids (TDS), percentage of dissolved oxygen (%DO), pH, salinity, and phosphates concentrations in summer. In contrast, ammoniacal nitrogen concentration was higher in winter. These findings are indicative of poorer water quality during summer. Multiple linear regression and redundancy analyzes showed that LULC and physical landscape features had different influences on the physiochemical variables across the different spatial scales and seasons. The landscape properties at all four spatial scales were good predictors of pond temperature, and %DO only in summer. Overall, variations in pond water quality were explained better by general landscape characteristics than by the LULC alone, at the catchment and 500m scale in winter and at the 100m scale in summer. This study highlights the importance of including different spatial scales, seasons, and landscape use when quantifying land-water interactions.

Keywords: land use, land cover; ponds; water quality; landscape properties; urban; Auckland

Introduction

Since the 1970s, researchers have explored the effects of land use/land cover (LULC) on freshwater quality (Rimer et al. 1978; Osborne and Wiley 1988; Shen et al. 2015; Zhang et al. 2018). A strong negative relationship between anthropogenic LULC and water quality has largely been reported and thus widely considered a primary stressor influencing freshwater ecosystem state. However, the effect of other stressors, including climate, geology and landscape features that contribute to altered conditions, cannot be ruled out (Bhat et al. 2020).

Ponds are the most dominant freshwater habitats and support more uncommon biodiversity than other freshwater ecosystems at a regional scale (Oertli 2018; Jooste et al. 2020; Lévesque et al. 2020). They have significant aesthetic, ecological, geochemical, cultural, and economic value (Wood et al. 2003; Hassall 2014; Mueller et al. 2016). Due to their small size and hence small water volume, ponds are sensitive to changes in LULC, mostly resulting from anthropogenic stressors. Stressors linked with anthropogenic LULC usually include decreased vegetation cover, increased impervious surfaces, soil erosion, contaminants and nutrient flux, all of which modify pond ecosystems' integrity (Brabec et al. 2002; Vander Laan et al. 2013; Anim et al. 2019). These stressors result in increased transfer of nutrients from surrounding catchments into the ponds (Declerck et al. 2006; Nielsen et al. 2012; Epele et al. 2018; Nobre et al. 2020). Anthropogenic activities occurring in catchments are associated directly or indirectly with major nonpoint pollutants such as nitrogen and phosphorus into ponds (Tu 2011; Nielsen et al. 2012; Nobre et al. 2020). These pollutants affect the pond ecosystems by altering the physicochemical characteristics and ecological health through eutrophication, which impacts the biota living in them.

Auckland is the most populated region of New Zealand, with its population concentrated in urban areas (Stats NZ 2020). Rapid urbanization resulting in LULC changes has been observed in the last decade (Larned et al. 2016; Gadd et al. 2020). These recent changes have resulted in increased impervious surfaces (e.g., roads, parking lots, and rooftops) and reduced forested and vegetated lands in these urban catchments of Auckland. These significant changes affect freshwater quality and impact biodiversity (Council 2005; Baillie and Neary 2015). While drinking water standards in Auckland are high, many urban freshwater systems are reported to be polluted and exhibit signs of ecological degradation (Larned et al. 2016; Larned et al. 2020).

Despite the relationship between LULC and water quality, linkages between one specific LULC type and different water quality variables are still controversial due to the differences in the study areas (Liu et al. 2018). These relationships are not consistent but vary geographically and with spatial scales (Declerck et al. 2006; Nielsen et al. 2012; Novikmec et al. 2016). Furthermore, studies have found that the influence of land cover for specific water quality measurements changes according to season (Buck et al.

2004; Pratt and Chang 2012). Pollutants and nutrients are transported from different landscapes, within the catchment areas, into aquatic systems through stormwater runoff from precipitation (Atique and An 2020). Hence, variability in precipitation between seasons influences surface runoff patterns, groundwater flow and outflows in and from aquatic and terrestrial ecosystems. The dynamics of this occurrence substantially impact pollutant concentrations, discharge, and storage (Chowdhury and Husain 2020).

Landscape-scale approaches are useful for exploring fundamental ecological patterns across a region and improving our knowledge about the influence of the surrounding landscape on the aquatic ecosystem (Epele et al. 2018). For example, variables like conductivity and TDS are governed mainly by the LULC at broader spatial scales like the catchment scale (Jayawardana et al. 2017; Olson and Hawkins 2017). By studying small, isolated water bodies (ponds), it is possible to quantify the spatial variation and the primary effect of LULC across broad regional scales (Epele et al. 2018). This quantification is feasible because of the large number of ponds that can be sampled within local and regional scales. Moreover, because human activities differ in intensity in different areas, water quality degradation might be spatially heterogeneous and seasonally confounded (Buck et al. 2004; Chen et al. 2016). There is a limited understanding of the spatio-temporal variation in water quality variables, and this imparts additional challenges in protecting water quality from degradation (Greig and Galatowitsch 2016; Epele et al. 2018). It is still unclear at what spatial scale LULC effects operate, and predicting these effects can be challenging (Ramião et al. 2020). Understanding the role of spatial scales in the relationship between landscape patterns and water quality in aquatic ecosystems is vital in protecting and improving water quality. This knowledge is required to plan, monitor, and manage landscape patterns (Zhang Y et al. 2019; Xu et al. 2020). This study evaluates the spatially varying relationships between LULC and physicochemical water quality in the pond ecosystem. Specifically, we aimed to i) determine if there are seasonal differences in the water quality in a pond ecosystem, ii) determine the relationships between different LULC types and the water quality variables at four spatial scales, and iii) identify the influence of season on the relationships between LULC and water quality. We hypothesized that i) water quality will be different between seasons. The difference is expected due to variation in the amount of precipitation and temperature associated with each season. High and frequent precipitation will increase the amount of runoff and dilute the water in the ponds. ii) water quality in summer will be poorer than in winter due to high evaporation rate. An increase in evaporation will lead to higher concentrations of ions in the water. iii) winter will have a greater influence on the relationship between water quality and LULC. Winter is associated with high precipitation; therefore, the ponds are likely to receive higher runoff with high ion concentrations from the landscape. iv) LULC at the catchment area will be the most important influencer of the water quality in ponds. The highest amount of runoff into the ponds comes from the catchment; hence any LULC type within the catchment area will have a greater influence on pond water quality.

