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Chlorophyll–Nutrient Relationships of an Artificial Inland Lagoon Equipped with Seawater Replenishment System in the Northern Red Sea (Gulf of Aqaba)

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Abstract: Data are reported for an inland artificial lagoon (Ayla) to evaluate the impact of the lagoon's modeled design and water replenishment system on its water quality and the coastal ecosystem. This study focused on Ayla's upper lagoon (UL) only, due to its isolation from the two other lagoons and the ambient seawater in the Gulf of Aqaba (GoA). Nutrient measurements (nitrite, nitrate, ammonium, phosphate, and silicate) in addition to Chlorophyll *a* (Chl *a*) data were collected between July 2012 and June 2013. Chl *a* values in the UL were not significantly different from ambient seawater in the GoA, and the UL did not show seasonal differences ($p = 0.456$). Significant variability for nitrite was observed in the UL between spring and summer ($p < 0.0001$) and between fall and winter ($p < 0.0001$). Nitrite showed a stronger seasonal effect in the GoA seawater than in the UL ($p = 0.056$). Phosphorus showed a seasonal effect and remained similar between the UL and GoA. Nutrient stoichiometry showed a Redfield-like nitrogen-to-phosphorus (N:P) ratio for the ambient GoA seawater around the inlet pumping source and an increased N:P ratio inside the UL. This study emphasizes the importance of modeled lagoon design and seawater replenishment system in preventing and inhibiting eutrophication of the lagoon and therefore minimizing contamination in the coastal ecosystem.

Keywords: chlorophyll; nutrient; stoichiometry; lagoon; seawater quality; Gulf of Aqaba; Red Sea; monitoring; eutrophication; artificial lagoon

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1. Introduction

Coral reef ecosystems are a complex interwoven assembly of different species, playing key roles in maintaining marine biodiversity [1,2]. A significant body of research on reef fish and corals has identified the Red Sea as a region of high diversity and endemism [2–4]. Coral reefs have been exposed to several stressors during the past years, either due to the massive anthropogenic activities or climate change, at the global scale [5], the Red Sea [1,3], and the Gulf of Aqaba (GoA) (Figure 1a) [6–9], which lead to the outbreak of disease in these corals [3,6,10]. Therefore, it is imperative to maintain a healthy water quality that guarantees a healthy and natural marine coastal ecosystem. Lagoons and coastal areas are stressed by several factors; geomorphological, hydrodynamic, abiotic, and biological changes are stressors, leading to environmental disturbances and fluctuations [11–13].

Not surprisingly, there is a scarcity of water quality and system dynamics data in public databases for artificial lagoons equipped with water replenishment systems. Such data are necessary to develop management plans capable of preserving the lagoons' natural chemical properties, productivity, and biodiversity [14–17]. A recent study by Rasheed et al. [18] highlights the impact of two small artificial lagoons (marinas) on the water quality in the GoA and illustrates the importance of environmental design studies for lagoons before any construction begins. The two lagoons discussed by Rasheed et al. [18] lacked a water circulation system, which rendered them subject to high levels of eutrophication that influenced the water quality inside the lagoons and in the adjacent GoA seawater. Ayla lagoon's design was subjected to different environmental models before the actual design was modeled and constructed, resulting in the design of a seawater pumping system which pumps ambient seawater from the GoA into the lagoons, in an attempt to minimize eutrophication and maintain "close to ambient" in-lagoon water quality, and thereafter minimal impact on the adjacent ambient water of the GoA.

