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Inorganic Phosphorus Fractions and Sorption Capacity of Sediments Correlated with Physicochemical Parameters of Water in Langat River, Selangor Malaysia

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ABSTRACT

This study investigates the physicochemical parameters of water, their association with inorganic phosphate fractions, and the sorption capacity of sediments. Water and sediment samples were collected from upstream, midstream, and downstream sections between November 2022 and June 2023. The water samples were analysed according to the American Public Health Association (APHA) guidelines for physicochemical parameters. Inorganic phosphate fractions in the sediments were quantified using the molybdenum blue colourimetric method. Sediment phosphate sorption capacity was assessed by measuring the resulting filtrate and applying regression correlation and Langmuir isotherm models to determine the relationships among the sediment samples. Sediment analysis of inorganic phosphorous fractions revealed varying percentages of Ca-P (32.6%), Rs-P (38.3%), and Fe-P (48.4%) dominating the upstream, midstream, and downstream sections, respectively. Sediment phosphate adsorption varied between sections (upstream: 4.00 to 18.21 mg/g vs. midstream: 4.36 to 21.10 mg/g vs downstream: 4.00 to 12.98 mg/g), with no significant differences between streams at specific phosphate concentrations. However, all the sections displayed a saturation point of approximately 20–25 mg/l. The Langmuir isotherm parameters accurately described P adsorption onto Langat River sediments, as

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indicated by the moderately high R^2 values for Q_{max} and R_L. The downstream section of the Langat River had elevated levels of EC, COD and SRP parameters and Ex-P, Al-P, Fe-P, and Ca-P fractions, except for the Rs-P fraction that dominated the midstream section, indicating collective effects of anthropogenic activities. Therefore, strict regulations to improve wastewater treatment and promote sustainable wastewater management are essential for reducing inorganic phosphorus pollution in the Langat River and protecting water quality.

Keywords: Anthropogenic, adsorption, correlation, fractions, isotherm

INTRODUCTION

Rivers are important sources of freshwater, satisfying the daily water demands essential for human consumption and various industrial and agricultural applications (Baggio et al., 2021). Unfortunately, these freshwater sources are threatened by pollution with orthophosphates from many anthropogenic sources (Kaushal et al., 2021). Phosphorous pollution in rivers, primarily from agricultural runoff, industrial discharge, and sewage treatment plant effluents, can lead to water quality deterioration, biodiversity loss, and ecosystem imbalances, posing a significant concern as rivers serve as water consumption sources (Giri, 2021; Khalil et al., 2023). This pollution accelerates the ageing of water bodies through eutrophication caused by excess nutrients, especially phosphorus (Kakade et al., 2021). Phosphorous pollution of rivers leads to the proliferation of algae and aquatic plants, reduced water clarity, unpleasant taste and odour, decreased oxygen levels, and changes in the visual attractiveness of river landscapes (Bozorg-Haddad et al., 2021). In addition, algal blooms fuelled by phosphorus pollution can produce toxins that are harmful to humans, leading to skin irritation, liver and kidney damage, neurological disorders, and respiratory complications (Sha et al., 2021).

The Langat River in Malaysia is an important water body known for its ecological importance and various land uses within its watershed, including urban, agricultural, and forested areas (Yusof et al., 2021). This makes it an ideal model for studying phosphorus dynamics in different environmental conditions. The choice of the Langat River as a model for this research is influenced by several factors. First, several studies reported that the Langat River receives phosphorus inputs from multiple sources, such as agricultural runoff, urban discharges, and natural weathering processes (Al-Odaini et al., 2013; Ahmed et al., 2022), reflecting the common challenges faced by many rivers worldwide. In 2006, the Department of Environment (DOE) in Malaysia announced that the Langat River was polluted due to the rapid industrialisation along the Langat River, which caused river pollution (Basheer et al., 2017). Furthermore, the Langat River has been the focus of environmental monitoring and management efforts due to concerns over water quality degradation, including eutrophication and algal blooms (Basheer et al., 2017). Additionally, it is a vital water resource for domestic, agricultural, and industrial purposes (Juahir et al., 2011), highlighting the importance of managing phosphorus inputs to ensure sustainable water use and ecosystem health (Loi et al., 2022).

Despite the Langat River being the water source for treatment plants, the river faces significant threats from phosphorus pollution from various anthropogenic activities. This pollution disrupts the well-being of river ecosystems, leading to eutrophication and the formation of harmful algal blooms. Although numerous studies have identified the Langat River as polluted, there is still a lack of comprehensive understanding of the extent and sources of phosphorus pollution. Moreover, the implications of this pollution on water quality, ecosystem health, and the sustainability of water use remain unclear. Therefore, there is a pressing need for research investigating the dynamics of phosphorus pollution in the Langat River, including its sources, transport pathways, and environmental impacts. Hence, this study aimed to determine the physicochemical parameters of water, their association with inorganic phosphorus fractions, and the sorption capacity of sediments in the Langat River.

