Water Quality and Flow into Lagoons of the Eastern Alaska Beaufort Sea Coast

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Table of Contents

1. Introduction

Global climate models project the strongest future warming in high latitudes, with temperature predications reaching as high as 7 to 8 degrees Celsius (^oC) and precipitation nearly doubling by the end of the 21st century (Fig. 1; IPCC AR5, 2013). Continued climate change will likely have severe consequences for systems throughout the Arctic, including two significant terrestrial-freshwater impacts: an increase in river discharge (Frey & McClelland, 2009) as well as permafrost degradation and reduction in permafrost extent (Schuur et al., 2008). Permafrost (perennially frozen ground) degradation is a hot topic of interest since large stocks of previously frozen and trapped carbon held in soils will become remobilized with the warming of the Arctic (Zimov et al., 2006). Thawing permafrost also creates an active layer (seasonally thawed soils), which changes landscape dynamics and influences hydrological flow paths through soil organic matter. Increasing river discharge and surface runoff in conjunction with permafrost degradation is predicted to increase the delivery of dissolved organic matter (DOM) to Arctic coastal waters (McClelland et al., 2012a; Holmes et al., 2012), thereby providing an important source of energy and nutrients that effects both water quality and biological production (Dunton et al., 2012).

Shallow lagoon systems, which occur along >50% of the Eastern Alaska Beaufort Sea coast, act as hotspots for biogeochemical cycling that supports highly productive food webs (McClelland et al., 2012b). DOM delivery to lagoons increases dramatically during the spring freshet (early spring snow melt), which is tightly coupled to seasonal changes in riverine-freshwater discharge and accounts for much of the variation in water quality in Arctic coastal waters (Holmes et al., 2012). However, river inputs vary widely over space and time, and nearshore watershed export via surface and subsurface flow paths may be an especially important driver of water quality along stretches of coastline without major rivers, and during mid-to-late summer when river flow is low. Given the difficulty to collect on site measurements in the high Arctic, techniques in GIS can be especially useful to estimate lagoon drainage areas and networks that reflect the variation in nearshore watershed export.

The goal of this study is to examine the relationship between watershed area and water quality in lagoon systems in order to make inferences about changes in water quality from varying magnitudes of freshwater flow. Furthermore, this study will serve as an initial benchmark for future studies that will examine the relative importance of subsurface flow paths in lagoons of the Eastern Alaska Beaufort Sea coast during summer-low flow conditions.

2. Methods

2.1 Study Site

Study sites for this project lie within the Tundra on the North Slope of Alaska and consist of four of the ten lagoons along the Eastern Alaska Beaufort Sea coast (Fig. 2a, b). The landscape draining into these lagoons is remarkably flat and is characterized by moss and low shrub dominated wetlands (Fig. 2b, c). These shallow lagoons differ by both their freshwater input from rivers and streams, and exchange with ocean shelf waters. For instance, Kaktovik Lagoon (KA) receives freshwater from small streams fed by runoff from the surrounding area, while Jago Lagoon (JA) receives larger amounts of freshwater from the Jago River. All four lagoons are protected by barriers islands that limit water exchange with the Beaufort Sea to shallow, local areas. However, there are potential differences in water exchange based on their degree of enclosure (e.g., JA is largely open; Angun (AN) and Nuvagapak (NU) are semi-enclosed, while KA is nearly fully enclosed). Furthermore, seasonal permafrost thaw and thermokarsting (land erosion) cause random depressions that alter hydrological flow paths across the landscape (Fig. 1c). In consequence, groundwater flow paths and shallow water tracks draining into the lagoons are the prominent watershed features of this region; especially in areas where elevation does not sufficiently channelize flow paths into streams or rivers.

2.2 Water Quality Dataset

The influence and magnitude of freshwater flow in conjunction with local lagoon buffering capabilities from the Beaufort Sea can have a substantial effect on local water quality. To examine this relationship, I have obtained a full dataset of water quality parameters along the Eastern Alaska Beaufort Sea coast from Dr. Tara Connelly at the University of Texas at Austin, Marine Science Institute (Table 1). I have focused only on data collected in August 2012 for the four lagoon sites because water quality was most heavily sampled during this time period. The water quality dataset consists of two-to-three replicates per lagoon site, and includes measurements for: temperature, salinity, dissolved oxygen, pH, chlorophyll a, bulk carbon and nitrogen, and $\delta^{13}C$ and $\delta^{15}N$ stable isotopes (Table 1).

2.3 GIS Methods

2.3.1 Obtaining Map Layers

The first step of this study was to obtain a DEM suitable for watershed delineation. Due to the remoteness of the North Slope of Alaska, the spatial extent for the NED30 from the online GIS-server did not cover the study area. However, I was successful in obtaining a NED 2 Arc Sec (34.6m resolution) DEM from the website: www.AlaskaMapped.org. In order to select lagoon drainage points—which will be discussed in more detail in the proceeding section—I obtained a NHD layer from the USGS Map Viewer website. Although other map layers were considered, these two layers were the most useful and formed the basis of my work.

2.3.2 Selecting Drainage Points

The second step of this study was to select drainage points that accurately outlined the watersheds exporting to the lagoon sites. After obtaining site locations, an excel file with the latitude and longitude values in decimal degrees was added as an attribute table to ArcGIS. Then the XY data was displayed, allowing for a visual of the potential drainage areas into the four lagoon sites (Table 1; Fig. 2b). Due to the lack of USGS gage coverage and the remarkable flatness of the study region, there is little observable evidence of a change in elevation that might result in channelized water flow paths and outlet points (Fig.2b; Fig.3a). Therefore it was necessary to choose drainage points based on the NHD layer obtained from the USGS Map Viewer website (Fig. 3b). These points, which were present in the NAD 1983 geographical coordinate system, were plotted and corrected for on the NED 2 Arc Sec DEM, which was displayed using the Albers_Conic_Equal_Area coordinate system. All additional map layers were generated and displayed in the Albers_Conic_Equal_Area coordinate system.