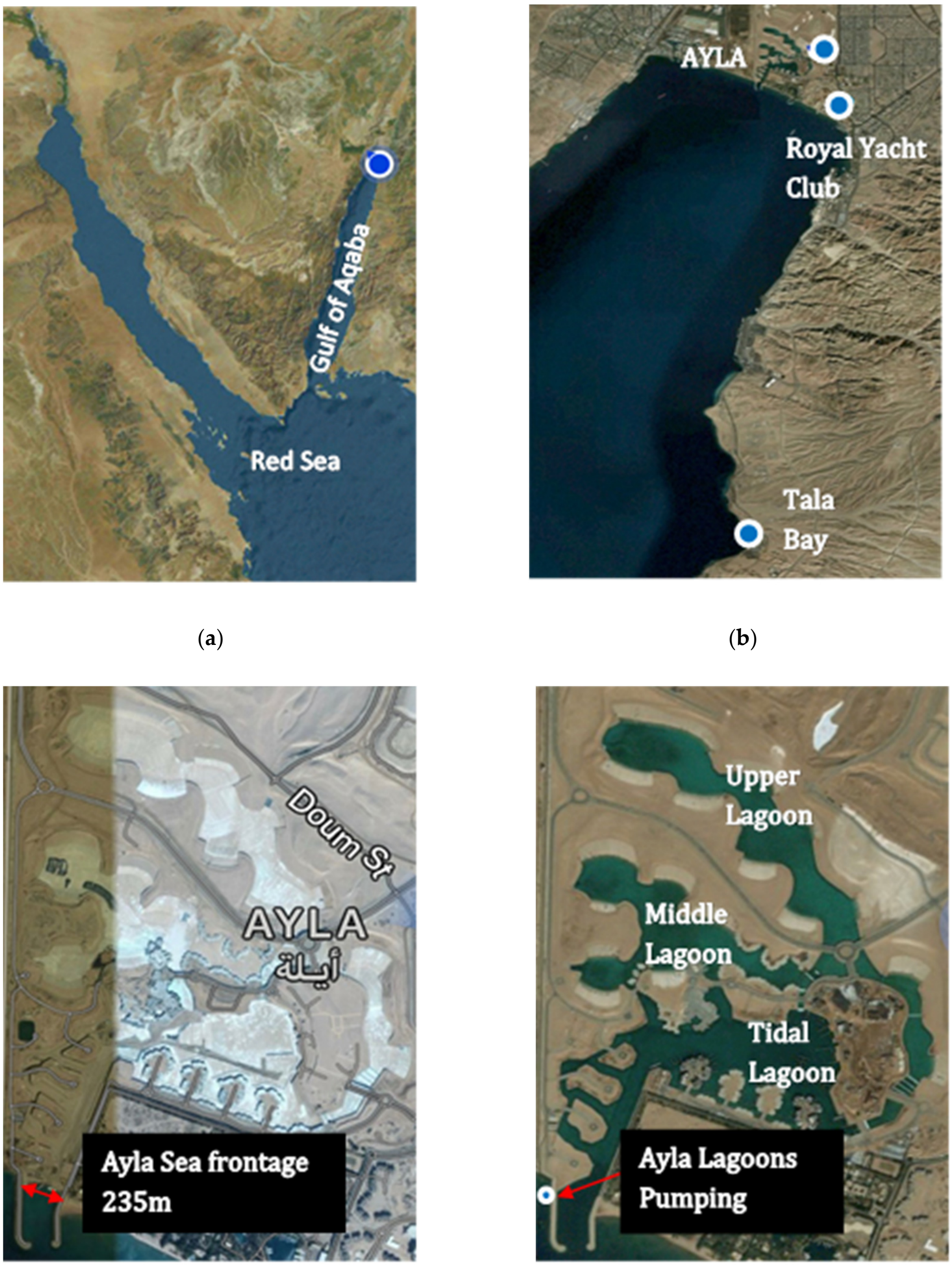
Eutrophication is a state of an aquatic ecosystem exposed to an increase in nutrient concentrations from point and non-point sources, leading to increased phytoplankton and algal biomass in the water column, and causing decreased levels of dissolved oxygen in water, which all can lead to deterioration of water quality and negatively impacts the ecosystem functioning in general, and coral reefs in particular [19–22]. The eutrophication status of two artificial lagoons, Royal Yacht Club (RYC) and Tala Bay (TB), in the GoA (Figure 1b) has been discussed by Rasheed et al. [18]. Briefly, the two lagoons were exposed to the adjacent "ambient" seawater through a single passageway, depending solely on natural exchange of water with the adjacent open seawater through the single lagoon opening. This study provides the first opportunity to compare water quality data from an artificial lagoon (Ayla lagoons) specially equipped with a seawater pumping system, which pumps ambient seawater into the lagoons to maintain "close to ambient" in-lagoon water quality. Such a system maintain the oligotrophic status of water and help in minimizing eutrophication which can adversely affect the health of the ecosystem in general and the more sensitive corals in particular [23], both in the lagoon and the GoA seawater.

Coastal ecosystems reside under several anthropogenic stressors that are leading to deterioration in water quality and are detrimental to many of the organisms living in these habitats [15,16,20,24–26]. The situation is even more challenging in the country of Jordan, which claims one of the smallest slices of this coastal pie along the GoA (Red Sea), with just 27 km providing Jordan with its only access to the sea. Thus, large development projects associated with tourism and transportation are all taking place within a small, semi-enclosed system and result in pollution, habitat destruction, and overfishing [4,8,27,28].

It has always been a challenge for investors to engage in touristic seafront developments, and this is especially challenging in areas where the coastline is limited, such as the Jordanian GoA. The Ayla Oasis project with its artificial inland lagoons systems attempted to present a potential solution by establishing a new mega-development project with minimal effects on the natural habitats in the short and valuable coastline of the GoA. With a seafront of 235 m over the GoA (Figure 1c), Ayla has developed an additional 17 km of waterfront to the Aqaba coastline, through man-made lagoons that are directly connected to the sea.

Studies indicate that healthy water quality in lagoons can be maintained through the provisioning of adequate flushing conditions and minimal discharge or runoff of pollutants such as sewage and nutrients into the lagoons [11,14,16–18,29]. In order to maintain reasonable water quality in the Ayla Oasis lagoons, international standards have been applied during the design, construction and operation, through engagement with marine experts who carefully developed a water quality model, recommended adequate water replenishment system before construction, and established a detailed water quality monitoring program during the operation.