MATERIALS AND METHODS

Study Area

The Langat River is the longest in the Malaysian State of Selangor (LUAS, 2015). It is located at 101°50″E, 3° 45″N, 101 °10″ E, 3 °15″ N, and is approximately 60 km long and 30 km wide, covering a total area of 1820 km². Figure 1 indicates the map of the study

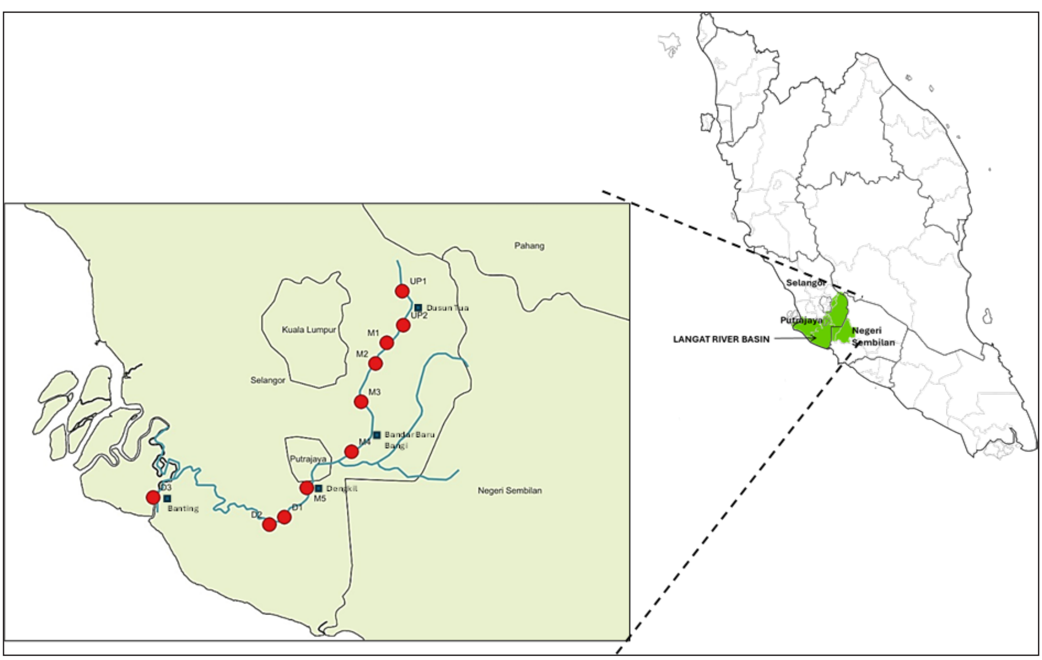

Figure 1. Map of Selangor, showing the sampling sites along the Langat River

location, showing the sampling sites, while Table 1 presents the list of Langat River study locations. The activities taking place by the river differ depending on the specific location. Small villages, orchards, and eco-tourism resorts predominantly occupy the upstream portions. The riverbanks are highly vulnerable to the possibility of collapsing. This region is susceptible to deforestation, intensified agriculture, and soil erosion (Basheer et al., 2017). The middle and downstream sections of the river are occupied by residential, industrial, and plantation areas. However, these areas are susceptible to pollution from several causes, including industrial, agricultural, and urban activities, both natural and human-induced (Zubir et al., 2016; Ahmed et al., 2022).

Table 1
Sampling locations of the Langat River

Location	Area	Latitude	Longitude	Sampling site
Upstream	Lui village	3.5931° N	101.8498° E	Pangsun recreational area and Sungai Congkak recreational forest.
Midstream	Kajang	3.2193° N	101.905° E	Dusun Tua, Long quarry road, Sg. Balak, Bangi and Dengkil.
Downstream	Banting	2°49’0”N	101°30’0”E.	Bukit Changgang, Labohan Dagang and Jugra

Sample Collection

Water samples from the Langat River were collected using a Van Dorn Vertical Sampler, and sediment samples were collected (~10 cm) using an Ekman grab sampler between November 2022 and June 2023 with designated points as UP1 and UP2 (upstream), M1-M5 (midstream), and D1-D3 (downstream). The glass bottles used for the water samples were acid-washed and rinsed with deionised water and then disinfected using five drops of an aqueous sodium thiosulfate solution to remove residual chlorine. Afterwards, the screw caps were loosely attached and covered with aluminium foil to prevent sticking during sterilisation (Wang & Ji, 2024). The bottles were placed in a dry oven heated to 170 ± 0.5 °C for an hour and then cooled. Sterile zip plastic bags were used for the sediment samples. All the samples were labelled according to the collection site and kept in a different cool box at 4°C before being transported to the Plant Systematic and Microbe Laboratory at the Department of Biology, Universiti Putra Malaysia. The water samples were immediately used for the determination of physicochemical parameters, while sediment samples were immediately freeze-dried and stored at -20°C (Chuang et al., 2021),