2.3.3 Watershed Delineation

Following the selection of lagoon drainage points, watersheds were delineated using the ArcGIS "Watershed Tool" function, which revealed four major watersheds and a nice agreement with the NHD layer outlining the HUC-12 watersheds (Fig. 3a, b; Fig. 4a). In Figure 4a, notice there are also several small linear watersheds, which likely represent small streams reaches. Following watershed delineation, I proceeded with methods learned from class to generate the watershed drainage networks, exhibiting stream vectors indicating the major water flow paths (Fig. 4b). Using the outlet points of the stream vectors, I identified the total flow accumulation and added these values for all vectors draining into each lagoon, thereby creating an estimate of watershed area based on flow accumulation. I also obtained the watershed area from the "Watershed Tool" function as a means of comparison. Finally, I continued with methods obtained from class to generate flow direction arrows of each stream link to further support the expected water movement throughout the drainage networks.

3. Results and Discussion

3.1 Watershed Characteristics

The four watersheds draining into the lagoon sites clearly differ in their watershed area based on flow accumulation and the "Watershed Tool" function, however, while there is a nice agreement between the two methods for KA and JA lagoons, there is a major discrepancy between the watershed areas for the AN and NU Lagoons (Table 2). At a closer view, a significant overlap exists between the outlined watershed area generated by the "Watershed Tool" function and the stream vectors draining into the AN and NU lagoons. Notice a major drainage network (outlined in yellow) that appears to lie within the AN watershed (#3) actually flows northeast into the NU Lagoon (Fig. 5). This northeasterly flow was supported by flow direction arrows generated for the stream links within the drainage networks. This suggests that the watershed outline and area created from the "Watershed Tool" function does not accurately characterize the drainage area for these two lagoons. Furthermore, the region containing watersheds #3 and #4 largely drain into NU Lagoon as supported by the flow direction of the stream vectors and the watershed area based on flow accumulation.

This major discrepancy is likely caused by the difference in DEM resolution used for these two methods. The "Watershed Tool" function automatically uses the "best available" DEM found in the GIS server. As a result, the watersheds delineated are likely based on a 90m resolution DEM covering this remote region. Flow accumulation, however, was generated from a NED 2Arc Sec DEM with a 34.6m resolution, and thus is expected to generate more robust results. At this end, the watershed areas based on flow accumulation likely represent the actual drainage areas, and serve as good estimates of the expected magnitude of freshwater flow to the four lagoon sites. The results clearly show a highest-lowest magnitude of freshwater flow from JA→NU→AN→KA Lagoons (Table 2). This indicates that JA and NU Lagoons are strongly influenced by freshwater from major river networks (e.g. Jago River), while AN and KA Lagoons may heavily rely on freshwater sourced from small fed streams and nearshore surface and subsurface export.

3.2 Flow Effects on Water Quality

Here this study aims to find a relationship between watershed area based on flow accumulation and water quality in lagoon systems in order to make inferences about changes in water quality from varying magnitudes of freshwater flow that occur during summer conditions. Lagoons draining larger watersheds may have lower salinities and temperature as a result of a greater freshwater flux through cold terrestrial soils. Lower dissolved oxygen (DO) levels are typically associated with higher microbial respiration; however, lagoon systems are dynamic and a high degree of mixing and turbulence may elevate DO levels, making results difficult to interpret. Lagoons draining larger watersheds are also expected to have higher quantities of bulk carbon and nutrients as a result of larger loads of DOM moving through the system. Isotopic composition proxies have recently been used to reveal the sources as well the lability (how easily consumed) of organic material. Here lagoons draining large watersheds might exhibit more depleted stable carbon and nitrogen isotope signatures (δ^{13}C ~ -27‰ and δ^{15}N ~ 0-1.5‰), suggesting a high delivery of labile allocthonous-fresh DOM from vegetation and organic rich soils, in comparison to lagoons with little terrestrial-freshwater influence (O'Leary, 1998). However, predegraded-older DOM with more depleted δ^{13}C and δ^{15}N signatures often has high residence times in the Arctic Ocean and a large degree of mixing with lagoons without substantial protection from barrier islands may make results difficult to interpret.

To examine the relationship between freshwater flow and water quality, several simple regression analyses were conducted with an R^2 value used to assess the correlation strength between variables (Fig. 6-8). It is clear that there is little variation in the water quality across lagoon sites, and no significant relationship between watershed area and any of the water quality variables (defined by a R^2 of near 1.0). The results show a decreases in salinity (R^2= 0.35), increase in DO (R^2= 0.62), and unchanging temperature (R^2=0.009) with larger freshwater inputs (Fig. 6). Furthermore, both bulk C and N decrease with watershed area (R^2= 0.17 and 0.21, respectively), while δ^{13}C becomes less depleted (R^2= 0.20) and δ^{15}N becomes more depleted (R^2= 0.51) with increasing freshwater inputs (Fig. 7, 8). Overall, the results are confusing and difficult to interpret. Nonetheless, they indicate this system is very dynamic, and simple regression analyses are not able to resolve any obvious regional differences in water quality that might arise from just variations in freshwater flow.

It is more likely; however, that lagoon water quality is driven by a combination of the magnitude of freshwater inputs, local mixing exchange with the Beaufort Sea, and seasonal effects on the discharge of riverborne constituents. For instance, KA lagoon—which is nearly entirely enclosed by barrier islands—has the lowest DO levels and the most depleted δ^{13}C signature, indicating there may be both higher inputs of modern DOM that is easily respired by microorganisms and less water exchange with the Beaufort Sea in comparison to the other lagoons. On the other hand, JA Lagoon, which has a substantial freshwater influence from the Jago River and is largely open to ocean waters, has high DO levels and the lowest bulk C and N concentrations. This indicates that the JA Lagoon may experience a larger amount of water exchange with the Beaufort Sea, thereby driving DO levels up and diluting C and N concentrations. It is also possible that the Jago River is delivering freshwater enriched in DO, via turbulence and diffusion, as well as recalcitrant forms of C and N that might occur during low summer flow. Furthermore, the semi-enclosed AN Lagoon experiences the least freshwater input, which supports the high salinity values and largely marine δ^{13}C and δ^{15}N signatures in comparison to the other lagoons. Finally, the highest C and N and less depleted δ^{15}N for NU Lagoon is consistent with a large freshwater influence as well as indicative of the importance of the abundant streams that occur along its coastline without any major rivers.