This study includes twelve months of data, starting when the Ayla lagoons were commissioned and filled with the GoA seawater in June 2012. The aims of this study are to provide the first baseline Chlorophyll *a* (Chl *a*) and nutrient concentration water quality monitoring data for a newly constructed and commissioned inland artificial lagoon (Ayla) and to investigate the role of the lagoon's modeled design and water replenishment system in affecting water quality inside the lagoon and on the coastal ecosystem of the GoA, comparing it to two other artificial lagoons lacking proper design and water replenishment systems in the GoA.



(**a**) (**b**)

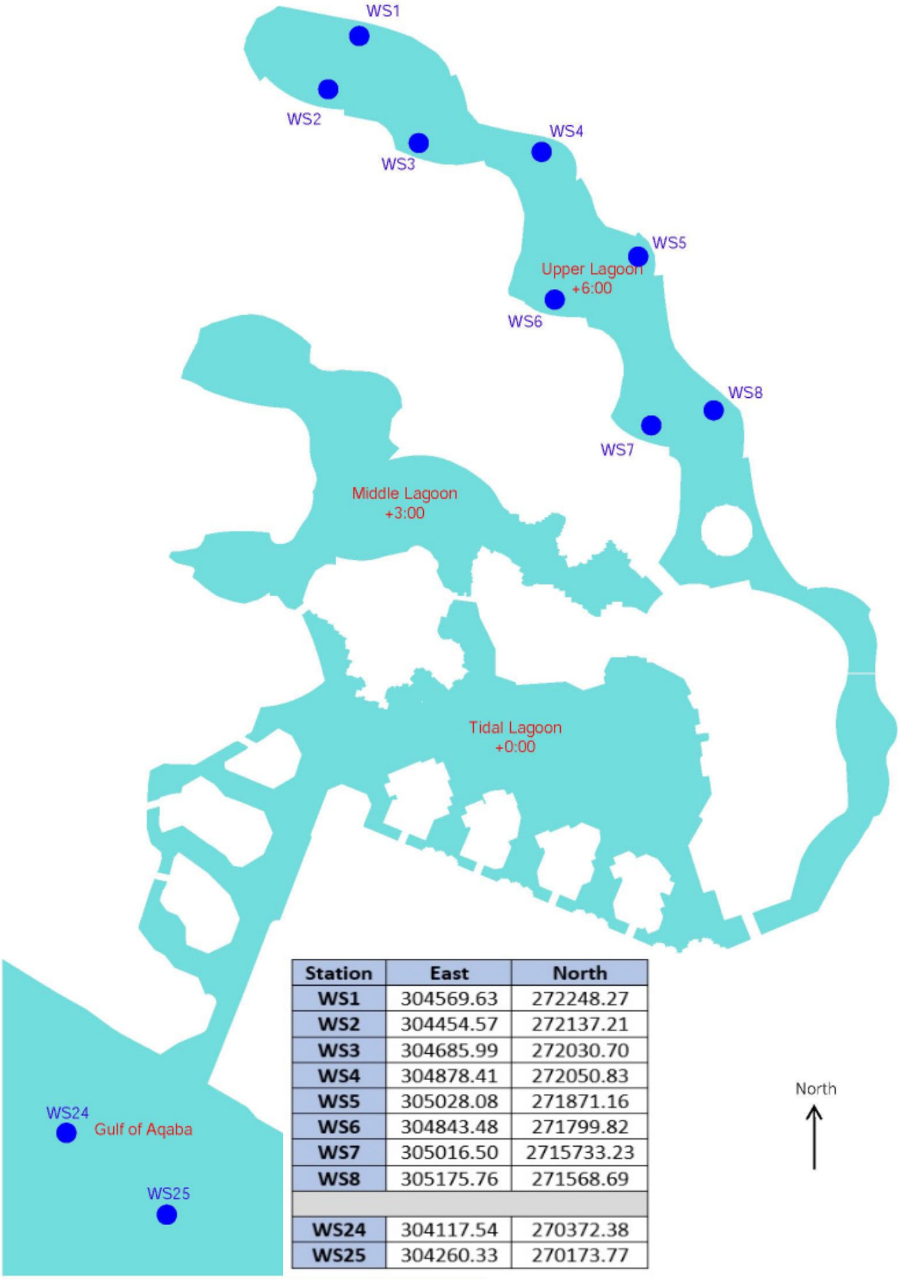
(**c**) (**d**)

Figure 1. Maps showing: (**a**) the location of the Gulf of Aqaba (GoA) in relation to the Red Sea; (**b**) the locations for Ayla, Royal Yacht Club, and Tala Bay in relation to the GoA; (**c**) Ayla lagoons before pumping in the water, showing the sea frontage of 235 m; (**d**) Ayla lagoons after they were filled with seawater pumped from the GoA in May 2012.