Determination of Water Physicochemical Parameters

The physicochemical parameters of the water samples were assessed following the American Public Health Association guidelines (APHA, 2005). On-site measurements of pH, electrical conductivity (EC), and dissolved oxygen (DO) were conducted with a Hach Multiparameter (HD401 probe meter). Other physicochemical parameters such as biological oxygen demand over five days (BOD_5), chemical oxygen demand (COD) and the soluble reactive phosphorous (SRP) were measured in the laboratory according to the methods of Nuruzzaman et al. (2017), Ma et al. (2016) and Murphy and Riley (1962), respectively.

Extraction of Inorganic Phosphate Fractions from Sediment Samples

The inorganic phosphate fractions of the sediment samples for exchangeable phosphate (Ex-P), iron-bound phosphate (Fe-P), reductant-soluble phosphate (Rs-P) and calcium-bound phosphate (Ca-P) were sequentially extracted as described by Zhang (2009). The concentration of each fraction was determined using the molybdenum blue colourimetric method established by Murphy and Riley (1962) according to Equation 1:

$$\text{Inorganic concentration (mg/kg)} = \frac{\text{Concentration of phosphorous (mg/L)} \times \text{Volume of extractant (L)}}{\text{Mass of sediment (kg)}} \quad [1]$$

Determination of Phosphate Sorption of Sediment

The phosphate sorption of the sediment samples was determined as outlined by Cui et al. (2018), and the resulting filtrate was quantified using the molybdenum blue colourimetric method by Murphy and Riley (1962). A regression correlation coefficient model was used to assess the linear relationship between the adsorption capacity of the sediments at equilibrium. The Langmuir isotherm equation model was used to determine the sorption capacity of the sediment and assess the relationship between the standard phosphate concentrations and the phosphate adsorbed at equilibrium in the sediment as in Langmuir Isotherm Equation 2:

$$\frac{i}{ge} = \frac{\frac{1}{kl \times gmax} \times \frac{1}{ce}}{\frac{1}{gmax}} \quad [2]$$

Statistical Analysis

All the samples were analysed in triplicate. The data were statistically analysed for descriptive statistics, analysis of variance (ANOVA) and regression correlation using JASP (Jeffreys's Amazing Statistics Programme) version 0.18.1 statistical software. Graphs were generated using Originlab and licenced under the GNU Affero General Public Licence.

RESULTS AND DISCUSSION

Physicochemical Parameters

The pH, DO, BOD, EC, COD, and SRP values of the water samples from the three sections of the Langat River are provided in Table 2, showing differences in the physical and chemical characteristics which impact the water quality. The pH range (pH 6.5–pH 7.23) observed in all locations was higher than that of pH 6.39 to pH 6.62 reported by Juahir et al. (2011). The marginal pH increase observed 23 years apart indicates that the Langat River maintains its capacity to regulate acidity and remains within the acceptance range of the World Health Organization. Decreased pH levels in the water downstream may indicate increased human activity or the decomposition of organic substances (Azrina et al., 2006; Aris et al., 2015). A similar pattern was also observed for EC, with slight downstream deterioration. Since this region was urban and bordered by plantations with dissolved ions from tidal impacts and industrial and agricultural discharges such as agricultural runoff, logging, and land clearance, higher EC values downstream were expected (Roy et al., 2018). This variation could result from natural factors such as the geology of the watershed, weathering processes, seasonal changes, and anthropogenic factors, including land use, human activities, and wastewater discharge (Yap, 2013).

Table 2
Physicochemical parameters of each section of Langat River

Location	pH	EC (µS/cm)	DO (mg/L)	BOD (mg/L)	COD (mg/L)	SRP (mg/L)
Upstream	7.23±0.32ac	27.55±2.91ac	9.06±1.97abc	0.45±0.38a	0.95±2.43a	0.13±0.07abc
Midstream	7.22±0.14bc	73.71±11.87bc	6.18±0.59ab	1.66±0.70b	14.05±1.17b	0.53±0.28ab
Downstream	6.87±0.15abc	81.72±10.74abc	2.22±0.43ac	1.97±0.95c	54.33±25.87c	0.64±0.09ac
WHO limit	6.5-8.5	400	5.0	3.0	25.0	0.03

Note. This means that shared letters are significantly different at $P < 0.05$.