Methods

Study area

The study was carried out in the Auckland region, located in the upper North Island of New Zealand. Auckland is located on latitude -36.848461 and longitude 174.763336. The Auckland region covers 5600km^2, representing two percent of the total area of New Zealand. The landmass of Auckland spans from the Awhitu peninsula in the south to the Te Ara dunes in the North. Auckland has a temperate climate, with humid and warm summers and mild and damp winters (Council 2015). Auckland has an average elevation of 42m and a maximum elevation of 459m above sea level (Gradwell 1971). The landform in Auckland consists of mountains, dunes, and rocks with volcanic cones. The geology in the region is dominated by sedimentary rocks made of sandstone and mudstone. The soil is predominantly loamy, formed from volcanic ash and lava. However, this rich soil has been podzolized by acid litter from kauri and other plants (Gradwell 1971; McClure 2016). Auckland is the most populated New Zealand region, with its population concentrated in urban areas (Stats NZ 2020). Fifty perennial ponds of varying sizes (22.7m^2 - 6957.2m^2) located in various landscapes were sampled (Table 1, Figure 1).

Data collection

The physicochemical, physical, and LULC data were collected from the ponds once during the summer (December to February) and winter (June to August) of 2017. The physicochemical water quality variables measured included pH, conductivity, temperature, TDS, %DO, salinity, phosphate (PO_4^{3-}), ammoniacal nitrogen (NH_3-H) and nitrate (NO_3-N). The physical parameters measured were pond area, rainfall, altitude, percentage slope and percentage macrophyte cover.

At each pond site, physicochemical variables were measured, and nutrient tests were carried out simultaneously (11:00 am - 2:00 pm New Zealand Standard Time) and recorded. The pH, conductivity, temperature, TDS, %DO, and salinity were measured with a calibrated Hanna multiparameter probe (Model H198194). The margin of error or sensitivity for the physicochemical variables of the Hanna probe were temperature, ± 0.15°C, pH ± 0.02, % DO ± 1.5%, conductivity ± 1µscm^{-1}, TDS ± 1ppm and salinity, PSU ± 0.01. The probe was left in the water column for five minutes to adjust to the conditions in the pond before readings were recorded. The concentrations of PO_4^{3-}, NH_3-H, and NO_3-N were measured with the HACH nutrient test kits (DR 200) after the accuracy of the test kit was validated with standard nutrients in the lab. The limits of detection (LOD) of these nutrient tests were PO_4^{3-} : 0.02-2.50mgl^{-1}, NH_3-H: 0.02-2.50mgl^{-1} and NO_3-N: 0.01-0.50mgl^{-1}.

LULC was estimated at four spatial scales: i) 10m immediately surrounding the pond representing the helophyte belt, ii) 100m radius from the center of the pond, iii) 500m radius from the center of the pond and, iv) the catchment area. The 10m and 100m and catchment scales were selected following the rationale of Novikmec et al. (2016) and Declerck et al. (2006), where the importance of LULC at these spatial scales on pond water quality were highlighted. The 10m and 100m represent the buffer zones of the ponds.

The LULC data were analyzed at 1:1000, at 30m resolution by measuring the area covered by each LULC type from aerial maps obtained from Geomaps from the Auckland Council (Council 2018). The LULC were categorized as grass, forest or urban (impervious surface) (Table 1). The area of some of the ponds identified on the Auckland Council shapefiles was obtained from the attributes table in ArcGIS version 10.4 (ESRI 2016). The catchment area was evaluated using GIS tools on a Digital Elevation Model (DEM) with a resolution of 80m obtained from Land Information New Zealand (LINZ) using the spatial analyst extension in ArcGIS 10.7.1 (ESRI 2019). The physical parameters measured were altitude, percentage slope and rainfall and percentage macrophyte cover per sampling period. The altitudes of the ponds were obtained from an aerial base map from the Auckland council Geomaps. The percentage slope was derived from the slope map calculated from the DEM. Percentage macrophyte cover of the ponds was visually estimated from the pond site relative to the total surface area of each pond at the time of sampling.

Data Analysis

The seasonal variation in the physicochemical water quality variables was compared using a Student's t-test. A permutational multivariate analysis of variance (PERMAVOVA) test was performed to test for differences in the water quality between the seasons. The correlations between percentage cover of each LULC type and water quality at different spatial scales were analyzed using Spearman's rank correlation. The p-values of the correlations were applied using Bonfonerri corrections. The relationships between water quality variables, physical parameters and LULC patterns were explored with a multivariate approach using multiple linear regression (MLR) modelling and redundancy analysis (RDA). The water quality data were transformed as Log (x + 1) and normalized for the RDA and the MLR (Ding et al. 2016). The physical parameters were also normalized. The MLR model was applied to evaluate the relationships between a response (i.e., a single water quality variable) and a single scale of LULC type in the presence of the physical parameters (predictors, i.e., percentage macrophyte cover, altitude, rainfall, catchment area, pond area, percentage slope). The forecasting ability of the MLR model was measured by the adjusted coefficient (adjusted R^2) (Xu et al., 2020). The best model for each physicochemical variable was defined as the 'objective' MLR model and was chosen in a stepwise MLR analysis based on: (i) the adjusted R^2 value of the model is the highest among all models, i.e., among all scales and (ii) the significance of the coefficients of the model and predictors (β) are equal to or less than 0.05 (Ding et al. 2016).