2. Materials and Methods

2.1. Study Site

The Ayla project contains three artificial inland lagoons, with a total area of 750,000 m^2. The upper and middle lagoons (in the north and center of the Ayla project, respectively) have water surfaces at 6.0 m and 3.0 m above sea level, respectively. The upper and middle lagoons have water volumes ~374,000 m^3 and ~246,500 m^3, respectively. Both have depths of ~1.95 m. The third lagoon (tidal lagoon) is directly connected to the gulf with a water surface the same as the sea level, water depth ~10.2 m, and water volume ~1,525,000 m^3 (Figures 1d and 2).



Station	East	North
WS1	304569.63	272248.27
WS2	304454.57	272137.21
WS3	304685.99	272030.70
WS4	304878.41	272050.83
WS5	305028.08	271871.16
WS6	304843.48	271799.82
WS7	305016.50	2715733.23
WS8	305175.76	271568.69
WS24	304117.54	270372.38
WS25	304260.33	270173.77

Figure 2. Map illustrating the locations of water sampling stations. Water samples collected from stations WS1 through WS8 inside the upper lagoon (UL). The two offshore stations WS24 (pumping station) and WS25 located outside the lagoons were used as reference stations, representing the ambient conditions in the Gulf of Aqaba (GoA) seawater.

At the design stage of the project, Ayla assigned water quality specialists to undertake a mathematical water quality model for the lagoons with the main objective being to investigate the potential for phytoplankton growth in the project's lagoon system. Due to the limited seafront on the GoA, the system was not capable of flushing itself adequately. Therefore, the water quality specialists recommended forced flushing. Accordingly, in order to maintain reasonable water quality in the Ayla lagoons, a seawater replenishment system was designed which consists of a pumping station, associated pipelines, and discharge weir structures to pump GoA water into the lagoons and propel it back to the GoA by gravity. In addition, the nontidal lagoons (UL and ML) were insulated to avoid contamination from surrounding groundwater.

During the excavation of the lagoons, a dewatering system was put in place and activated to allow for the excavation in dry conditions. Excavation works were completed in April 2012 for the three lagoons, with the exception of a dam that was kept between the tidal lagoon and the GoA. Water pumping into the lagoons started in May 2012, with partial activation of the pumping system, and they took one week to be filled with water. This was followed by the opening of the dam between the tidal lagoon and the seawater, which was kept until the three lagoons were full of water to avoid sedimentation into the tidal lagoon. The water quality monitoring program was established, and samples were collected starting June 2012.

In this study, samples were collected from a total 10 stations, with 8 stations located in the UL only and covering the most of its area. The UL was of special interest to this study, since it has water input from the exclusively pumped ambient GoA seawater, without interference from other lagoons. An additional two stations (WS24 and WS25) located in offshore water of the GoA, outside the lagoon system and 100 m distant from the breakwaters, were selected and used as a reference location to indicate the ambient seawater conditions and to detect any impact from the lagoon water (Figure 2).

2.2. *Sampling Frequency and Sample Collection*

To study the seasonal changes in environmental conditions (nutrients) and their relationships with Chl *a*, samples were collected every month for 12 months to represent all four seasons during the period between July 2012 and June 2013: spring (March, April, and May), summer (June, July, and August), fall (September, October, and November), and winter (December, January, and February). Samples were collected in triplicates from each station at 1 m depth using 1 L sterile high-density polyethylene (HDPE) containers using standard aseptic techniques. Collected samples were immediately stored in the same container in a dark, cooled (ca. 1–4 °C) chest-box and transported to the laboratory (ca. 2–3 h later) for processing.

2.3. *In Situ Measurements*

In situ measurements of multiple parameters were recorded for each sampling station simultaneous to water sampling. Salinity was measured using self-contained conductivity, temperature, and depth meters (CTD) Model Ocean Sensors OS200 and OS453. Dissolved oxygen (DO) was measured using a precalibrated portable dissolved oxygen meter model YS1 58 equipped with a 5739 probe (YSI Inc. Yellow Springs, OH, USA). The pH was measured using an HI-8424 handheld water-resistant pH meter (Hanna Instruments Ltd., Bedfordshire, UK). Water transparency was estimated using a white Secchi disc, 30 cm in diameter [30].

2.4. *Sample Processing*

Immediately after arriving at the laboratory, samples were vacuum filtered, using 0.45 μm cellulose acetate membrane filters, into sterile HDPE containers and stored at −20 °C until further analysis. Filters were also kept at −20 °C and used for Chl *a* analysis.

Chl *a* was determined by fluorometry [31], where the 0.45 μm cellulose acetate membrane filters were transferred to 15 mL polyethylene tubes followed by overnight pigment extraction at 4 °C in 90%

(v/v) aqueous methanol, then measured using TD-700 fluorometer (Turner Designs, Sunnyvale, WA, USA); the detection limit for Chl *a* was 0.01 µg/L using 25 mm diameter test tubes.

Before chemical analysis, frozen samples were thawed at room temperature with shaking. Nutrient concentrations (nitrite, nitrate, ammonium, phosphate, and reactive silicate) were measured according to [32]. The detection limits for the nitrate, nitrite, ammonia, phosphate, and silicate were ±0.1, ±0.01, ±0.1, ±0.01, and ±0.5 µM, respectively.