Dissolved oxygen is crucial for river health and overall water quality, and low DO levels can have detrimental effects (Haider et al., 2012); thus, effective management strategies to maintain healthy river ecosystems are needed. The same trend of variations in DO in this study was observed by Abidin et al. (2018), and these changes were attributed to temperature, organic matter, and human activities (Vigiak et al., 2019). Since the upstream region has the shallowest and greatest river flow, which can result in quick reaeration rates and reduced organic matter, more DO is anticipated there. Conversely, higher organic pollution and waterborne microbial activity caused reduced DO downstream (Bozorg-Haddad et al., 2021; Wang et al., 2016). The oxygen content may be reduced by increased organic pollutants, which would be detrimental to the water quality. However, BOD and COD levels were greater downstream compared to the DO. High BOD levels can be caused by organic pollution, microbiological contamination, industrial discharge, and human sewage (Vigiak et al., 2019). However, Chapra et al. (2021) believe that water temperature is the primary variable influencing BOD level, which impacts a river's ability to absorb BOD. The elevated COD levels downstream differ from those reported by Basheer et al. (2017) but are consistent with Loi et al. (2022). According to the DOE (2012), COD levels >25 mg/L fall under Class III (moderately polluted), which can negatively impact the river by depleting oxygen and deteriorating water quality, leading to organic matter loading (Ibrahim et al., 2021). These findings highlight the complex nature of DO, BOD and COD variations in the Langat River, which is influenced by a combination of natural and anthropogenic factors. Given that the Langat River is a major river in Selangor and provides water to several locations (Abidin et al., 2018), the ecology and the water supply may be at risk if no effective mitigation is taken.

The downstream area measured up to 0.64 ± 0.09 mg/l of SRP, and this increase could have resulted from phosphate-containing chemicals associated with urban and agricultural areas, among other sources (Bol et al., 2018). Eutrophication, which can result in excessive algae growth and decreased DO levels, may occur because of increased SRP levels downstream (Billah et al., 2019). Although Simonetti et al. (2019) highlighted that land erosion and subsequent entry into aquatic ecosystems were the cause of the increased phosphorus in water, an interchange of SRP from sediment to water and vice versa cannot be completely disregarded.

Inorganic Phosphate Fractionation

Table 3 displays the average concentration of inorganic phosphate measured from three different sections of the Langat River. According to Yusof et al. (2021), erosion and land use affected the distribution of nutrients in the Langat River. All sampling sites have a modest Ex-P content, suggesting that most inorganic phosphate is indirectly preserved in the sediment by establishing bonds with other elements, with few phosphate ions available for exchange from sediment to water and vice versa.

The bioavailable phosphorus reservoir known as Ex-P can release its contents when the concentration of soluble phosphate decreases. At an average of 11.5 ± 0.09 mg/kg, the downstream sediment had the most Ex-P but only marginally non-extractable phosphorus (Rs-P), suggesting a greater likelihood of a high P concentration in the water in this area. According to Hoffman et al. (2009), farming activities such as dredging and palm oil plantations, along with wastewater discharge from sewage treatment plants, could cause elevated Ex-P concentrations downstream of the Langat River's bed sediments. However, the low Ex-P level in the upstream Langat River segment is more indicative of the silt than a phosphorus deficiency. The rapid water flow from upstream moved most of the Ex-P to midstream and downstream, and sandy sediments unable to absorb P were the defining upstream features (Howell, 2010). In essence, the availability of Ex-P in the water and sediment may be influenced by the internal loading of legacy phosphorus in sediments, particularly in areas with a high sediment P/Fe ratio (Orihel et al., 2017).

Table 3
Distribution of inorganic phosphorous fractions (mg/kg) in the sediment samples for different sections of Langat River

Sampling site	**Ex-P**	**Rs-P**	**Al-P**	**Fe-P**	**Ca-P**
Upstream	7.75 ± 0.07ac (10.4%)	17.75 ± 0.34ac (23.8%)	13.5 ± 0.08ac (18.1%)	11.25 ± 0.11ab (15.1%)	24.25 ± 0.15a (32.6%)
Midstream	8.60 ± 0.28b (7.9%)	41.4 ± 0.40bc (38.3%)	21.4 ± 0.16bc (19.8%)	16.5 ± 0.14ab (15.2%)	20.3 ± 0.18b (18.8%)
Downstream	11.5 ± 0.09ac (5.0%)	30.5 ± 0.08abc (13.3%)	41.3 ± 0.36abc (17.9%)	111.3 ± 0.16c (48.4%)	35.5 ± 0.11c (15.4%)

Note. This means that shared letters are significantly different at P <0.05.

