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Preliminary Findings on Temporal and Spatial Variations in Phosphate Dynamics in Riverine Systems in Samoa

Taema Imo[1*], Patila Amosa[2], Roya Ieremia[3], Tina Mareko[3], Taua Veni-Nun Yan[3]

[1]Faculty of Science, The National University of Samoa, Apia, Samoa
[2]Office of the Vice-Chancellor, The National University of Samoa, Apia, Samoa
[3]Department of Science, The National University of Samoa, Apia, Samoa
Email: taema.imo@gmail.com

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Abstract

This study investigates the temporal and spatial variations of phosphate concentrations in riverine systems, highlighting their relationship with precipitation patterns and temperature. Monthly climate data reveal distinct wet and dry seasons, with precipitation peaking in December and January at over 450 mm and 525 mm, respectively, and reaching its lowest levels in June and July at approximately 75 mm. Maximum and minimum temperatures remain stable, averaging 30˚C and 25˚C, respectively. Phosphate concentrations follow a seasonal pattern, with low levels (1.0 - 1.3 mg/L) recorded from July to November. Peaks occur in December (3.50 ± 0.63 mg/L) and June (4.00 ± 1.34 mg/L), coinciding with periods of heavy rainfall. Increased precipitation likely contributes to runoff from agricultural and residential areas, introducing higher phosphate loads into water bodies. Site-specific analysis reveals statistically significant differences ($p < 0.05$), in phosphate levels, influenced by land use, vegetation cover, and human activities. The lower stream, subject to cumulative upstream runoff, exhibits the highest variability, while the upper stream shows reduced concentrations due to minimal human interference and better vegetation cover. This study provides critical insights into the interplay between climatic variables and nutrient dynamics, offering valuable implications for water quality management and the preservation of aquatic ecosystems in Samoa.

Keywords

Ecosystem Services, River Ecosystems, Nutrients, Climate Change, Samoa

1. Introduction

The Pacific region, including Samoa, has long been a focal point for understanding the intricate relationship between nutrient pollution and its impacts on aquatic systems. Research highlights the unique challenges faced by island nations, where small land areas, reliance on subsistence farming, and close proximity of human settlements to water bodies intensify vulnerability to nutrient runoff. Among these pollutants, phosphates (PO_4^{3-}) and nitrates (NO_3^{-1}) stand out as the most pervasive contaminants in aquatic ecosystems. Runoff from agricultural lands, especially where fertilizers are extensively used, has been identified as a significant contributor to these elevated nutrient levels in rivers (Badamasi et al., 2019). Phosphates, the most common form of phosphorus found in natural waters (Shen et al., 2020), are moderately soluble and less mobile in soil and groundwater compared to nitrates. However, their accumulation in water bodies results in eutrophication, a pressing global concern that brings widespread ecological disruptions to riverine systems (Tanaka et al., 2021).

Eutrophication triggers a cascade of harmful effects, from the creation of hypoxic conditions that suffocate aquatic life (USGS, 2020) to the rampant overgrowth of algae. These algal blooms produce toxins, shift species composition, and lead to declines in biodiversity (NOAA, 2024). Compounding this issue is the connection between eutrophication and climate variability. Fluctuations in climate can lead to profound changes in ecosystem composition, function, and the services these ecosystems provide (Dokulil & Teubner, 2010). Recent findings shed light on how precipitation and temperature variability influence the movement of nutrients into aquatic ecosystems. Heavy precipitation accelerates the flow of nutrients, particularly nitrogen and phosphorus, into rivers (Tong et al., 2022). On the other hand, temperature moderates nutrient export levels, primarily by driving biochemical reactions that affect nutrient cycling (Soana et al., 2024).

The link between nutrient cycling and broader climate dynamics is also evident in changes to atmospheric CO_2 levels. For example, the interplay between phosphorus (P) dynamics and rising CO_2 concentrations has been shown to reduce the terrestrial carbon sink by approximately 26%, emphasizing the critical role of nutrient management in tropical ecosystems (Yang et al., 2016). Additionally, drought conditions, common in tropical rainforests, can alter soil biogeochemistry, disrupting the availability and cycling of phosphorus (Fu & Zhang, 2020). These effects ripple beyond aquatic ecosystems, posing risks to human health as communities dependent on rivers for drinking water and agriculture face the challenges of degraded water quality.