2.5. Statistical Analysis

Statistical analysis for water quality (Chl *a* and nutrients) was performed using analysis of variance (ANOVA); two-way ANOVA was used for comparisons between season across sites, and one-way ANOVA was used for comparisons between season within sites. ANOVA analysis was followed by the post hoc test of Holm–Sidak multiple comparisons to quantify the effects of site and/or season on the levels of Chl *a* and nutrients. Although Tukey SD or Scheffe analysis could be used; Holm–Sidak analysis was used as it is often more powerful. Brown–Forsythe test was used to quantify differences in variability between sites or seasons. Levels were deemed significant if the *p*-values were less than 0.05. Statistical analyses were performed using GraphPad Prism 7.

3. Results

Chl *a* levels and variability between samples varied between seasons and sites (Figure 3, Supplementary File S2). There was no overall difference in Chl *a* levels between the UL and reference sites (stations WS24 and WS25 representing the ambient seawater conditions in the GoA) ($p = 0.456$), but there were seasonal differences. These differences were stronger in ambient conditions ($p = 0.0064$) than in the UL ($p = 0.1049$), with values in fall being significantly lower than summer in ambient water ($p = 0.002$) and in the UL ($p < 0.0001$) (Supplementary File S3). Overall, there was more heterogeneity in variability in the UL ($p = 0.009$) than in ambient water ($p = 0.678$). In particular, there was significantly more variability in spring than summer ($p = 0.012$) and in fall than winter ($p < 0.0001$) in the UL.

Overall, ammonium levels were higher in the UL than in ambient water ($p = 0.0138$) (Figure 3). There was a decrease in ammonium levels during fall compared to other seasons, the decrease being stronger in ambient conditions than in the UL, though that decrease is not significant.

Nitrate levels showed a different pattern than ammonium (Figure 3). A clear contrast between the UL and ambient conditions is observed, with the ambient water being more stable than the water in the UL, and more heterogeneity being observed in the UL. Although nitrate levels remained relatively stable and similar across seasons and between the UL and ambient conditions, there was a lot of variability in the UL between spring and fall seasons. This could be seen as a pattern similar to the one observed for Chl *a*, as shown in Figure 3. Stable values were observed in ambient water during spring and summer. In comparison, the UL showed higher nitrate levels during both seasons than in ambient conditions but, most importantly, a large increase in variability. Nitrate levels showed a tendency to decrease during fall in both ambient conditions and the UL. A difference in variability was observed in the UL between seasons, showing significant variability between spring and summer ($p < 0.0001$) and between fall and winter ($p < 0.0001$). Finally, winter values showed similar variability to that observed in summer.

Nitrite level changes (Figure 3) show a different pattern than that of nitrate. There is no noticeable change in variability across seasons but a more marked difference in levels between them. Also, the difference between the UL and ambient conditions was not significant ($p = 0.055$). There is a strong seasonal effect inside the UL and in the ambient seawater ($p < 0.0001$). Except between summer and fall, seasonal changes are significant in both UL and ambient waters (Supplementary File S3).

Although phosphate levels remained quite similar between the UL and ambient conditions, they show changes between seasons (Figure 3). These differences, though quite comparable between sites, appear significant only in the UL because of larger sample sizes for the UL (Supplementary File S3).

Silicate levels were overall higher in the UL than in ambient water ($p = 0.001$) (Figure 3). There is also a significant seasonal effect over the UL and ambient water ($p = 0.0002$). Again the seasonal differences are significant only in the UL because of larger sample size ($n = 8$ stations for the UL; $n = 2$ stations the reference sites) (Supplementary File S3). Summer and fall were noticeable for a difference in variability between the UL and ambient conditions ($p = 0.0029$ and $p = 0.0153$, respectively) (Figure 3).