The amount of Rs-P acquired by the midstream and downstream was double that of the upstream, with the midstream achieving the highest average of 41.4 ± 0.40 mg/kg. Except for Rs-P, the downstream section maintained the highest overall phosphate fractions, and this may be due to the unique midstream characteristics such as pollution sources, flow dynamics, and sediment characteristics. The midstream has a lot of different streams and runoff sources that come together and mix. It could cause more phosphate to enter the water from agricultural runoff, industrial discharges, and urban waste (Roy et al., 2021). The physical features of the midstream segment, including elevated water flow and turbulence, could have played a pivotal role. Increased water movement enhances the interaction between the water and riverbed sediments, potentially releasing phosphates bound to the sediments and raising the Rs-P concentration midstream (Liao et al., 2020). Turbulence also helps keep the phosphates in suspension, which keeps them from settling and makes them easier to use in their soluble form (Helard et al., 2019). Major agricultural, industrial, and urban areas surround the midstream of the Langat River, providing different sources of Rs-P. These anthropogenic activities in the midstream may have led to more soluble reductant phosphate buildup in the area, potentially contributing to the observed elevated Rs-P levels. Furthermore, the type of land used within this area could potentially introduce organic matter into the river, influencing the Rs-P concentration. Transferring iron and aluminium to deeper sediment profiles involving fresh, less decomposed organic matter could also contribute to midstream accumulation (Tadini et al., 2019). Thus, it significantly influences this distribution by maintaining insoluble phosphorus in the sediment (Van Den Broeck et al., 2004).

Inorganic phosphate linked to aluminium and iron compounds supports appropriate amounts of inorganic phosphate despite Ex-P shortages in every region of Sungai Langat.

The two primary metal-bound bioavailable forms of P are Al-P and Fe-P. Under favourable redox, pH, and other environmental circumstances, these phosphorous forms can be transformed into SRP and released into the surrounding water (Ni et al., 2016). The Al-P concentration increased twofold from upstream to downstream, which is consistent with the findings of Welch et al. (2017). Factors like resuspension and redistribution of alum floc, flood, site-specific hydrodynamics, and geochemical factors transport contaminated sediment, potentially increasing the Al-P concentration downstream (León et al., 2017; Yuan et al., 2019; Hoffman et al., 2009). However, any excess Al-P may have ecological implications, such as nutrient loading and the alteration of phosphorus availability in the river, potentially affecting sediment composition and the abundance and distribution of bottom-dwelling organisms (Emelko et al., 2015; Dadi et al., 2023). In the long term, this may increase the risk of aluminium and nitrate contamination in the Langat River.

The significant iron accumulation caused by industrial and human activities discharging chemical wastes from the surrounding area into the Langat River may have resulted in very high concentrations of Fe-P (111.3 ± 0.16 mg/kg) in the downstream sediment (Bing et al., 2013), attributed to iron-bound at lower pH levels and phosphate mobilisation by Ca-P (Gao et al., 2020) but upstream and midstream sections contained approximately 10% of the downstream Fe-P, possibly due to a lack in the sediment's capacity to retain Fe through the reductive dissolution of Fe-P (Chen et al., 2019). The reductive dissolution of iron oxides can cause phosphate release from sediments in low-oxygen environments, such as upstream areas, particularly if the sediments have a high phosphorous/iron ratio (Table 3).

Ca-P is found in upstream and downstream sediments (Table 3), with downstream sediments usually exhibiting the highest Ca-P concentrations (Jalali & Peikam, 2013). Particularly in alkaline conditions of the overlying water in eutrophic lakes, Ca-P is often regarded as very inert and stays buried in sediments for a long period with relatively poor bioavailability (Ni et al., 2016). According to Han et al. (2022), high calcium ions and phosphorus levels in the downstream area can be attributed to various natural and man-made factors that alter nutrient dynamics and sediment composition. While phosphate adsorption onto calcite and carbonate dissolution may contribute to an increase in Ca-P concentration in estuarine environments (Flower et al., 2022), reductive conditions, alkalisation, and human sources are the main causes in urbanised areas (Huang et al., 2020).

This variability in SRP distribution underscores the influence of diverse environmental factors and sediment characteristics on the downstream sediment composition. Most of the P fraction was high in the downstream sediments, demonstrating the impact of both river current and sediment type. Silt containing small particles and resembling clay provides a variety of options for storing P in sediments downstream and has significant implications for the water quality (Basheer et al., 2017). Thus, it emphasises the importance of considering the intricate processes by which phosphorus is stored and transformed in catchment systems when assessing its availability and possible effects on water quality. The rate at which sediments flush depends on the river flow (Batalla & Vericat, 2008). Particles from upstream and midstream flow downstream, creating a tranquil flow and reducing shear due to the action of water flow (Beltaos & Burrell, 2016), thereby causing high P sedimentation. High phosphorous sedimentation shall be avoided since the Langat River, which is part of the Langat River Basin, is one of the major sources of potable water in Selangor State, supplying drinking water to almost one-third of the population in the state of Selangor (Ahmed et al., 2019).