In Samoa, climate variability magnifies these challenges, as extreme weather events such as cyclones and heavy rainfall increase nutrient pollution. During intense rainfall, surface runoff intensifies, carrying surges of nutrients into rivers and streams. These sudden nutrient influxes alter the chemical composition of water bodies, fostering algal blooms and depleting oxygen levels. Such episodic disruptions can destabilize the balance of riverine ecosystems, making them increasingly vulnerable to future disturbances (SPREP, 2007).

Temperature variability further compounds these issues. Higher temperatures during dry seasons accelerate the breakdown of organic matter in soils, releasing phosphates and nitrates into water bodies. Concurrently, elevated temperatures enhance microbial activity, speeding up decomposition and raising nutrient concentrations. These complex feedback loops between climate variables and nutrient dynamics underscore the intricate connections within tropical ecosystems (Samoa Meteorological Services, 2024).

Samoa's geographic and ecological characteristics exacerbate its susceptibility to these environmental stresses. The steep volcanic topography and nutrient-rich soils of the islands are highly prone to erosion, particularly during heavy rainfall. This erosion introduces sediments loaded with nutrients into rivers, amplifying eutrophication's impacts. Moreover, the interconnectedness of terrestrial and aquatic systems in such a small island setting means that disturbances in one area can have far-reaching consequences throughout the ecosystem. These compounded vulnerabilities call for holistic, integrated approaches to environmental management. This study explores the temporal and spatial variability of phosphate dynamics in riverine systems under the influence of precipitation and temperature changes. Temporal variations are observed as seasonal fluctuations in phosphate levels, often linked to shifts in rainfall intensity, storm events, and temperature cycles. Periods of heavy rainfall can result in increased runoff, carrying higher loads of phosphate into waterways, while drier periods may reduce this input. Spatially, phosphate concentrations vary across different riverine sites depending on land use, catchment characteristics, and proximity to pollution sources, such as agricultural and urban areas.

Ultimately, addressing these issues necessitates a deeper understanding of the processes driving nutrient pollution and their ecological repercussions. By investigating the direct effects of human activities and climate on nutrient dynamics—and examining how these factors interact—it will become possible to craft strategies that mitigate nutrient pollution and bolster the resilience of Samoa's riverine ecosystems. Such efforts are vital for preserving not only the environment but also the well-being of the communities that rely on it.

2. Methodology

2.1. Study Area

The study was conducted at the Falese'ela River, located in the village of Falese'ela on the main island of Upolu in Samoa. The approximate geographical coordinates for the village, through which the Falese'ela River flows, are 13˚ 55' 55" south and 171˚ 58' 3" west (**Figure 1**). The Falese'ela River is a key freshwater system that supports local communities by providing water for agriculture, household use, and recreational activities. Its surrounding landscape is characterized by dense tropical vegetation, with a mix of subsistence farming and natural forested areas. The selected study site encompasses both upstream, midstream, and downstream sections of the river, allowing for a comprehensive analysis of spatial variations in phosphate concentrations and environmental conditions. Sampling points were strategically distributed to capture potential influences from land use patterns, including agricultural practices and residential developments, that could contribute to nutrient runoff. Data collection was undertaken during both the wet and dry seasons to assess the impact of seasonal climate variability on nutrient dynamics within the riverine ecosystem.