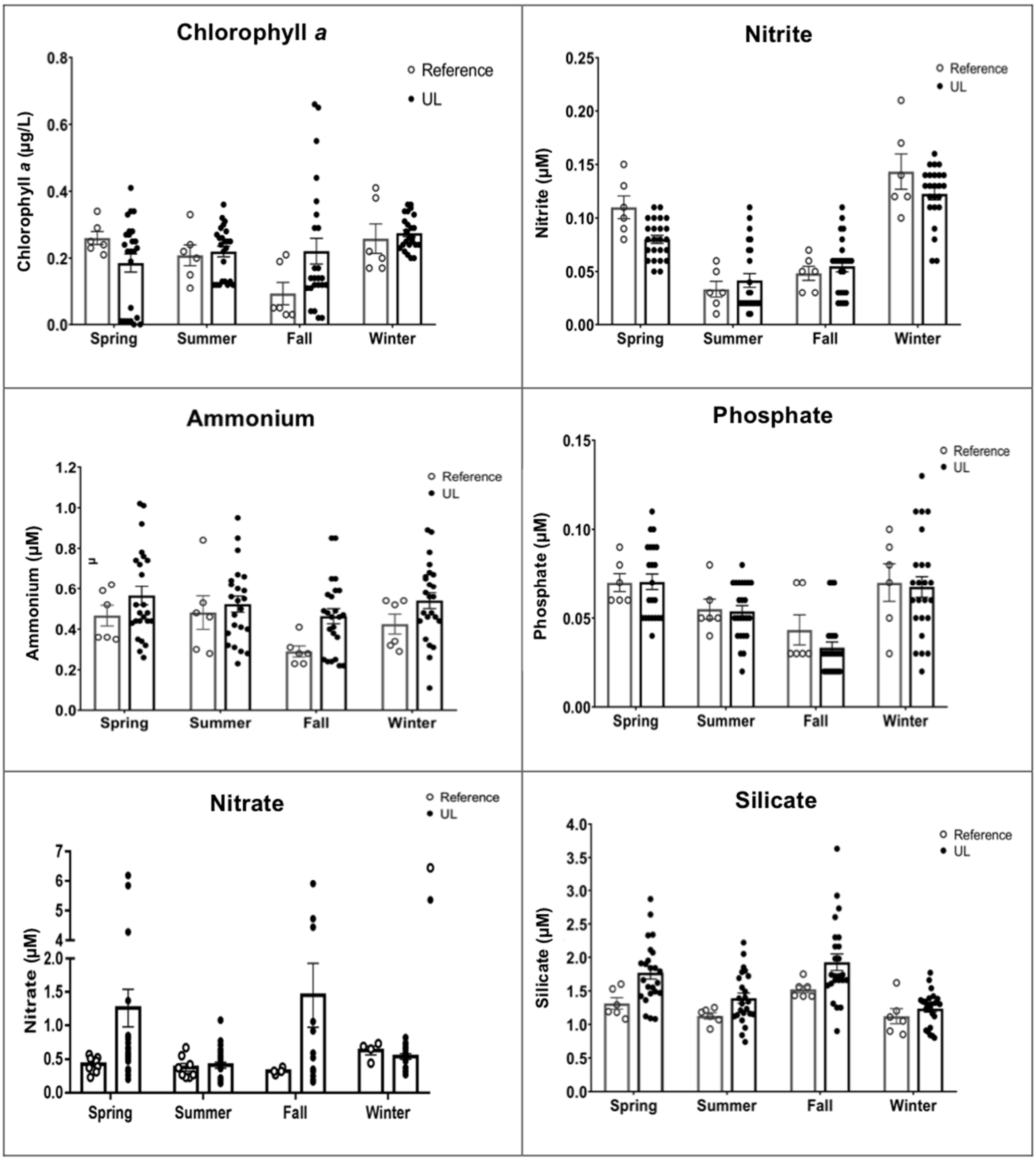


Figure 3. Seasonal water quality parameters as measured in Ayla's upper lagoon (UL) and the offshore reference stations of the Gulf of Aqaba (GoA). Seasonal average concentrations of Chl *a* (µg/L), ammonium (NH_4-N; µM), nitrate (NO_3-N; µM), nitrite (NO_2; µM), phosphate (PO_4-P; µM), and silicate (SiO_2; µM) were measured between July 2012 and June 2013. UL shows significant Chl *a* heterogeneity between seasons, while the reference stations (ambient seawater conditions) show significant differences between seasons.

4. Discussion

Ayla's UL experiences more widely varying temperatures (16.2–28.8 °C), as shown in Supplementary Files S1 and S2 and discussed by Manasrah [29], than the ambient conditions in the GoA water (22.7–27.7 °C) [18,27,29,33–36]. In particular, the UL has much lower winter temperatures (16.2–21.8 °C) than the ambient GoA water conditions (21.9–23.8 °C); this is due to the UL's shallow depth (~2 m) and high surface area, which makes it more vulnerable to losing heat due to surface wind effects, therefore decreasing its temperature during the winter. Dissolved oxygen concentrations showed an inverse pattern with temperature, increasing during winter and decreasing during summer, as shown in Supplementary Files S1 and S2 and discussed for the UL by Manasrah [29]. A similar pattern was observed for the GoA by others [18,27,28].

Inorganic nutrient (ammonium, nitrate, nitrite, phosphate, and silicate) availability is crucial for primary productivity and phytoplankton growth. High concentrations of Chl *a* and nutrients observed during the winter in both the UL and the reference stations (Figure 3, Supplementary File S2) occur in the GoA due to the vertical mixing of the water column during the winter season [27]. At the same time, no significant differences in Chl *a* values were observed between the UL and reference sites, which can be also related to the low pumping rate of water during these months (ranging from 5.5–6.1 $m^3 s^{-1}$), as reported by Manasrah [29]. Also, the atmospheric dry deposition from the Saharan dust [37] can be another reason for the increase in silicate during the fall in both the GoA and UL (Figure 3). Such an increase in silicate may be another player in the increased productivity observed only in the UL. Besides, the small water volume of the UL and the lack of exposure to vertical water mixing can lead to that increase in Chl *a* values in the UL compared with GoA. In the spring, Chl *a* values remained elevated in both reference and UL stations, and the UL values were divided into two groups: one with very low concentrations and one with concentrations ranging between 0.2 and 0.4 µg/L (Figure 3, Supplementary File S2).