Correlation Coefficient of Water Parameters and Inorganic Phosphorous Fractions from Sediments

Table 4 illustrates the correlation between SRP fractions and water parameters, showing a positive correlation between Ex-P, Al-P, and Fe-P fractions and EC, COD, and SRP. It suggests that variations in the EC, COD, and SRP levels in water are accompanied by corresponding changes in the Langat River's Ex-P, Al-P, and Fe-P fractions of phosphorus. More focus must be given to trophic status and trophic development content in sediments due to their dual roles (sink or source) under certain environmental conditions to ensure that the Langat River can accommodate life and maintain water quality (Zhou et al., 2001). The Ex-P and Rs-P values can describe the balance and availability of SRP. However, the current study shows that both factors moderately impacted SRP availability in water and sediment.

The EC and COD values have a stronger association with SRP availability than other parameters, suggesting that the equilibrium of the inorganic phosphate fractions in the sediment depends on EC and COD (Saha et al., 2022). EC caused by agricultural runoff or wastewater discharge and COD from microbial decomposition will affect phosphorous chemical bonds and potential nutrient release (Jiao et al., 2021). Nonetheless, these data emphasise the importance of considering both EC and COD on the bioavailability of mobile and less mobile phosphorus fractions to understand the eutrophication potential of water bodies (Lee et al., 2013). EC also contributes to changes in ionic strength and pH which impact the solubility and availability of insoluble phosphorous in the sediment (Wang et al., 2017). It is demonstrated by the moderately positive correlation between Rs-P and EC. Consequently, higher EC levels indicate conditions conducive to releasing Rs-P and Ex-P into the water column, potentially contributing to eutrophication and other water quality issues.

Since the most common form of SRP in sediment is Rs-P, and its concentration is often 1000-fold higher than in water (Pardo et al., 1998), the effect of these parameters is undeniable. Overall, all the data suggested that Rs-P is less influenced by pH, DO, and COD, indicating that Rs-P is strongly bound to iron and aluminium oxides in the sediments,

Table 4
Correlation matrix of inorganic phosphate fractions and physicochemical parameters of Langat River water samples

Parameter	Ex-P	Al-P	Fe-P	Rs-P	Ca-P	pH	EC	DO	BOD	COD	SRP
1. Ex-P	1.00										
2. Al-P	0.998*	1.00									
3. Fe-P	0.985	0.973	1.00								
4. Rs-P	0.260	0.319	0.092	1.00							
5. Ca-P	0.891	0.862	0.955	-0.206	1.00						
6. pH	-0.790	-0.751	-0.883	0.386	-0.982	1.00					
7. EC	0.883	0.910	0.790	0.683	0.574	-0.411	1.00				
8. DO	-0.912	-0.936	-0.829	-0.633	-0.627	0.470	-0.998*	1.00			
9. BOD	0.620	0.667	0.477	0.919	0.197	-0.010	0.916	-0.887	1.00		
10. COD	0.997*	1.000**	0.970	0.330	0.856	-0.744	0.915	-0.940	0.676	1.00	
11. SRP	0.821	0.855	0.712	0.764	0.473	-0.300	0.993	-0.983	0.957	0.861	1.00

Note. * $p < .05$, ** $p < .01$.

making it less responsive to any changes in pH or any microbial activity and organic matter decomposition (Wang et al., 2017). However, modest correlations between Rs-P and SRP suggest that Rs-P is less dynamic due to its slower release (Zhou et al., 2021). It might be due to microbial activity breaking down organic matter in anoxic environments, as suggested by a moderately negative association between Rs-P and DO (Lin et al., 2020). The moderate correlation of Ex-P to BOD indicated that Ex-P is widely used to support microbial growth, participate in organic matter decomposition, and subsequently increase BOD levels (Reusser et al., 2023). However, the availability of Ex-P can be affected by pH and DO. In low pH conditions, SRP is more likely to be absorbed by aluminium and iron hydroxides. It is more severe in anoxic conditions, ultimately reducing its bioavailability, as evidenced by the negative correlation between Ex-P, pH, and DO.