3.3 Future Work

Previous work has been done on the seasonal water quality across all ten lagoons of the Eastern Alaskan Beaufort Sea coast; however, only four lagoon drainage areas and their respective water quality for August 2012 was used here (Connelly et al., 2014). To gain a better understanding of the relationship between seasonal water quality and the magnitude of freshwater flow, a more extensive dataset should be considered and all lagoon drainage areas should be delineated. Furthermore, this study only used a 30m resolution DEM to determine watershed area as our measure of freshwater flow, while using more complex techniques with Lidar data to obtain DEM's at the 1m resolution scale would yield more accurate measures of lagoon drainage areas and alleviate this as potential cause of error.

Emerging GIS tools are being used to trace the movement of groundwater through soils, which would be very interesting to apply to high arctic coastal systems. Groundwater flow through the active layer is already recognized as a source of DOM to streams and rivers (Striegl et al., 2005), and can be a significant source of DOM to Arctic coastal waters, especially along stretches of coastline without major rivers, and during mid-to-late summer when river flow is low (Frey & McClelland, 2009). This phenomenon unique to Arctic coastal systems has been largely overlooked and would improve our understanding of the effect of subsurface freshwater inputs on lagoon water quality.

Acknowledgements

I would like to thank Dr. Tara Connelly for providing me the necessary water quality data and valuable information regarding the lagoon study sites. I would also like to thank Dr. James McClelland for his help in generating ideas regarding this project. Finally, I would like to thank Dr. David Maidment for teaching a great class!

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Tables

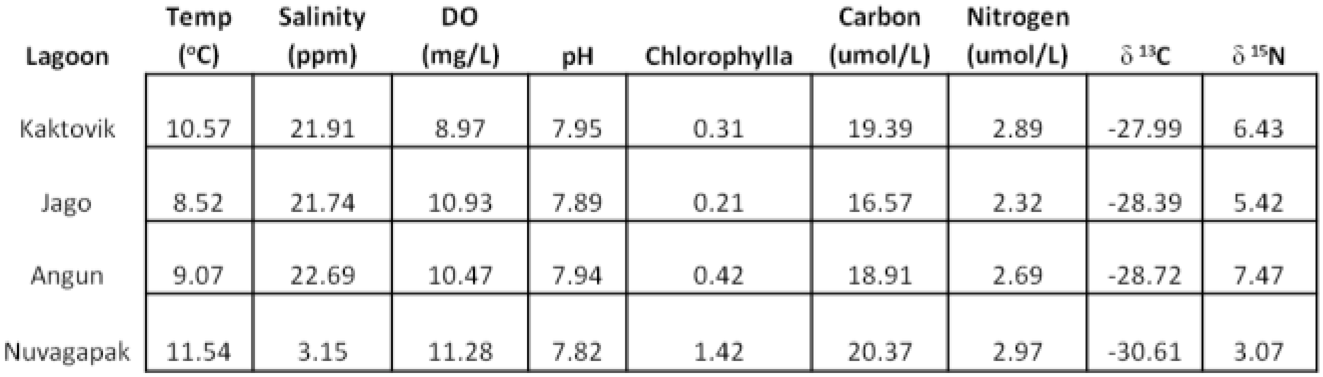
Table 1. Water quality parameters and measurements obtained on August 2012 by Dr. Tara Connelly, University of Texas at Austin, Marine Science Institute. Lagoon names and abbreviations are as followed: Kaktovik (KA), Jago (JA), Angun (AN), and Nuvagapak (NU).

Lagoon	LatDD	LongDD	Date Sampled	Temp (°C)	Salinity (ppm)	DO (mg/L)	pH	Chlorophyll a	Carbon (umol/L)	Nitrogen (umol/L)	δ ^{13}C	δ ^{15}N
KA-1	70.09	-143.63	8/7/2012	10.8	23.29	8.3	7.96	0.572	18.51	3.07	-28.05	6.38
KA-2	70.10	-143.59	8/7/2012	11.53	22.96	7.9	8.04	0.195	19.11	2.90	-28.06	7.86
KA-3	70.12	-143.57	8/15/2012	9.39	19.49	10.7	7.84	0.168	20.56	2.69	-27.85	5.06
JA-1	70.11	-143.51	8/11/2012	8.23	21.77	10.85	7.92	0.182	12.69	1.59	-28.66	4.82
JA-2	70.12	-143.44	8/11/2012	8.27	22.09	10.82	8	0.216	12.09	1.89	-28.52	5.51
JA-3	70.13	-143.39	8/15/2012	9.07	21.35	11.12	7.76	0.220	24.91	3.48	-27.99	5.92
AN-1	69.97	-142.50	8/12/2012	9.45	23.78	10.29	7.87	0.268	17.29	2.53	-28.56	6.78
AN-2	69.96	-142.45	8/12/2012	8.68	21.59	10.64	8.01	0.578	20.53	2.85	-28.87	8.16
NU-1	69.88	-142.19	8/10/2012	11.5	2.33	11.37	7.6	1.034	16.28	2.48	-30.41	3.19
NU-2	69.89	-142.24	8/10/2012	11.5	2.33	11.37	7.6	1.174	20.67	2.65	-30.44	2.85
NU-3	69.91	-142.32	8/10/2012	11.63	4.79	11.11	8.25	2.048	24.18	3.78	-30.98	3.16

Table 2. Watershed area draining into lagoon sites based on flow accumulation and the "Watershed Tool" function (labeled "Watershed Area" here). Notice a major discrepancy between the two methods for the Angun and Nuvagapak Lagoons.