There were no significant differences in Chl *a* values between the ambient water in the GoA and inside the UL. At the same time, seasonal differences were significant in the ambient water and not significant in the UL (Supplementary File S3), indicating the potential of maintaining a low Chl *a* level in the UL achieved by the increased pumping rate of ambient water into the lagoon, leading to decreased residence time and a maximum Chl *a* value of 0.66 µg/L. Despite the high nutrient concentrations recorded during March 2013, a sharp drop in Chl *a* values was observed followed by rapid recovery in April 2013 (Supplementary Files S1 and S2). The low Chl *a* to nutrient concentration ratio during such a very short period contradicts the traditional eutrophication models and may support the top-down control of the trophic web suggested by Pérez-Ruzafa et al. [38], where the rapid growth of primary producers in response to nutrient inputs is controlled by zooplankton in the short term, which in turn is simultaneously controlled by the higher trophic level organisms. Overall, Chl *a* values in the UL were maintained under the acceptable threshold value of 1 µg/L for healthy marine water quality [22,24,26,28] and do not contribute to any health risks for the ambient coastal ecosystem of the GoA.

A seasonal effect was observed in nitrite levels in both the UL and ambient seawater ($p < 0.0001$), but differences between the UL and ambient conditions were not significant ($p = 0.138$). The elevation of nitrite in the UL during the winter is consistent with that in ambient water (Figure 3) and similar to that observed by others [18,27,28,39]. This result indicates that ambient water is a major contributor to the loading of nitrite in the winter, when the nutrient-rich deep water is coastally upwelled and mixed with surface ambient seawater. This trend is observed in the fall and increases significantly in the winter [27].

Several studies have discussed marine water quality and the adequate nutrient maximum values in order to maintain healthy marine coastal ecosystems, particularly healthy coral reef communities. Few of these studies established liberal high threshold nutrient values, such as those set by Speijers et al. [40] for the Netherlands, Bricker et al. [41] for the United States of America, and Environment Australia [42] for Australia and New Zealand's waters. Other studies were more conservative in setting the maximum threshold values for oligotrophic waters guaranteeing healthy coral reef system, setting these as 1 µM of dissolved inorganic nitrogen (DIN; sum of nitrate, nitrite, and ammonium), 0.1 µM dissolved inorganic phosphate (DIP), and 1 µg/L Chl *a* [18,24,26,43]. The GoA water is considered to be oligotrophic environment [23,27], and a set of maximum nutrient threshold values have been established for the oligotrophic waters of the Jordanian Gulf of Aqaba water by Badran and Zibdeh [39], outlined as 1.5 µM DIN, 0.15 µM DIP, and 1 µg/L Chl *a*. In order to determine the oligotrophic status of marine environments, several models have been established to indicate the limiting or polluting nutrient affecting a water body [44–47]. The most popular model is the Redfield nitrogen-to-phosphorus (N:P) ratio of 16:1, which is indicative of an ambient stoichiometry of nitrogen and phosphorus; N limitation is indicated by a ratio lower than 16:1 and limitation by P availability is indicated by a ratio higher than 16:1 [46,48]. The nutrient that is limiting primary productivity in the oligotrophic water of the GoA has been reported to be DIN [28,49].

Table 1 shows water quality inside Ayla's UL and compares it with the RYC and TB lagoons (Figure 1b), evaluated by Rasheed et al. [18], in the GoA. The numbers in the table were put into context using the percentage of values exceeding the thresholds of oligotrophic status established by Badran and Zibdah [39]. Although Ayla's UL showed 19% DIN and 2% DIP exceedance of the threshold values of 1.5 and 0.15 µM, respectively, the Chl *a* values never exceeded the thresholds of 1 µg/L. This clearly demonstrates the effectiveness of Ayla's water replenishment system in maintaining an oligotrophic water quality corresponding to the water quality standards set by the several stringent threshold standards [19,24,39,43]. At the pumping inlet (WS24) and the reference station (WS25) for Ayla lagoon, DIN, DIP, and Chl *a* recorded 0% violation for the oligotrophic status thresholds. The DIN:DIP (16:1) ratio of the pumping inlet in Ayla's UL is in congruence with the Redfield ratio, which makes it a good quality water for replenishing the lagoon system. At the same time, the high DIN:DIP (25:1) ratio observed in the Ayla's UL water along with low water primary productivity (Chl *a* values less than the threshold values for oligotrophic water) denote that phosphate is limiting in the Ayla's UL water. A similar conclusion was reported by Rasheed et al. [18], indicating that phosphorus was the limiting nutrient in TB. The elevation in DIN in the UL could be related to sources other than the inlet water.