Phosphate Sorption Isotherm

Phosphate adsorption capacity was tested to ascertain the sediment's capacity to absorb P from the Langat River at different locations along the Langat River (Figure 2). Even though there is a difference in the P adsorption range between the different P standard concentrations for the three streams, there is no significant difference between the streams for each specific P standard concentration. The upstream sediment samples exhibited adsorption capacities ranging from 4.00 to 18.21 mg/g of sediment per mg/L of phosphate. The midstream and downstream sediment samples demonstrated adsorption capacities between 4.36 and 21.10 mg/g and 4.00 to 12.98 mg/g of sediment, respectively. Nonetheless, all sediments showed a phosphate adsorption capacity limit between 20–25 mg/L.

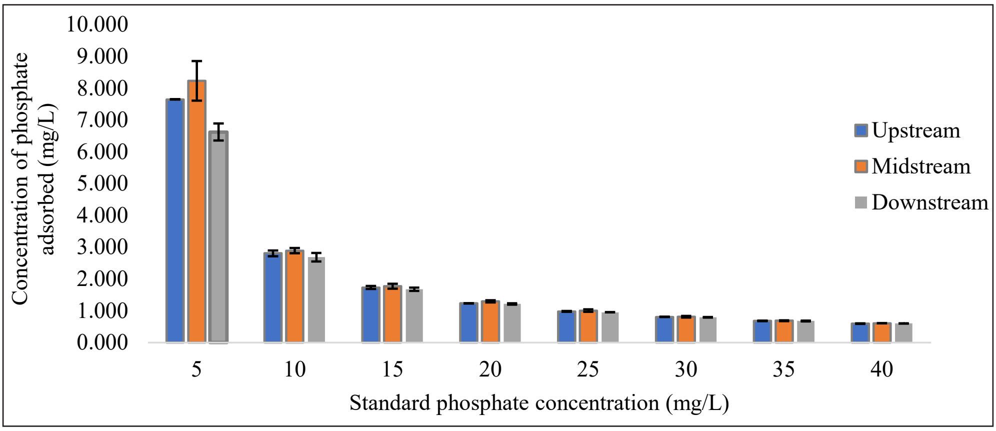

Figure 2. The phosphate adsorption capacity of the sediments collected from different sections of the Langat River

Similar variations in phosphate adsorption capabilities have been found throughout different segments of the Langat River. The Langat River's poor to moderate phosphate adsorption capacities were initially attributed to sewage sludge, pollutants, sediment properties, and mineral composition. Earlier studies on the Langat River Basin have proposed numerous elements influencing phosphate adsorption capabilities. Kadhum et al. (2015) have identified heavy metal contamination, which affected water characteristics such as pH and subsequently influenced sediment adsorption capacity for phosphate. Zainol et al. (2021) highlighted the unique characteristics of the sediment, particularly the impact of the silty clay's composition on its capacity to adsorb phosphate. However, Ahmed et al. (2022) concluded that the primary factors affecting the phosphate sorption capacities of rivers are water pollution and sewage sludge resulting from various human activities. The variations in phosphate adsorption per unit weight of particulate matter in different rivers imply that specific sediment characteristics contribute to adsorption capacity where phosphorus bonding is weaker in calcareous sediment compared to iron-containing sediments (Yuan et al., 2019; Ji et al., 2022).

The regression parameters for the Langmuir isotherm model for the phosphate adsorption process for Langat River sediments are shown in Table 5, with the R^2 values for the Langmuir model demonstrating the moderately high relationship between Q_{max} and $R_{L.}$ It suggests that the Q_{max} and R_L values obtained are statistically valid and reasonably fit the observed data. It implies that the Langmuir isotherm model adequately describes how phosphates adhere to sediment particles in the Langat River. Shafie et al. (2013) and Hafeznezami et al. (2016) suggested that the cation exchange capacity in the Langat River's sediments, which is influenced by pH, salinity, and electrical conductivity, could enhance this correlation. However, the influence of climate change on the capacity and adsorption of sediment must not be ignored, as Ebrahimian et al. (2018) reported that climate change affected the correlation between the different sediments in the Langat River.

Table 5
Langmuir isotherm parameters for the phosphate adsorption process of the sediments

Sampling site	**Linear equation**	**Qmax**	**RL**	**R2**
Upstream	y = 23.102 × + 3.917	0.269	0.366	0.743
Midstream	y = 25.205 × + 3.860	0.265	0.416	0.713
Downstream	y = 15.720 × + 2.617	0.395	0.366	0.797