Redundancy analysis (RDA) was used to explore the relationships between LULC, water quality and physical factors at each spatial scale and explain the variation in water quality by landscape features (Ding et al. 2016; Shi et al. 2017; Song et al. 2020). The full RDA simultaneously examined the impacts of multiple LULC and physical parameters on water quality (dependent variable) (Zhang et al. 2019). Partial RDA (p-RDA) were performed to examine the effect of LULC alone on the water quality removing the effect of physical variables. The analyses were done using PERMANOVA + (version 7.0.13) software extension (Clarke and Gorley 2006), R version 3.6. 1: (R Core Team 2019), and SPSS (version 25) software (IBM 2017).

Results

Seasonal variations in the physicochemical water quality variables

There were seasonal differences in levels of the physicochemical variables measured. In particular, the pH ($t = 2.36$, $p = 0.02$) of the water and phosphate concentrations ($t = 3.97$, $p < 0.001$) were significantly higher in summer than in winter (Table 2). Overall, we found more variation in water quality in the ponds in summer (distance among ponds in summer = 3.74, winter = 3.58). A multivariate PERMANOVA analysis indicated a significant seasonal difference in the physicochemical water quality variables ($F_{1, 98} = 17.11$, $p < 0.001$).

Correlation of LULC at multiple spatial scales with water quality variables

Generally, there was a weak correlation between the physicochemical variables and the three LULC types. In summer, at the 500m scale, the percentage of grass cover was negatively correlated with temperature ($\rho = -0.4$), and urban cover was positively correlated with %DO ($\rho = 0.4$). However, in winter, urban cover at the 500m and catchment scales were significantly positively correlated with pH ($\rho = 0.4$, $p = 0.04$). Urban cover at catchment scale was negatively correlated with NH_3-H ($\rho = -0.5$, $p = 0.05$) (Supplementary Table 1).

Relationships between the physical, LULC and physicochemical variables at multiple scales

In summer, the LULC and physical parameters at the 10m, 100m and catchment scale significantly explained the variation in pH levels of the ponds. The LULC and physical parameters at all four spatial scales (10m, 100m, 500m, and catchment) significantly explained the variation in %DO and temperature. LULC and physical parameters at 10m and 500m explained the variation in TDS. LULC and physical parameters at 10m and 500m explained the variation in salinity and conductivity, respectively (Table 3).

The predictability (β) of water quality variables differed with scale and seasons (Table 3). In summer pH, and %DO provided the best model at catchment scales. The key predictors for pH were pond area ($\beta = 0.49$), catchment area ($\beta = -0.30$) and urban cover ($\beta = 0.28$). Key predictors of %DO were pond area ($\beta = 0.35$), rainfall ($\beta = 0.31$) and macrophyte cover ($\beta = -0.34$). The best model for temperature, conductivity and

TDS was at 500m. The key predictors of temperature were macrophyte cover (β = -0.43), pond area (β = 0.39), and forest cover (β = 0.31). The key predictor for conductivity was urban cover (β = 0.32) and for TDS were rainfall (-0.34) and urban cover (β = 0.32).

In winter, LULC and physical features at the 100m and 500m scale explained the variation in %DO. The LULC and physical parameters at 100m explained the variation in salinity levels. The best model for %DO was at 500m, and the key predictor was rainfall (β = 0.48). The best model for salinity was at 100m, and the best predictor was rainfall (β = -0.34).

The full RDA models explained between 29% and 34% of the variation in water quality in summer at all four spatial scales, but less variation (between 16% and 26%) was accounted for in winter. The model at the 10m scale had the highest variance (R^2 = 0.34) in summer, while the model at catchment area scale had the highest variance (R^2 = 0.26) in winter. The partial RDA models explained a maximum of 10% and 12% of the variation in water quality at all four spatial scales in summer and winter, respectively (Figure 2). In the full models, phosphate levels were positively associated with rainfall in summer but negatively associated in winter. Percentage macrophyte cover was negatively associated with temperature in summer but positively associated in winter at all four spatial scales (Figure 2 and Figure 3).

Discussion

The quality of water in a freshwater ecosystem is critical for aquatic ecosystem resilience, governing ecological quality, particularly the health of the biotic community. Our results show significant seasonal variation in the physicochemical variables comparable to previous studies (e.g. Zhang et al. 2019; Ray et al. 2020; Xu et al. 2020). The spatio-temporal variation of the water quality variables can be associated with the spatial and temporal dissimilarities in catchment characteristics (Pratt and Chang 2012). These findings are indicative of the importance of considering the seasonal and different spatial characteristics of LULC on pond ecosystems. Temperatures are higher in summer because of longer photoperiods and higher sun intensity compared to winter. Increase in temperatures during summer leads to increased photosynthesis and increased degradation of organic substances. (e.g. microbial degradation) through photooxidation, photodegradation and the subsequent excessive release of ions into water bodies (Carey

2005; Ray et al. 2020). These processes contributed to the high pH recorded in summer. In contrast, lower pH in winter is likely due to high precipitation diluting the effect of alkaline materials in the water (Tyagi et al. 2020) and an overall dilution of the concentration of chemicals in the pond (Ray et al. 2020).

We found rainfall to predict salinity and TDS levels in summer. High evaporation and low precipitation in summer resulted in a reduction in the water volume, leading to an increase in the salt concentration of the water, possibly contributing to the high TDS, salinity and conductivity levels in the ponds in summer. The concentration of TDS may also reflect anthropogenic impacts on the ecosystem (Pratt and Chang 2012; Olson and Hawkins 2017; Omoigberale et al. 2020). Our results suggest that urban cover is positively associated with conductivity levels.