Lagoon	Flow Accumulation (km^2)	Watershed Area (km^2)
Kaktovik	195.8	264.5
Jago	1793.3	2065.7
Angun	321.1	1929.2
Nuvagapak	1455.6	987.9

Table 3. Water quality parameters; replicates averaged per lagoon site. Data obtained from Dr. Tara Connelly at the University of Texas at Austin, Marine Science Institute.



Lagoon	Temp (°C)	Salinity (ppm)	DO (mg/L)	pH	Chlorophylla	Carbon (umol/L)	Nitrogen (umol/L)	δ ^{13}C	δ ^{15}N
Kaktovik	10.57	21.91	8.97	7.95	0.31	19.39	2.89	-27.99	6.43
Jago	8.52	21.74	10.93	7.89	0.21	16.57	2.32	-28.39	5.42
Angun	9.07	22.69	10.47	7.94	0.42	18.91	2.69	-28.72	7.47
Nuvagapak	11.54	3.15	11.28	7.82	1.42	20.37	2.97	-30.61	3.07

Figures

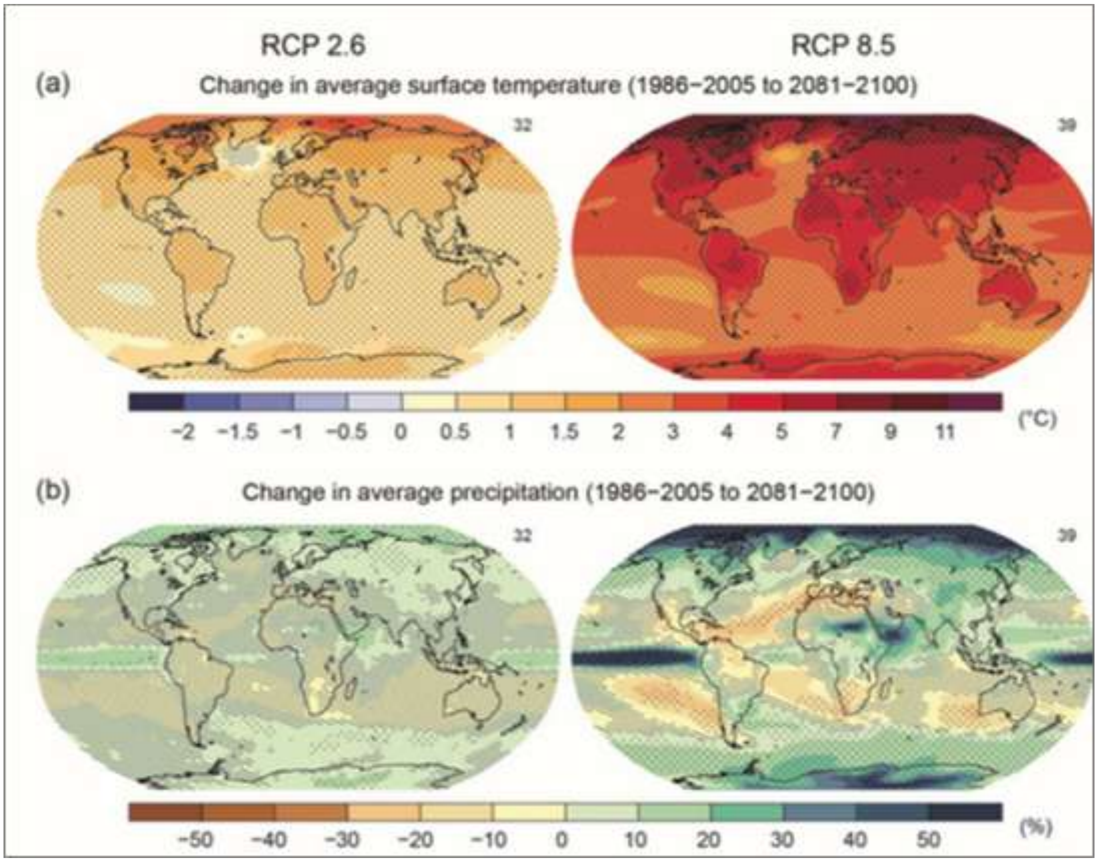


Figure 1. (a) Predicted changes in the average global surface temperature (Celsius) and (b) precipitation into the 21st century. Source: IPCC AR5, 2013.