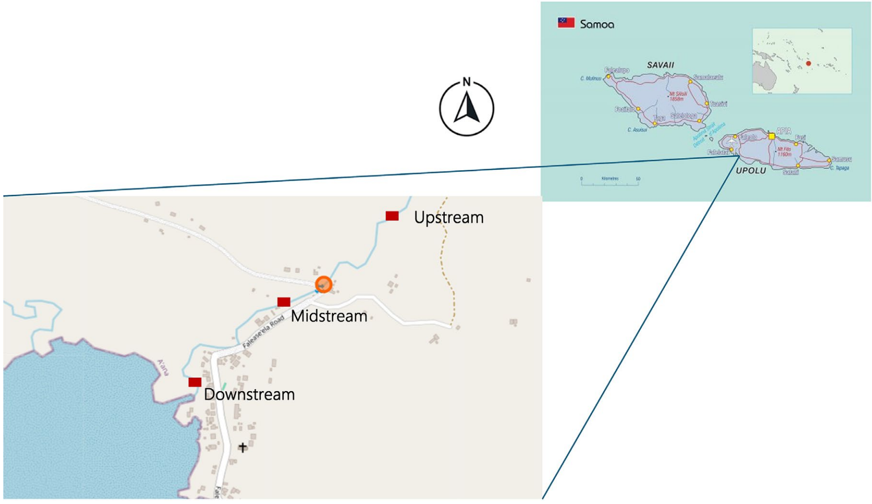

Figure 1. Sampling sites. (Sources: MNRE, 2024; https://sdd.spc.int/ws).

2.2. Sample Collection

Water samples were collected at each designated site using standardized procedures to ensure consistency and accuracy. Samples were stored in pre-cleaned, air-tight containers and transported on ice to the laboratory for further analysis (EPA, 1983). Key parameters measured included concentrations of phosphates (PO_4^{3-}) as well as temperature, pH, and dissolved oxygen levels. These variables were chosen to evaluate the relationship between nutrient loads and water quality in the Falese'ela River

2.3. Sample Collection

A vanadate-molybdate reagent was prepared by carefully mixing ammonium molybdate and ammonium metavanadate in hydrochloric acid (HCl). The solution was standardized meticulously to ensure consistency and accuracy in subsequent analyses. The vanadate-molybdate reagent is well-established in phosphate analysis due to its ability to react with orthophosphates to form a yellow-colored complex, which is quantifiable through spectrophotometric methods. The preparation process involved maintaining precise reagent concentrations to ensure the reproducibility of results, aligning with established protocols such as those outlined in APHA (1992). To calibrate the analytical process, a series of calibration standards were prepared using a standard phosphate solution with a known and verified concentration of phosphate ions. Aliquots of varying volumes of the phosphate standard solution were transferred into volumetric flasks, ensuring accurate measurement using calibrated pipettes. The vanadate-molybdate reagent was then added to each flask, and the solutions were diluted to the mark with deionized water. This preparation allowed the generation of calibration standards that spanned a wide range of phosphate concentrations, providing a robust basis for quantifying unknown samples. The prepared calibration standards underwent analysis using a UV/visible spectrophotometer equipped with a 2.5-cm light path and an infrared photocell. The instrument was configured to operate within a wavelength range of 700 - 880 nm. Specifically, the absorbance of each standard was measured at 880 nm, the optimal wavelength for detecting the yellow vanadate-molybdate-phosphate complex, as this wavelength provides maximum sensitivity and minimal interference from other compounds. The spectrophotometer was calibrated before use to ensure accurate and precise measurements, and all readings were performed in triplicate to enhance reliability. The absorbance data collected for each calibration standard were used to construct a calibration curve that established a linear relationship between absorbance and phosphate concentration. This curve served as the foundation for determining the phosphate concentrations in unknown samples. Rigorous quality control measures, such as the inclusion of blanks and replicate standards, were implemented to ensure the validity of the analytical process. Furthermore, the method adhered to strict laboratory practices to minimize errors. The glassware used in the preparation and analysis was thoroughly cleaned and rinsed with deionized water to prevent contamination. Deionized water was also utilized throughout the procedure to ensure the purity of solutions and reagents. The vanadate-molybdate method, combined with spectrophotometric analysis, has been recognized as a reliable and accurate approach for quantifying phosphate in environmental samples (Phansi et al., 2022), making it a valuable tool for monitoring nutrient pollution in aquatic systems.