Secondly, reduction in water volume leads to enhanced concentration of nutrients (Carey 2005; Nobre et al. 2020). In contrast, during winter, high precipitation and low evaporation increase runoff and leaching of nutrients from the ground into soils and aquatic ecosystems (Malcolm et al. 2018). The high concentration of ammoniacal nitrogen observed in our study in winter may be due to this leaching process (Larned et al. 2016; Shi et al. 2017; Malcolm et al. 2018). Contrary to ammoniacal nitrogen, we found that levels of phosphates were higher in summer. High photosynthesis rate during summer leads to an increase in pH. Increase in pH negatively affects phosphates' binding to sediments, resulting in the release of phosphates in the water (Søndergaard 2007). Our results are similar to Carpenter et al. (2018) and Zhang et al. (2019), who also reported high phosphorus levels in summer in watersheds within agricultural fields in the United States of America, and reservoirs in China, respectively. Carpenter et al. (2018) and Zhang et al. (2019) found a positive association between agriculture and urban land cover with phosphate levels in summer. The concentration of nitrates did not differ between the seasons in our study. According to NIWA (2019), nitrate concentrations in New Zealand lakes do not show seasonal differences, similar to our findings.

Direct comparison among freshwater ecosystems in different studies can be misleading because of variation in the environmental variables measured (Novikmec et al. 2016). Our results indicated that LULC at the catchment scale and the 500m scale significantly explained variation in the water quality of ponds in winter. This varying spatial relationship between LULC patterns and water quality variables has been described in other studies (Houlahan and Findlay 2004; Novikmec et al. 2016; Zhou et al. 2016; Nobre et al. 2020). This variation is because pollution sources and watershed characteristics vary spatially and can differ with region (Tu 2011; Novikmec et al. 2016; Zhou et al. 2016; Nobre et al. 2020). For example, researchers found that land use at the catchment scale was a key driver of water quality in lakes in Denmark and ponds in Slovakia (Nielsen et al. 2012; Novikmec et al. 2016). In the South Island of New Zealand, Galbraith and Burns (2007) also reported that catchment LULC is a major driver of the water quality of lentic ecosystems. In summer, however, after accounting for the effect of physical features, we found that LULC was significantly associated with water quality only at the 100m scale. This result is similar to findings by Declerck et al. (2006), who reported that adjoining land use of ponds in agricultural areas was significant in defining the water quality.

Our RDA results showed a seasonal difference in interactions between LULC and physicochemical water quality parameters. Our models for summer, especially the full models (R^2: 29-34%), explained a higher proportion of variability in our dataset compared to winter, contrary to our original hypothesis. The high variation in summer accounted for by the models is similar to the finding by Xu et al. (2020) and Zhang et al. (2019). This higher variation may be due to the highly polluted or concentrated runoff input in summer as opposed to winter when high rainfall results in less concentrated runoff. During summer, nutrients are transported to aquatic systems through subsurface flows, making the influence of LULC and physical features more significant on the physicochemical water quality variables (Zhang et al. 2019). Variability in the impact of LULC has been linked to high levels of precipitation (Nobre et al. 2020). Therefore, it is not surprising that the influence of LULC on water quality was more consistent in summer than in winter and that we observed an interactive effect of precipitation variability and LULC at different spatial scales. There is still, however, considerable unexplained variance. Other factors were not measured in our study, such as the type of underlying soil, age of the pond, surface flow, trophic state, fish presence, and algal biomass. These unaccounted geomorphological, hydrological and biological factors are likely to increase variability in our measures (Novikmec et al. 2016; Nobre et al. 2020). Furthermore, the relatively high variance explained in the full model compared to the partial model and the weak correlations between the water quality variables and LULC types are indicative of the vital role of the physical features. This importance is further strengthened by physical parameters such as rainfall, macrophyte cover and pond area being significant predictors of pH, %DO, temperature and salinity.

Our RDA results showed a seasonal difference in interactions between LULC and physicochemical water quality parameters. This seasonal difference may also be best explained by the difference in overland runoff between summer and winter. Variability in the impact of LULC has been linked to high levels of precipitation (Nobre et al. 2020). Therefore, it is not surprising that the influence of LULC on water quality was more consistent in summer than in winter and that we observed an interactive effect of precipitation variability and LULC at different spatial scales.

It is important to note that the variables we measured did not show similar trends and correlations in the two seasons studied. Nitrate concentration was weakly negatively associated with impervious surfaces but positively associated with grass and forest cover at both the catchment and 500m scales in summer. Ammoniacal nitrogen was negatively associated with catchment scale urban cover in both seasons. These associations indicate the complexity of water quality determinants in anthropogenically influenced landscapes (Gadd et al. 2020). Low water quality due to high nitrogen loads appears not to be a feature of more urban land use. We also found that urban cover was weakly positively related to phosphorus load in summer but negatively associated in winter at the catchment scale. It is likely that the phosphorus input into our study ponds came from household runoff and pet faeces facilitated by stormwater runoff into the ponds, as reported by Müller et al. (2020) and Hobbie et al. (2017). However, this seasonal disparity in the relationship may also be in part due to the level of precipitation.

Overall, we found that the variation of water quality variables is explained better by LULC at the catchment scale and 500m scale. However, some water quality variables such as pH, %DO, TDS and temperature had strong associations with LULC and physical parameters at smaller scales (10m and 100m) in summer. These effects of scale imply that management protocols need to be applied on a large scale, but the impacts of management at a small scale should also be considered (Xu et al. 2020).

Implications for freshwater systems management

The protection and restoration of freshwater systems require a basic understanding of catchment LULC changes and the response of the ecosystems to these changes. Our study provides a foundation for understanding these interactions for the Auckland region. We found that the water quality of freshwater systems is strongly linked to the type of land use at larger scales. The relationships we found led us to recommend that as catchments become increasingly urbanized, management measures should be instituted to minimize overland runoff flux that carries pollutants into the ponds. For instance, catchment-scale stormwater control measures that have retention, detention, infiltration and harvesting objectives (e.g., bioretention systems) could be incorporated in urban development to capture and treat polluted stormwater before it reaches ponds (Hatt et al. 2009; Bell et al. 2017). Based on our study results, we also conclude that interventions are critical in summer to minimize the worsening of water quality.