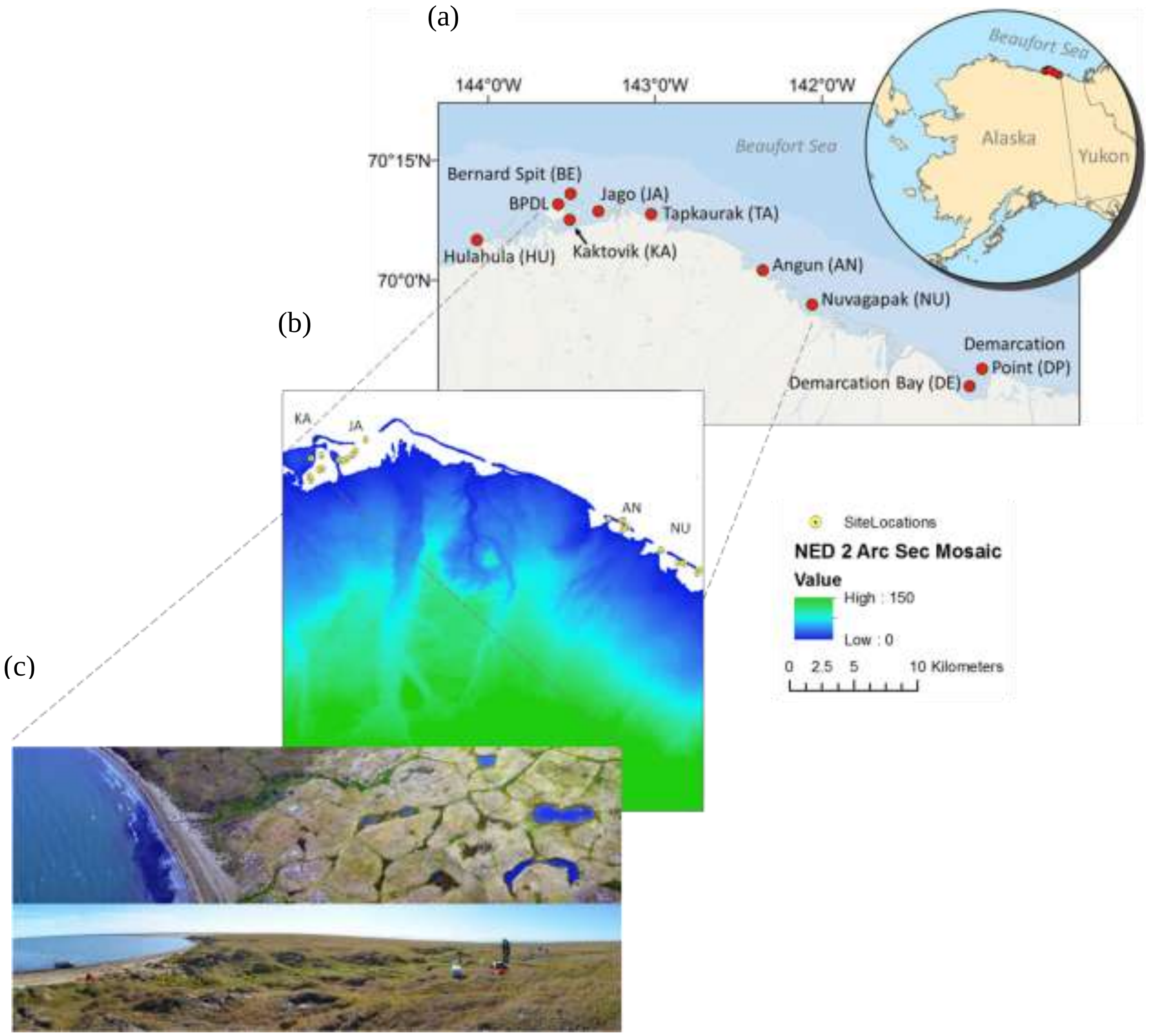


Figure 2. (a) Map of the Eastern Alaska Beaufort Sea coast provided by Dr. James W. McClelland, University of Texas at Austin, Marine Science Institute. (b) NED 2 Arc Sec Mosaic, showing evidence of major hydrological flow paths draining into the study site locations: Kaktovik (KA), Jago (JA), Angun (AN), and Nuvagapak (NU) lagoons. NED obtained from the websites: www.AlaskaMapped.org. (c) Areal and ground panoramic imagery of the coastline of Kaktovik Lagoon, provided by Dr. James W. McClelland.