Table 1. Comparisons of the frequency of exceedance (%) oligotrophic test for DIN, DIP, and Chl *a* in different lagoons. Ayla's upper lagoon (UL) is compared to other lagoons in the Gulf of Aqaba (GoA) (Tala Bay lagoon and Royal Yacht Club lagoon), according to threshold values (1.5 µM, 0.15 µM, and 1 µg/L respectively) set for GoA by Badran and Zibdah [39].

Lagoon	Location	DIN (%)	DIP (%)	Chl *a* (%)	DIN:DIP (µM:µM)	Reference
Ayla Upper Lagoon	Inside Upper Lagoon	19	2	0 [1]	25 [2]	This study
	Pumping Inlet	0	0	0	16	
	Reference	0	0	0	19	
Tala Bay Lagoon	Inside Lagoon	85	9	36	46	[18]
	Entrance	25	4	6	21	
	Reference	4	0	1	15	
Royal Yacht Club Lagoon	Inside Lagoon	40	<1	7	24	[18]
	Entrance	21	1	1	20	
	Reference	10	0	1	16	

[1] Chl *a* value in the UL never exceeded that of oligotrophic conditions. [2] Six outlier points excluded.

Previous studies have suggested the importance of introducing water circulation systems to increase water exchange for the purpose of eutrophication management in lagoons [15,18,27]. At the same time, there has been a lack of studies documenting the implementation of replenishment systems to manage the trophic status of either natural or artificial lagoons. Given the lack of water quality data from artificial lagoons with seawater replenishment systems, most comparisons in this study were done via correlation to reference stations located in the adjacent GoA seawater.

Some comparisons were done with the other two lagoons [18], lacking water pumping systems and only allowed to exchange seawater naturally through a single lagoon opening to the ambient seawater, resulting in poor water quality compared to ambient GoA water quality [18]. This comparison emphasized the importance of lagoon design, water circulation, and flushing in maintaining healthy coastal seawater quality.

In order to evaluate the temporal extent of the trophic state of the UL after several years of commissioning, a few data points (Chl *a* and nutrients) have been collected as part of the water quality monitoring program for the Ayla lagoons during the years 2018–2019 (Supplementary File S1). The average Chl *a* values recorded were 0.42, 0.23, 0.41, and 0.72 µg/L for the seasons spring, summer, fall, and winter, respectively. During this period, the maximum Chl *a* value recorded was 0.78 µg/L, which is still under the acceptable threshold value of 1 µg/L for healthy marine water quality [22,26,28]. As the Ayla lagoon system has an active water pipeline pumping into the lagoons, we have no comparable water quality data from artificial lagoons with proper water exchange elsewhere. With that caveat, and when compared after several years and with GoA ambient seawater, the data suggest that the Ayla lagoon is considerably oligotrophic when compared with the other eutrophic artificial lagoons in the GoA or worldwide [18,27,41,49]. This pattern may be explained by the lack of water replenishment pumping systems in the other artificial or natural lagoons and by the lack of properly modeled lagoon design, in comparison to the UL of Ayla, resulting in the big differences in nutrient characteristics and healthier water in the UL and the adjacent coastal ecosystem over space and time.

5. Conclusions

This study highlights the importance of implementing a carefully modeled design and emphasizing the need of provisioning a proper seawater replenishment system in the construction of any lagoon project, especially tourist lagoons. This shall maintain healthy water quality inside the lagoon, prevent and inhibit eutrophication inside the lagoon, and also save and preserve the coastal ecosystem from contamination.

On the other hand, this study gives preliminary insights into the utility of artificial lagoons equipped with seawater replenishment systems, where water pumping into the lagoons can be tweaked, in studying the dynamics of inland artificial lagoons once they are commissioned and how such systems develop in terms of water quality.

Supplementary Materials: The following are available online at http://www.mdpi.com/2077-1312/8/3/147/s1, S1: Excel spreadsheet containing raw data points and values used in this study, in addition to some descriptive statistics. S2: Word document containing descriptive analysis figures for Chl *a* and physical parameters. S3: Word document containing a table showing Holm-Sidak's multiple comparison tests for seasonal Chl *a* and nutrient (ammonium, nitrate, nitrite, phosphate, and silicate) values.

Author Contributions: Conceptualization, M.M.D.A.-R.; data curation, M.M.D.A.-R., A.S.-P. and M.S.; formal analysis, M.M.D.A.-R. and A.S.-P.; investigation, M.M.D.A.-R. and M.S.; methodology, M.M.D.A.-R., A.S.-P. and M.S.; project administration, M.M.D.A.-R.; resources, M.M.D.A.-R. and M.S.; supervision, M.M.D.A.-R. and M.S.; visualization, M.M.D.A.-R., A.S.-P. and M.S.; writing—original draft, M.M.D.A.-R.; writing—review & editing, M.M.D.A.-R., A.S.-P. and M.S. All authors have read and agreed to the published version of the manuscript.

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