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Table 1. Summary of physical and landcover parameters of the ponds.

Table 2. Summary of physicochemical variables in summer and winter.

Table 3. Predicting ability (adjusted R^2) for the multiple linear regression (MLR) models at the four spatial scales for each water physicochemical variable in a) summer and b) winter.

Figure 1. Map of Auckland region showing the location of the 50 ponds sampled.

Figure 2. Ordination diagrams of the physicochemical water quality variables and landscape features at four spatial scales in summer according to redundancy analyzes.

Figure 3. Ordination diagrams of the physicochemical water quality variables and landscape features at four spatial scales in winter according to redundancy analyzes.

Supplementary Table 1. Spearman's rank correlations between physicochemical variables and LULC at four spatial scales in a) summer and b) winter.

Table 1 Summary of physical and landcover parameters of the ponds

Table 1. Summary of physical and landcover parameters of the ponds. Average values with standard deviations (SD) are reported.

Parameters	Parameter	Minimum	Maximum	Average ± SD
Catchment physical structure	% Slope	11.13	39.3	29.7 ± 10.7
	Catchment area (m^2)	428	31762	3635.7 ± 5258.2
	% Macrophyte cover	0	99	32 ± 33
Pond topography	Altitude (m)	3	346	37.7 ± 48.6
	Area (m^2)	22.7	6957.2	1698.5 ± 1977.4
Local climate	Rainfall mm (Winter)	54	175	88.9 ± 32.4
	Rainfall mm (Summer)	12	31	27.8 ± 7.0
LULC at 10m	Forest (%)	0	100	48.4 ± 32.0
	Grass (%)	0	100	44.1 ± 30.4
	Urban (%)	0	80	6.2 ± 15.0
LULC at 100m	Forest (%)	0.8	83.0	26.4 ± 19.2
	Grass (%)	0.7	93.8	51.7 ± 25.9
	Urban (%)	0	71.0	18.0 ± 19.8
LULC 500m	Forest (%)	1	63	18.3 ± 15.2
	Grass (%)	3	97	480.8 ± 25.8
	Urban (%)	1	94	28.2 ± 29.5
LULC at catchment area	Forest (%)	0	90	28.8 ± 31.8
	Grass (%)	1	99	54.9 ± 35.6
	Urban (%)	0	92	12.4 ± 22.5

Table 2 Summary of physicochemical variables in summer and winter

Table 2 Summary of the physicochemical variables in summer and winter. Significant at $p < 0.05$ are in bold. Cond.: conductivity, Sal.: salinity, Temp.: Temperature.

Variables	**Summer**		**Winter**		**t value**	**p value**
	Range	Average	Range	Average		
pH	4.44 - 8.01	6.63 ± 0.67	4.22 - 7.49	6.33 ± 0.59	2.4	**0.02**
%DO	25.30 - 129.21	73.49 ± 31.53	11.27 - 162.40	56.59 ± 26.25	2.9	**<0.01**
Cond (μScm^{-1})	21.6 - 920.3	228.8 ± 180.5	14.44 - 434.7	147.1 ± 75.70	2.8	**<0.01**
TDS (ppm)	28.7 - 460.7	117.7 ± 98.7	20.7- 218.3	80.5 ± 43.30	2.7	**<0.01**
Sal (psu)	0.01- 0.50	0.12 ± 0.10	0.01 - 0.52	0.08 ± 0.07	2.7	**<0.01**
Temp (ºC)	19.37 - 32.34	23.89 ±2.63	8.39 - 16.83	13.41 ± 1.93	23.3	**<0.001**
NO_3-N (mgl^{-1})	0.01 - 0.92	0.17 ± 0.23	0.01 -0.52	0.18 ± 0.21	0.2	0.8
PO_4^{3-} (mgl^{-1})	0.06 -2.5	1.03 ± 0.85	0.02 - 2.50	0.47 ± 0.65	4.0	**<0.001**
NH_3-H (mgl^{-1})	0.05 -1.17	0.20 ±0.17	0.02 - 1.66	0.20 ± 0.27	2.8	**<0.01**

Table 3 Predicting ability (adjusted R2) for the multiple linear regression (MLR) models at the four spatial scales for each water physicochemical variable in a) summer and b) winter

Table 3 Predicting ability (adjusted R^2) for the multiple linear regression (MLR) models at the four spatial scales for each water physicochemical variable in a) summer and b) winter. Objective models with $p < 0.05$ are in bold. Negative adjusted R^2 implies that the predictors' explanation power is extremely low or negligible in explaining variations in the response variable.

Spatial scale	**Physicochemical (response) variables**									
	Prediction	pH	%DO	Con. (μScm^{-1})	TDS (ppm)	Sal. (psu)	Tem. (°C)	NO_3-N (mgl^{-1})	PO_4^{3-} (mgl^{-1})	NH_3-H (mgl^{-1})
Summer										
10m	p value	**0.01**	**<0.001**	0.1	**0.03**	**0.04**	**0.002**	0.4	0.06	0.7
	Adj. R^2	0.2	0.47	0.12	0.18	0.17	0.32	0.02	0.15	0.1
100m	p value	**0.02**	**<0.001**	0.2	0.2	0.3	**<0.001**	0.36	0.1	0.1
	Adj. R^2	0.20	0.41	0.08	0.07	0.03	0.33	0.02	0.29	0.13
500m	p value	0.6	**<0.001**	**0.01**	**0.03**	0.2	**<0.001**	0.5	0.4	0.6
	Adj.R^2	0.28	0.43	0.25	0.19	0.1	0.41	-0.004	0.04	-0.1
Catchment	p value	< **0.01**	**<0.001**	0.05	0.09	0.2	**0.001**	0.4	0.3	0.6
	Adj.R^2	0.3	0.5	0.16	0.12	0.05	0.35	0.01	0.04	-0.04
Winter										
10m	p value	0.2	0.1	0.4	0.3	0.1	0.2	0.5	0.6	0.6
	Adj. R^2	0.1	0.1	0.003	0.03	0.1	0.05	-0.02	-0.04	-0.04
100m	p value	0.1	**0.03**	0.4	0.4	**0.03**	0.2	0.3	0.3	0.6
	Adj. R^2	0.1	0.2	0.01	0.01	0.2	0.04	-0.02	0.04	-0.03
500m	p value	0.1	**0.02**	0.3	0.1	0.1	0.1	0.3	0.5	0.9
	Adj. R^2	0.11	0.2	0.04	0.09	0.1	0.1	0.05	-0.02	-0.11
Catchment	p value	0.1	0.6	0.5	0.4	0.1	0.2	0.8	0.4	0.6
	Adj. R^2	0.1	0.15	-0.02	0.01	0.1	0.06	-0.07	0.01	-0.03