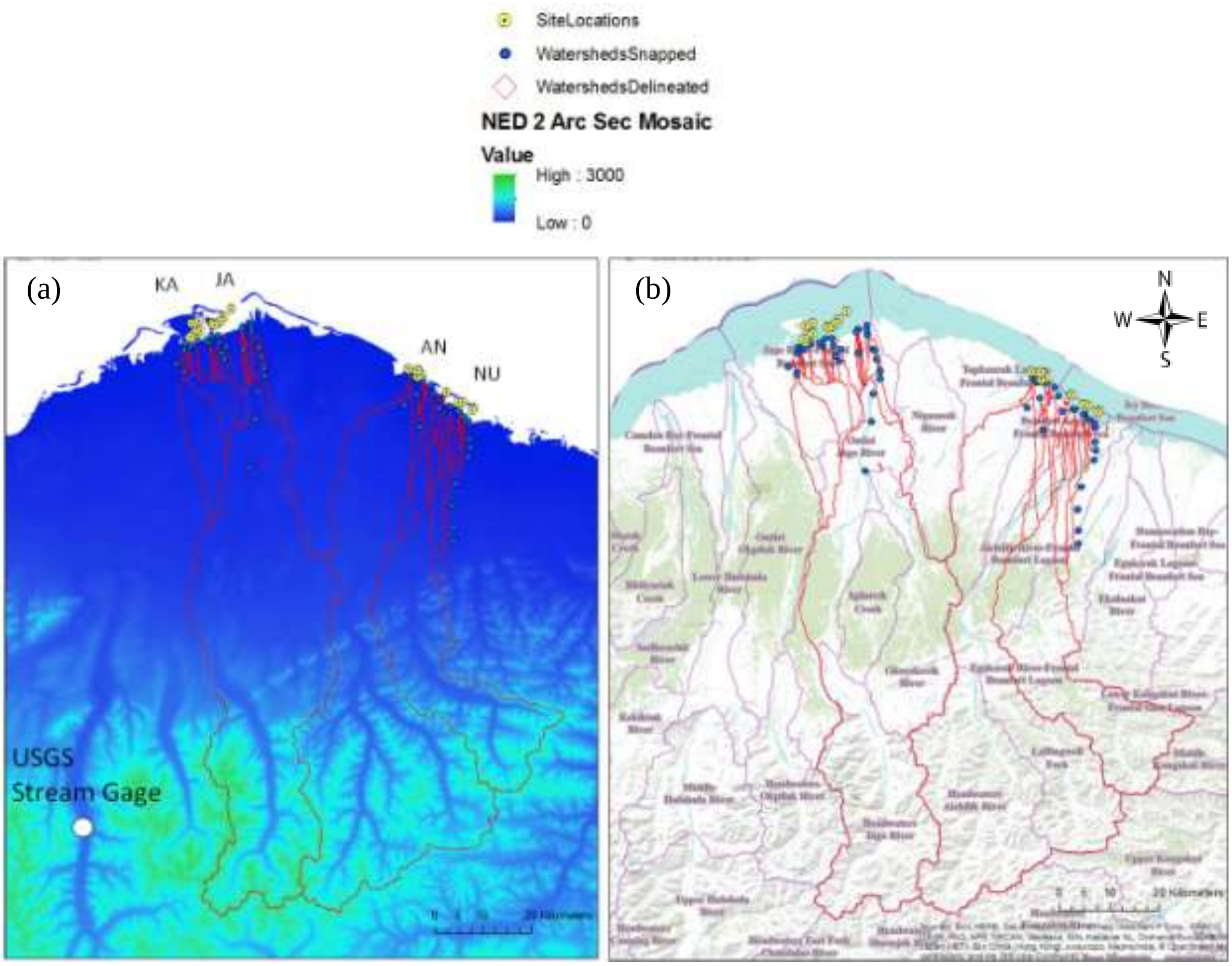


Figure 3. (a) Watersheds delineated (outlined in red) using the ArcGIS “Watershed Tool” function. Notice here the only USGS stream gage is far outside the drainage areas for the lagoon study sites. (b) NHD layer overlain with watershed outlines to show a nice agreement with various HUC-12 watersheds. NHD layer was obtained from the USGS Map Viewer website. The points labeled “WatershedSnapped” indicate the corrected drainage points, which is also true for the proceeding graphs. Multiple drainage points were selected (including some further inland) in order to increase the likelihood of capturing the entire drainage area.

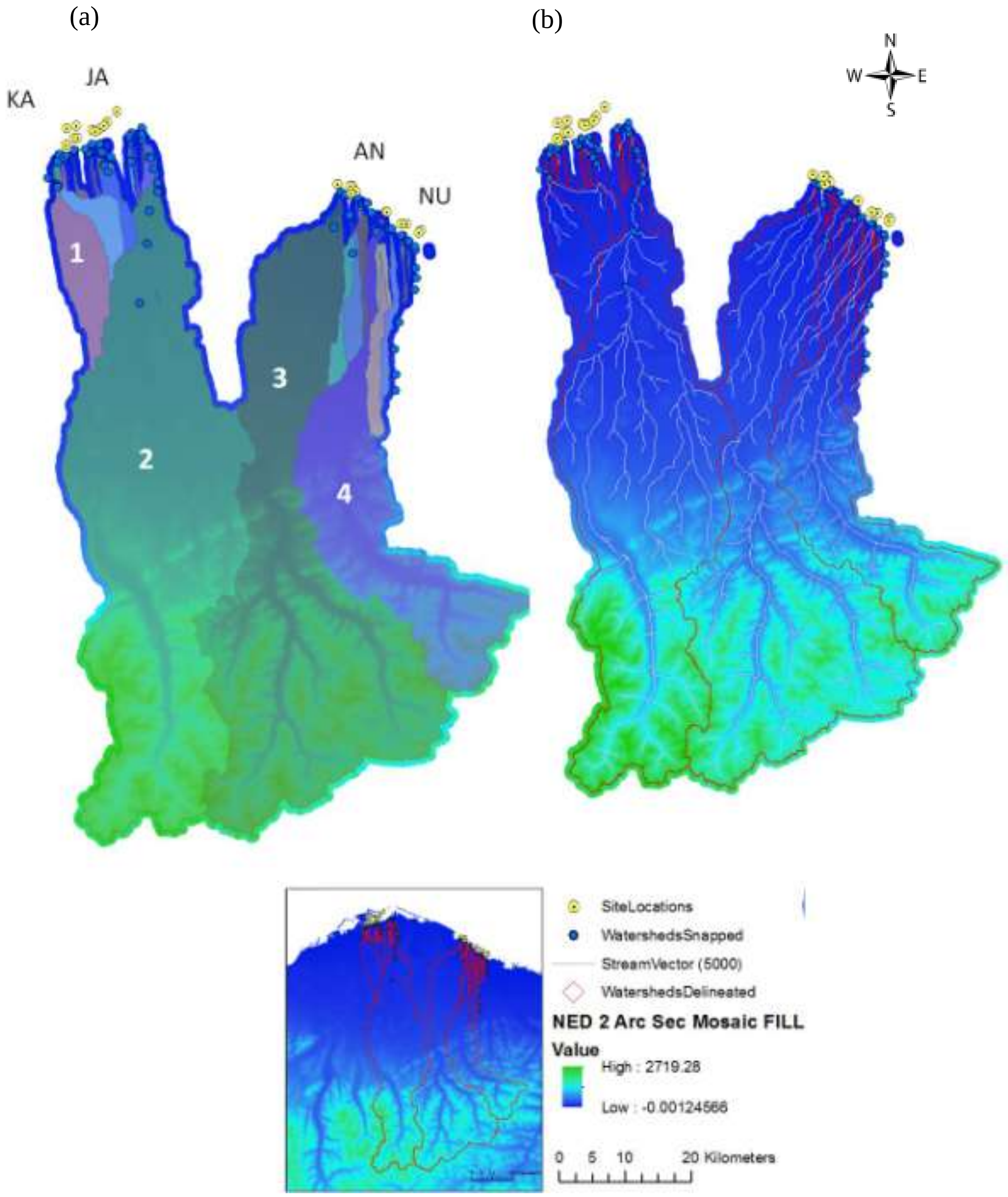


Figure 4. (a) Map of the four major watersheds and stream reaches draining into lagoon sites. (b) Map of the major stream vectors (flow paths) for each watershed draining into lagoon sites. Stream vectors were generated using a threshold of >5000 flow accumulation.