2.4. Data Analysis

The data analysis was conducted using SPSS v26, a widely recognized statistical software for robust data handling and analysis. An ANOVA test was employed to determine whether statistically significant differences existed in phosphate levels across the sampling sites ($p < 0.05$). This method allowed for the comparison of mean phosphate concentrations to identify spatial variations. The test also evaluated the potential influence of environmental factors, specifically temperature and precipitation conditions, on phosphate dynamics. This comparison helped assess whether these variables had a significant effect on phosphate levels in the riverine system. In addition to ANOVA, a post-hoc test (Tukey's HSD) was applied when significant differences were observed, enabling a pairwise comparison of sampling months ($p < 0.05$) to pinpoint which months exhibited the most notable variations in phosphate levels. Correlation analysis was also performed to investigate the strength and direction of the relationship between phosphate concentrations and environmental variables such as precipitation intensity and temperature fluctuations. Descriptive statistics, including mean, standard deviation, and range, were calculated to provide an overall summary of phosphate levels during the study period. All statistical tests were conducted with appropriate checks for assumptions, such as homogeneity of variances and normality of data distribution, to ensure the robustness of the analysis. These methodological precautions were essential to derive meaningful conclusions about the factors driving phosphate variability within the riverine system.

3. Results and Discussion

Figure 2 illustrates the climate patterns, presenting data on monthly precipitation and temperature. Precipitation peaks in December and January, exceeding 450 mm (17.8 in) and 525 mm (20.7 in), respectively, before dropping to its lowest levels in June and July at approximately 75 mm (3 in). Maximum temperatures remain consistently around 30˚C (86˚ F) throughout the year, while minimum temperatures remain steady near 25˚C (77˚ F). This chart highlights a warm and stable climate with distinct wet and dry seasons.

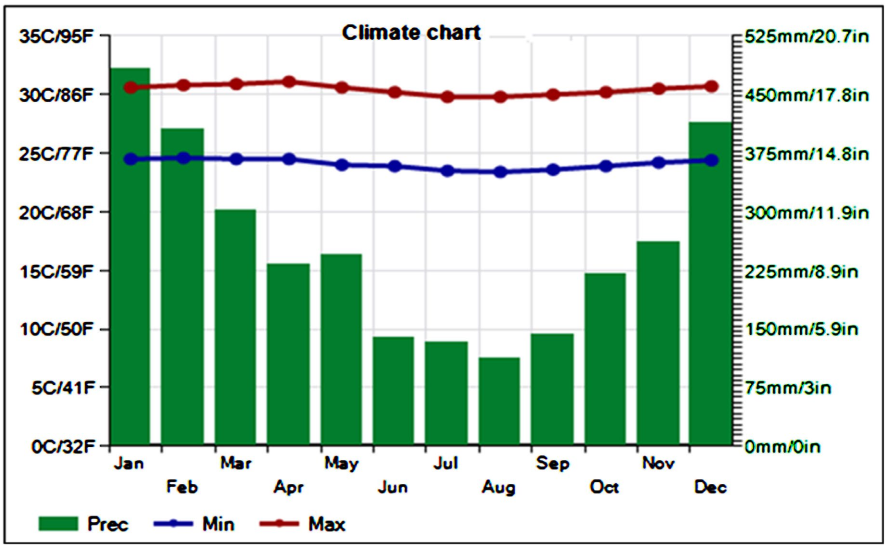

Figure 2. Annual rainfall and average temperature.[1]

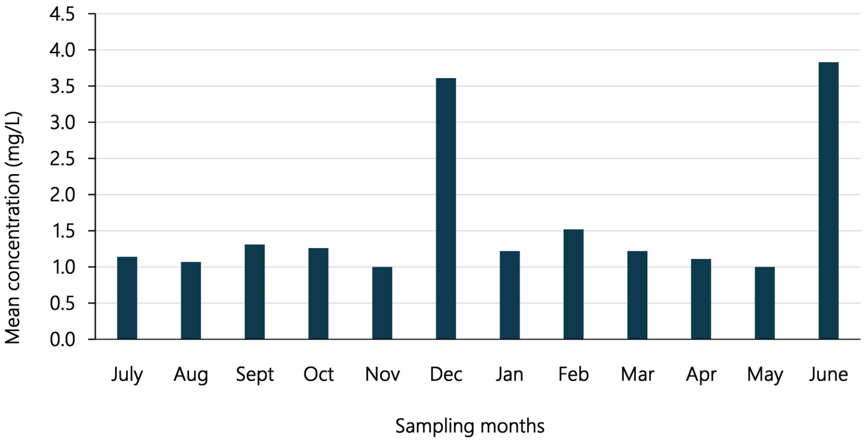

Figure 3. Phosphate concentration and sampling months.