Figure 1 Map of Auckland region showing the location of the 50 ponds sampled

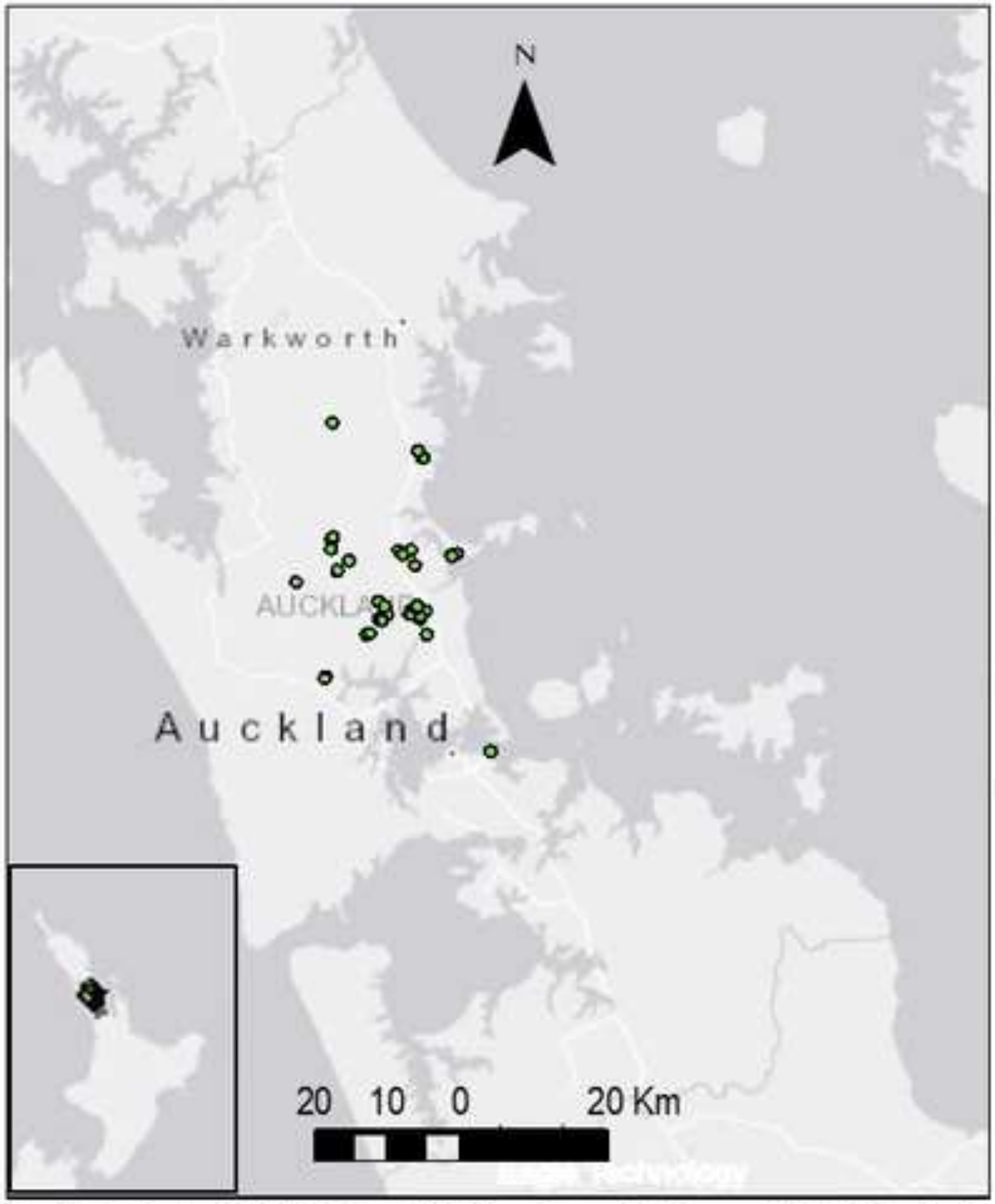

Figure 1 A map of Auckland showing the distribution of the 50 ponds sampled (map on the left), inset is the map of the North Island, New Zealand with a dark portion indicating the location of the Auckland Region. Basemap; New Zealand light grey canvas from Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Figure 2. Ordination diagrams of the physicochemical water quality variables and landscape features at four spatial scales in summer according to redundancy analyzes