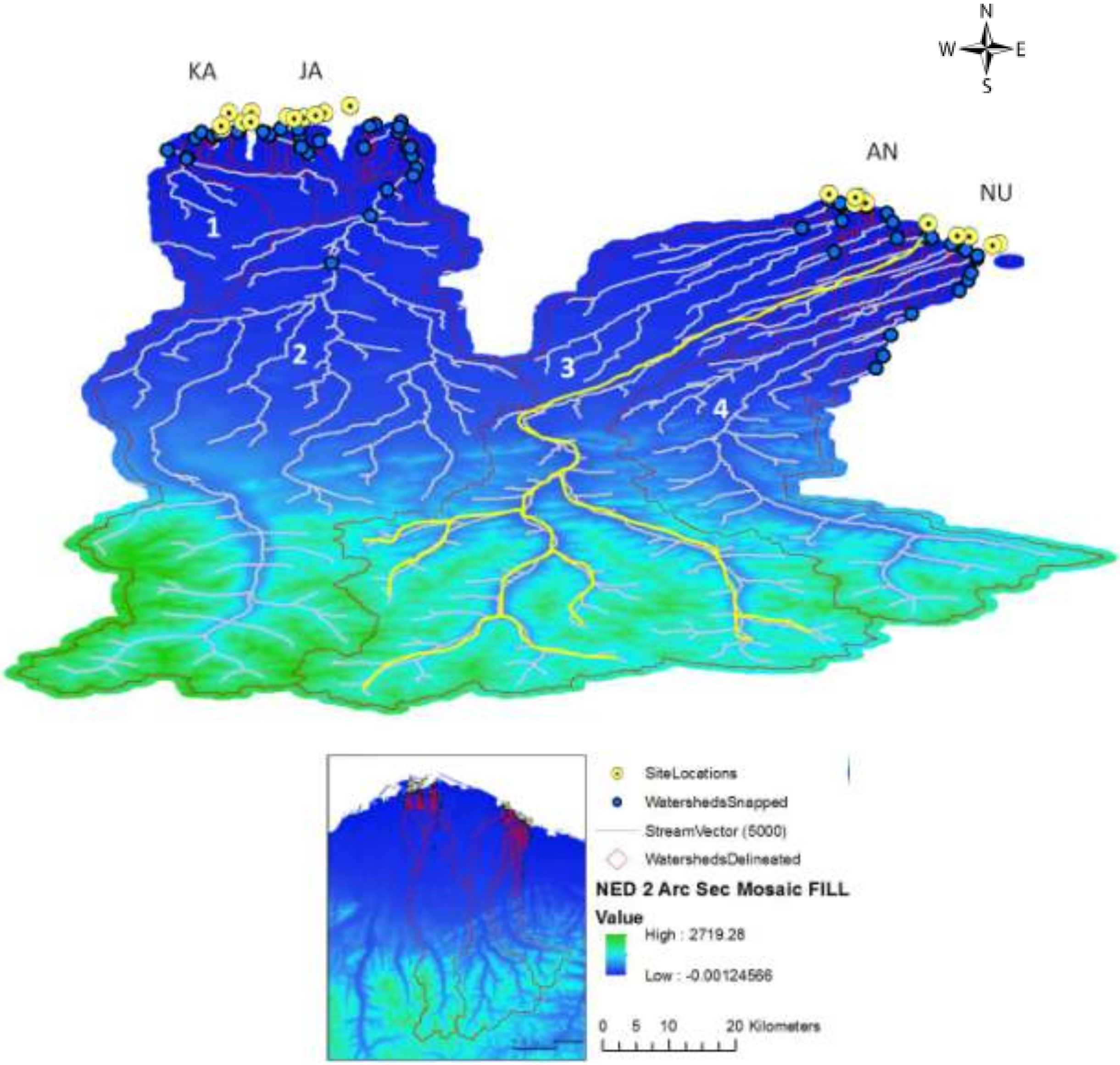


Figure 5. Map of the watersheds and stream vectors draining into lagoon sites. Outlined in yellow is a major flow path actually flowing into Nuvagapak Lagoon (NU). The geographical coordinate system was change to the NAD 1983 for a better view of the curvature of the flow paths.

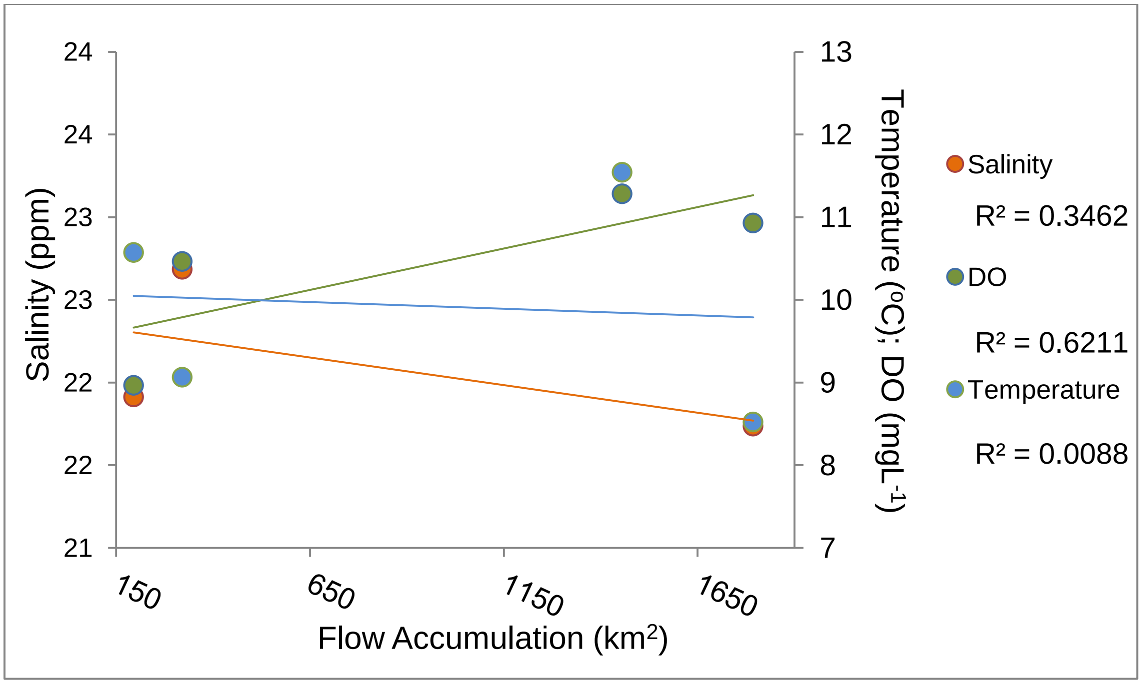


Figure 6. Variations in the salinity, dissolved oxygen (DO), and temperature (Celsius) of lagoon seawater with increasing watershed area based on flow accumulation. Trend lines and R^2 values indicate where a potential relationship may exist.