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[1] Source: https://www.climatestotravel.com/climate/samoa.

Figure 3 depicts the variations in phosphate concentrations throughout the sampling period from July to June. Between July and November, phosphate levels remain relatively low, ranging from 1.0 to 1.3 mg/L. In December, there is a sharp increase, with concentrations peaking at 3.5 mg/L, followed by a decline in January to 1.5 mg/L. From February to May, the concentrations exhibit slight stabilization, fluctuating between 1.2 and 1.8 mg/L. A notable rise is observed in June, where phosphate levels reach their highest concentration of approximately 4.0 mg/L. The spikes in phosphate concentrations during December and June appear to align with periods of heavy rainfall. Increased precipitation likely results in greater runoff from agricultural lands and residential areas, introducing higher amounts of phosphates into water bodies. In contrast, the lower concentrations recorded between July and November may correspond to drier months, during which reduced runoff minimizes the flow of nutrients into aquatic systems. This relationship emphasizes the significant influence of seasonal precipitation on phosphate levels. Furthermore, reduced water levels caused by lower precipitation or higher evaporation rates can decrease the dilution of phosphates in water bodies, leading to increased concentrations (Oremo et al., 2020).

The results in **Table 1** indicate that the mean phosphate concentrations across the three sampling sites are significantly different ($p < 0.05$), suggesting that site location has a measurable impact on phosphate levels. Several site-specific factors—such as land use, water flow, vegetation cover, and human activities—likely contribute to these differences. For instance, the upper stream site may have lower phosphate levels due to minimal human activities and better vegetation cover, which can naturally limit nutrient runoff. In contrast, the middle stream site might exhibit intermediate phosphate concentrations, influenced by moderate levels of urban or agricultural runoff. The lower stream site is likely to have the highest phosphate concentrations, as pollutants and runoff from upstream areas accumulate in this location. These findings underscore the statistically significant differences in phosphate concentrations among the sampling sites. The observed variability can be attributed to local environmental factors, including the intensity of agricultural and residential runoff, differences in precipitation patterns affecting nutrient flow, and pollution sources or geographical characteristics unique to each site.

Table 1. ANOVA test.

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	336476.4	1	336476.4	39.4277	0.004	4.35124
Within Groups	170680.1	20	8534.007			
Total	507156.5	21				

In **Figure 4**, phosphate concentrations across all three sites remain relatively stable from July to October, clustering around 1 mg/L. This stability suggests consistent environmental conditions during these months. However, from November to January, phosphate levels gradually increase, with the mid-stream peaking in December at approximately 2 mg/L. The most notable trend occurs in June, when the lower stream experiences a significant spike, reaching around 6 mg/L. During this period, the upper and mid-streams also display increases, though these are less pronounced compared to the lower stream. The fluctuations in phosphate concentrations may be linked to seasonal variations, such as rainfall or agricultural cycles. For instance, the spike observed in June could result from fertilizer runoff during the planting season or heavy rainfall washing nutrients into the stream (Oremo et al., 2019; Ebrahimi & Ojani, 2024). Stream characteristics further influence these variations, with the lower stream exhibiting the highest variability, likely due to the downstream accumulation of nutrients or pollutants. Human activities, such as agricultural practices and industrial discharges, are additional contributors to localized spikes, particularly in areas where such influences are prominent (Salas & Subburayalu, 2019; Xu et al., 2020). The stable concentrations observed from July to October and February to April indicate minimal environmental disturbances or consistent management practices during these periods. Conversely, the drastic spike in June highlights the lower stream's susceptibility to external influences, possibly due to its downstream position, where runoff tends to accumulate. This underscores the necessity of consistent monitoring and mitigation measures to address these periodic spikes, which may harm aquatic ecosystems. The results presented in **Figure 4** emphasize the dynamic nature of phosphate concentrations and the interplay between natural factors and human activities, offering critical insights for targeted environmental management strategies. The correlation analysis reveals a very weak relationship between phosphate concentration, rainfall data, and temperature. This correlation is not statistically significant, indicating the importance of considering additional variables or employing more complex models to better understand the factors influencing phosphate concentrations. Adaptive management strategies,