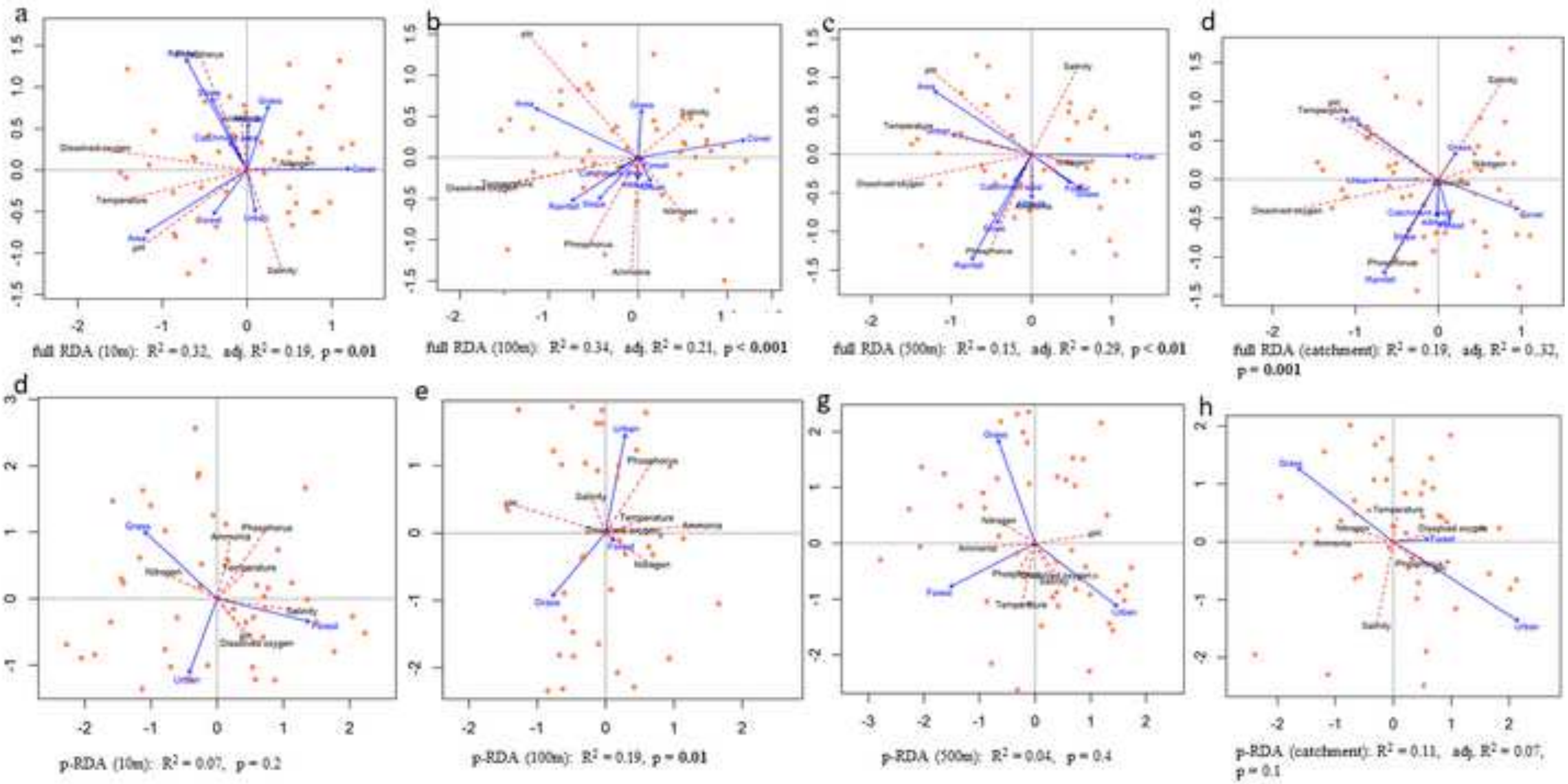

Figure 2 Ordination diagrams of the physicochemical water quality variables (red dotted lines) and landscape features (blue lines) at four spatial scales in summer according to the results of full RDA (a, b, c, and d) and p-RDA (e, f, g, and h). Cover represents percentage macrophyte cover. R^2, adjusted R^2 and p-values for each model is reported. Significant $p < 0.05$ are in bold. Non objective models have no adjusted R^2 value.

Figure 3. Ordination diagrams of the physicochemical water quality variables and landscape features at four spatial scales in winter according to redundancy analyzes