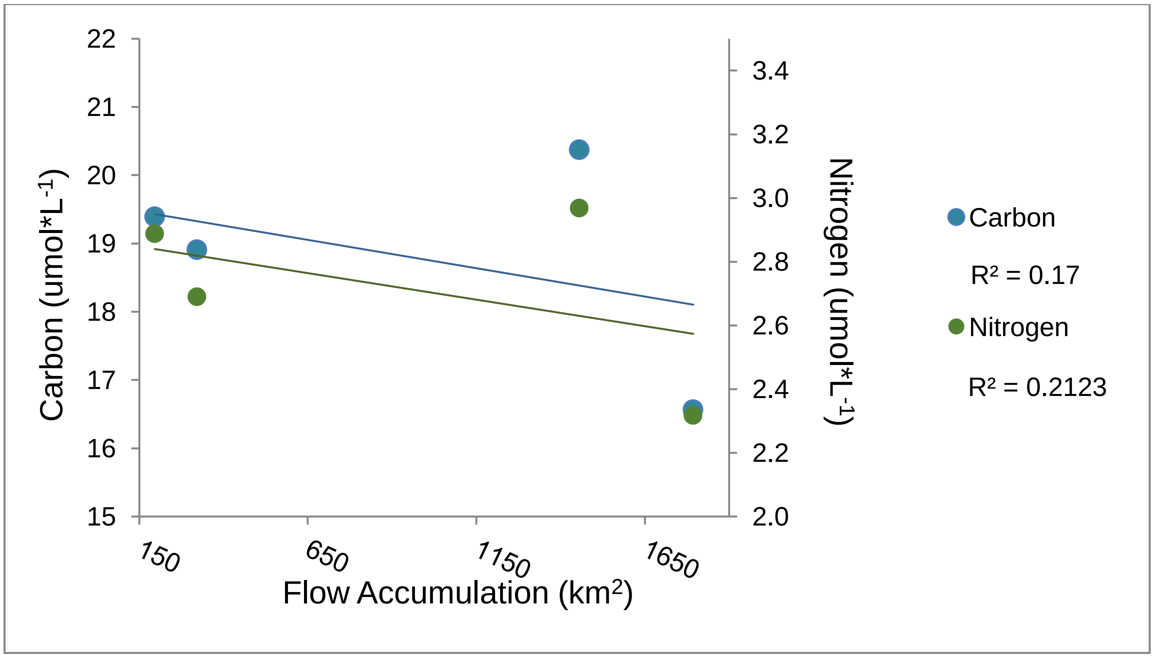


Figure 7. Variations in the bulk measurements of carbon and nitrogen of lagoon seawater with increasing watershed area based on flow accumulation. Trend lines and R^2 values indicate where a potential relationship may exist.

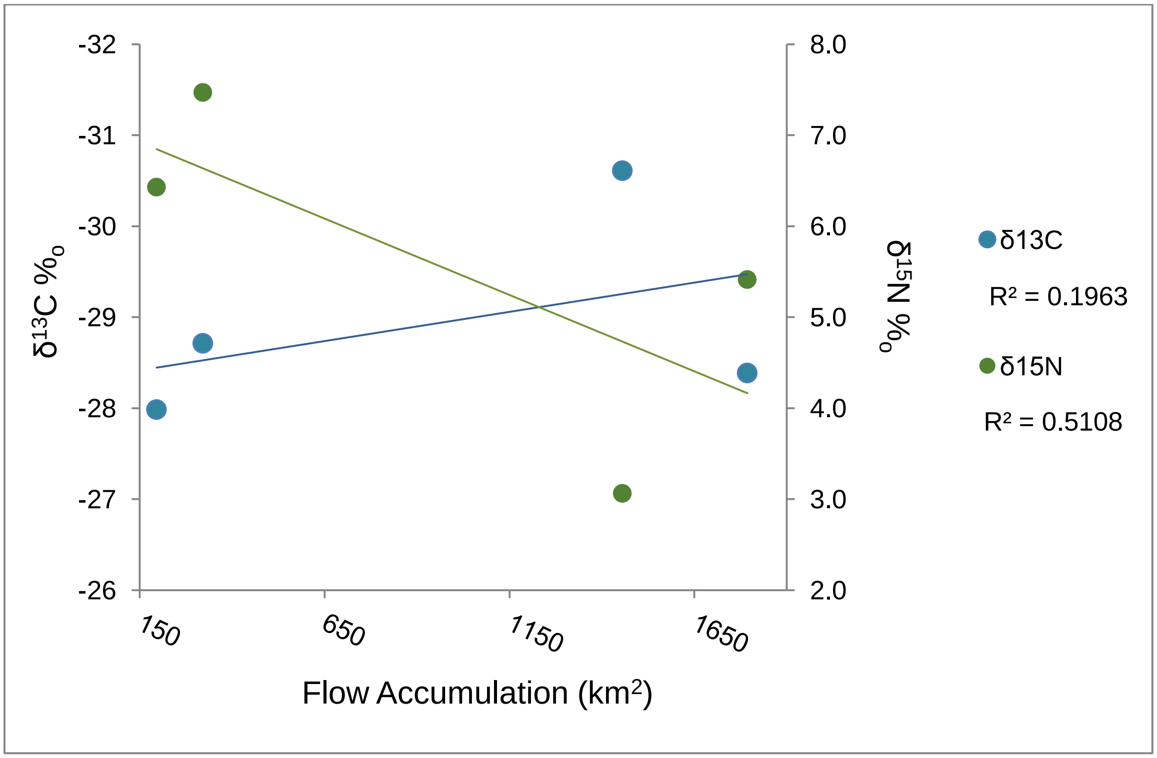


Figure 8. Variations in the stable carbon and nitrogen isotope signatures of lagoon seawater with increasing watershed area based on flow accumulation. Trend lines and R^2 values indicate where a potential relationship may exist.