All sediments along the Langat River have a low capacity to adsorb inorganic phosphate, as indicated by the low adsorption capacity (Q_{max}). Other than the sediment type and the river flow, various physicochemical factors, such as the phosphate concentration, temperature, pH, and the presence of other ions or molecules, can influence the phosphate adsorption capacity of sediments (Azam et al., 2019). Del Bubba et al. (2003) emphasised the role of physicochemical properties in adsorption capacity, with the former showing a significant relationship between maximum P adsorption capacities and properties such as Ca and Mg content, grain size, and porosity. Tang et al. (2014) showed a strong correlation between maximum phosphorus adsorption capacities and sediment oxalate-extractable ion (Feox), total iron (FeT) and total phosphorus (TP) concentrations. The diminished adsorption capacity of sediment, particularly upstream and midstream, to adsorb phosphorous may be attributed to a reduced attraction between phosphate and sediment or limitations in available adsorption sites (C. Han et al., 2020). Despite these sediments' limited phosphate adsorption capacity, they were ideal for inorganic phosphate adsorption because the R_L value ranged from 0 to 1. The Langat River sediments' low inorganic phosphate absorption capacity (Q_{max}) may increase the risk of eutrophication (Loi et al., 2022). The SRP in the water cannot be stored in the sediment, even though the sediment tends to store it (R_L value) because R_L declines. At the same time, the depth and width increase and the river current diminishes, so there is a greater risk of eutrophication downstream. As a result, the location's SRP content is higher. Previous studies have shown a correlation between lower to moderate sediment phosphate adsorption capacity and increased phosphorus levels in water that have led to eutrophication in rivers (Yin et al., 2017; Pu et al., 2021).

The Langat River's water quality and sediment composition indicate significant spatial variations, with the midstream section experiencing higher water parameters and the downstream section facing greater risks of eutrophication due to elevated SRP and inorganic phosphate concentrations. The correlation between water parameters and phosphate fractions suggests that as EC, COD, and SRP levels increase, the inorganic phosphate levels in the river also tend to rise. The moderate adsorption of phosphate by sediments is mostly affected by changes in their composition, such as the presence of aluminium, iron, and calcium compounds due to human activities, as well as physicochemical factors such as pH, electrical conductivity, and the presence of contaminants.

This study provides valuable insights into the potential risks of phosphorus disposal from agricultural, industrial, and urban runoff into river bodies. This idea is essential for developing sustainable mitigation practices to minimise nutrient pollution, thereby protecting river water quality and ecosystem health (Haque, 2021). The demonstrated inorganic phosphorus fractions in Langat River sediments, as well as their bioavailability, contribute to improving phosphorus recovery processes and reducing environmental impacts associated with the disposal of phosphorus-containing compounds (Kalkhoff et al., 2016). However, the inorganic phosphorus fractions' location along the river's sediments and their relationships with physicochemical parameters explain how water quality parameters affect the phosphate fractions' presence. It is important to create effective conservation strategies to protect biodiversity and keep the ecological balance between river sediments and water (Smits et al., 2019). Furthermore, sediments' low to moderate sorption capacity throughout the river contributes to our understanding of the retention and release of phosphorus in the river environment. It can improve sediment management practices, such as dredging and sediment capping, to minimise phosphorus release and mitigate its impact on water quality (Yang et al., 2020).

Climate change can also substantially impact sediment dynamics and sorption capacity in rivers such as Sungai Langat (Lim et al., 2013a; 2013b). Elevated temperatures expedite sediments' chemical reactions, which may modify the intensity of phosphorus binding (Costa et al., 2018). Furthermore, increased temperatures stimulate the functioning of living organisms, consequently modifying the decomposition of organic matter and the circulation of nutrients. Amin et al. (2019) found that this modifies the uptake and discharge of phosphorus. Climate change also results in heightened and fluctuating precipitation patterns, which directly affect the movement and behaviour of sediment. Heavy precipitation amplifies erosion and runoff, leading to a greater influx of sediments into the river and modifying their ability to be absorbed (H. Han et al., 2020). Moreover, the variability in river flows can result in the dispersion or accumulation of contaminants, which might impact the sediment's capacity to absorb nutrients such as phosphorus (Zhang et al., 2019). Climate change-induced modifications in hydrological patterns result in diverse impacts on the capacity of sediment to sorb substances. Modifications in fluid movement patterns impact the transportation and settling of sediment, which in turn affects the stability and effectiveness of sediment layers in capturing particles (Azari et al., 2015).

CONCLUSION

The river sediments exhibited varying levels of phosphate adsorption capacity, ranging from low to moderate in both the upstream and downstream sections. However, a higher level of adsorption was reported in the midstream area. The inorganic phosphate fractions exhibited significant positive connections with EC, COD, and SRP, while the pH and DO levels showed substantial negative correlations with the inorganic phosphate fractions. The Langmuir isotherm models precisely determined the differences in adsorption capacities among the research locations, with Ex-P, Al-P, Fe-P, and Ca-P being dominant downstream and Rs-P dominating midstream.

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