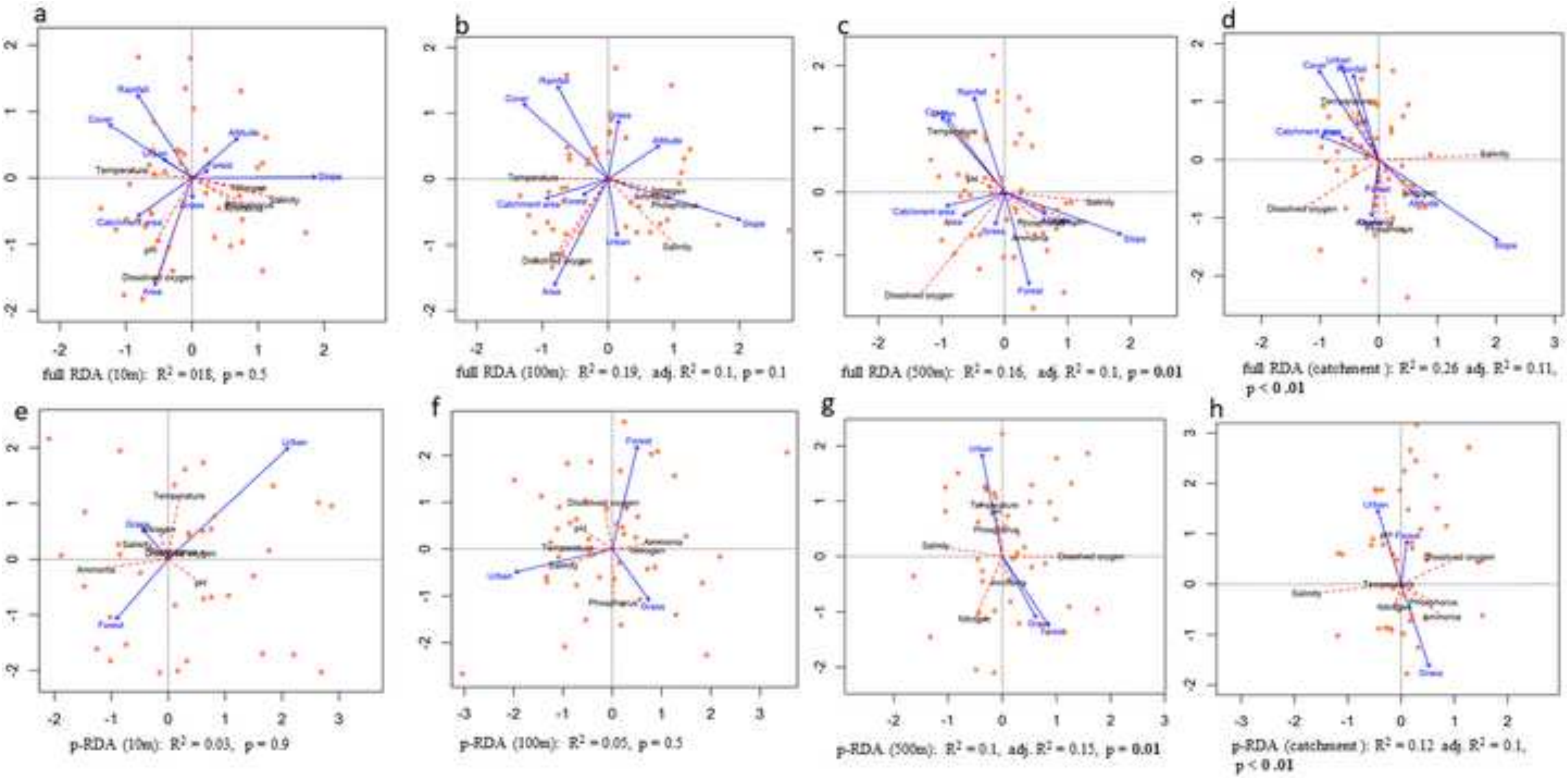

Figure 3. Ordination diagrams of the physicochemical water quality variables (red dotted lines) and landscape features (blue lines) at four spatial scales in winter according to the results of full RDA (a, b, c, and d) and p-RDA (e, f, g, and h). Cover represents percentage macrophyte cover. R^2, adjusted R^2 and p-values for each model is reported. Significant $p < 0.05$ are in bold. Non objective models have no adjusted R^2 value.

Supplementary Table 1. Spearman rank correlations rank between physicochemical variables and LULC at multiple spatial scales in a) summer and b) winter. Significant correlations with Bonfonerri corrections ($p < 0.05$) are in bold. Con.: conductivity, Sal.: salinity, Tem.: Temperature, NO_3-N: Nitrate, PO_4^{3-}: Phosphate, NH_3-H: Ammoniacal nitrogen.

Spatial scale	**LULC types**	**Physicochemical variables**								
		pH	% DO	Con. (μScm^{-1})	TDS (ppm)	Sal. (psu)	Tem. (^{o}C)	NO_3-N (mgl^{-1})	PO_4^{3-} (mgl^{-1})	NH_3-H (mgl^{-1})
		Summer								
10m	Forest	0.2	0.2	0.2	0.3	0.3	0.1	-0.3	0.1	0.0
	Grass	-0.2	-0.2	-0.2	-0.2	-0.3	0.0	0.2	0.1	0.1
	Urban	0.1	-0.1	0.0	0.0	0.0	-0.1	0.1	-0.3	-0.2
100m	Forest	-0.1	0.1	-0.1	-0.1	-0.1	0.0	0.0	0.0	-0.1
	Grass	0.1	-0.1	0.0	0.0	0.0	0.0	0.0	-0.2	-0.1
	Urban	-0.1	-0.1	0.2	0.3	0.3	0.0	0.1	0.2	0.2
500m	Forest	-0.3	-0.3	0.0	0.0	0.1	-0.1	0.0	0.0	0.1
	Grass	-0.2	-0.2	-0.3	-0.3	-0.3	-0.4	0.1	-0.1	0.1
	Urban	0.3	0.4	0.1	0.1	0.0	0.3	-0.1	0.1	-0.3
Catchment	Forest	-0.2	0.0	-0.1	-0.1	-0.1	-0.2	0.0	0.1	0.0
	Grass	-0.1	-0.2	0.0	0.0	0.0	0.1	0.1	-0.2	0.2
	Urban	0.3	0.2	0.1	0.1	0.1	0.0	-0.2	0.0	-0.2
		Winter								
10m	Forest	0.0	-0.1	0.1	0.2	0.1	-0.1	-0.1	0.0	0.1
	Grass	-0.1	0.1	-0.2	-0.2	-0.1	0.0	0.1	0.0	0.0
	Urban	0.2	0.0	0.1	0.0	0.1	0.0	0.1	0.2	-0.2
100m	Forest	0.0	0.2	-0.1	-0.1	-0.2	-0.1	0.1	-0.1	0.0
	Grass	0.0	-0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Urban	0.1	0.1	0.1	0.2	0.2	0.1	-0.1	0.2	-0.2
500m	Forest	-0.3	0.0	0.2	0.1	0.0	-0.3	0.1	0.1	0.2
	Grass	-0.3	0.1	-0.2	-0.3	-0.3	-0.1	0.2	-0.1	-0.1
	Urban	**0.4**	0.0	0.0	0.1	0.1	0.3	-0.1	0.0	-0.2
Catchment	Forest	-0.2	0.0	0.0	0.1	0.0	-0.3	0.1	0.0	0.1
	Grass	-0.1	0.0	0.1	-0.3	0.0	0.0	0.0	0.1	0.2
	Urban	**0.4**	0.0	-0.2	0.1	0.0	0.3	0.0	-0.1	**-0.5**

Abigail Kuranchie (AK) is a PhD student with the School of Natural and Computational Sciences, Massey University. Her research interest is the conservation of freshwater ecosystems, especially marginal freshwater systems such as ponds. She uses both field and laboratory assessments to understand her study systems.

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