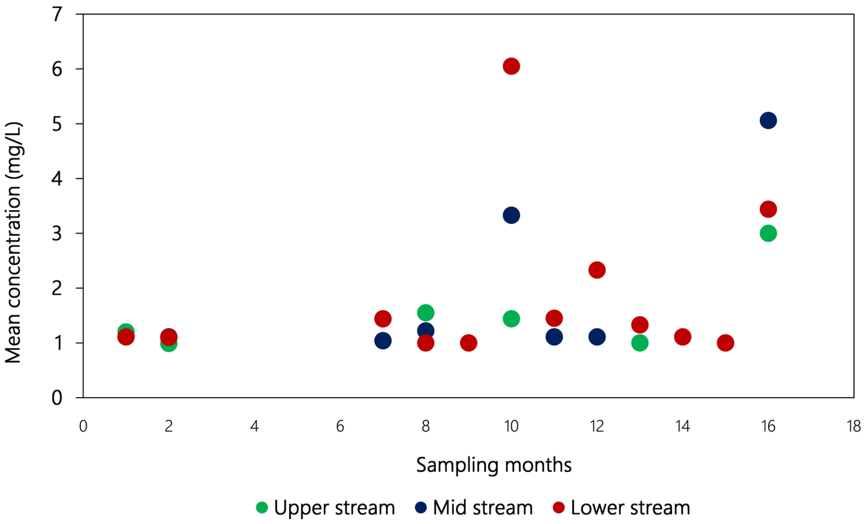

Figure 4. Phosphate concentration, sampling sites and sampling months.

such as implementing buffer zones and improving agricultural practices, can help mitigate the effects of climate change on phosphate levels. Additionally, ongoing monitoring and modeling efforts are essential for predicting future trends and formulating appropriate responses.

4. Conclusion

The study highlights the dynamic relationship between climate patterns, seasonal precipitation, and phosphate concentration variations in riverine systems. Distinct wet and dry seasons significantly influence phosphate dynamics, with precipitation peaks in December and January leading to increased nutrient runoff and elevated phosphate levels. This trend is further evident in the spikes observed in December and June, likely driven by heavy rainfall and agricultural activities. Conversely, the relatively low phosphate concentrations recorded during the drier months (July to November) underscore the importance of seasonal runoff in shaping nutrient flow. Site-specific factors play a critical role, as evidenced by the statistically significant differences in phosphate concentrations across the three sampling sites. Variability is influenced by environmental characteristics such as land use, vegetation cover, and human activity, with downstream sites experiencing the highest concentrations due to pollutant accumulation. Despite the weak correlation between phosphate concentrations, rainfall, and temperature, the findings emphasize the necessity of considering additional variables and complex interactions to better understand nutrient dynamics. Adaptive management strategies, including buffer zones, improved agricultural practices, and consistent monitoring, are essential for mitigating climate change impacts on water quality. By addressing natural and anthropogenic factors, these insights provide a foundation for sustainable water quality management and the protection of aquatic ecosystems. Continued research and proactive measures will be vital to safeguarding riverine systems in a changing climate.

Conflicts of Interest

I, Taema Imo hereby disclose the following potential conflicts of interest related to my involvement in the research publication titled “Preliminary Findings on the Temporal and Spatial Variations of Phosphate Dynamics in Riverine Systems: Implications for Water Quality Management in a Changing Climate”. The authors of this research paper declare that they have no actual or potential conflicts of interest related to this study. I have no personal relationships, interests, affiliations, or business activity with individuals or entities that have a vested interest in the research presented in the Publication.

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