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Phosphorus Accumulation Rate (PAR) in Lake Sediments around Eppawala Phosphate Deposit (EPD): A Case Study for Prospecting New Phosphorus Sources

N.P. Dushyantha[a,*], N.P. Ratnayake[b], P.V.A. Hemalal[b], C.L. Jayawardena[b], A.S. Ratnayake[a], H.M.R. Premasiri[b], R.M.P. Dilshara[b]

[a]Department of Applied Earth Sciences, Faculty of Applied Sciences, Uva Wellassa University, Passaara Road, Badulla 90000, Sri Lanka

[b]Department of Earth Resources Engineering, Faculty of Engineering, University of Moratuwa, Katubedda 10400, Sri Lanka

*** Corresponding author email address**: nimila.dush@uwu.ac.lk

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Abstract:

Currently, rock phosphate is predominantly used to produce phosphorus based mineral fertilizers for agricultural purposes. However, since rock phosphate is a finite and non-renewable resource, it leads the whole world vulnerable to a future phosphorus scarcity. Therefore, prospecting of new phosphorus sources is essential to address the phosphorus scarcity via a sustainable manner. In this regard, lake sediments around Eppawala phosphate deposit (EPD) in Sri Lanka is identified as a new area of interest. With respect to the location of EPD, there are two upstream lakes (Ihalahalmilla lake (L1) and Koon lake (L2)) and one downstream lake (Kiralogama lake (L3)) in the area which are fed by Jaya-Ganga. To assess the potential of these lake sediments as a phosphorus source, core sediment samples were obtained and analyzed to determine average sedimentation rates (ASRs), mass accumulation rates (MARs) and phosphorus accumulation rates (PARs) based on P_2O_5%. The results reveal that L3 has the highest ASR (2.190 mm yr^{-1}), MAR (2935 g m^{-2} yr^{-1}) and PAR (22.31 g m^{-2} yr^{-1}) over the two upstream lakes. Therefore, it is evident that phosphate-bearing materials derived from the EPD have been continuously accumulated in the downstream lake sediment column with a high PAR. As a result, downstream lake sediments show the potential of being a secondary phosphorus source which can contributes to the phosphorus supply in local context. However, novel phosphorus extraction techniques need to be developed to get the maximum use of these lake sediments for a sustainable management of this secondary source.

Keywords: Phosphorus exploration, Weathering, Eppawala Phosphate Deposit, Sediment accumulation

1. Introduction

Phosphorus is an essential nutrient in global food production, and it is an important commodity in agriculture as water. This element is used in agriculture in terms of phosphate fertilizers. However, phosphorus does not have any substitution or synthetic version in agriculture, to date [1]–[3]. Phosphate fertilizers have been used to produce food to feed billions of people over the past few decades to maintain the nutritional security of the global population. Rock phosphate, the main source of phosphorus to produce phosphate fertilizers, is known as a finite and non-renewable resource like fossil fuels, coal, rocks and minerals including rare earth elements [4]. Therefore, the lack of availability and accessibility in natural rock phosphate resources have lead the whole world to experience uncertainty in phosphorus supply and ultimately face a phosphorus scarcity in the future [5], [6]. This emerging problem needs to be addressed in a sustainable and integrated manner as it threatens the future food security with ever-increasing global population. Therefore, phosphorus has been continuously recognized as one of the critical elements in the world, resulting in a pressing requirement for recovering phosphorus from alternative sources such as food waste, excreta and manure, and prospecting new phosphorus sources to cater the future phosphorus demand [7], [8]. In this regard, lake sediments around a major phosphate deposit can be considered as a new area of interest to explore for a secondary phosphate source as a novel opportunity.

Lakes accumulate materials derived from the surrounding areas for many decades, and thus, lake sediments consist of lake inputs, watershed inputs, groundwater inputs and atmospheric inputs. Therefore, lake sediment is an essential medium to locate commercially viable mineral resources to extract economically now or in the future [9], [10]. Due to the physical and chemical weathering, and erosion in the catchment area, materials are liberated as smaller particles from parent rocks. These particles move along with the runoff as sediments and enter the nearby water channels [11]. Since the moving water has high kinetic energy, they transport sediments downstream (i.e. fluvial transport). When sediments enter the final sink area, they are deposited due to the stagnant nature of the water within the lake [12]. If valuable minerals accumulate through a similar process in lake sediments, it is possible to form a lacustrine deposit in the lake basin. In this regard, the rates of sedimentation and mass accumulation play an important role in assessing the quantity, minability and extractability of lake sediments as an economically viable resource.

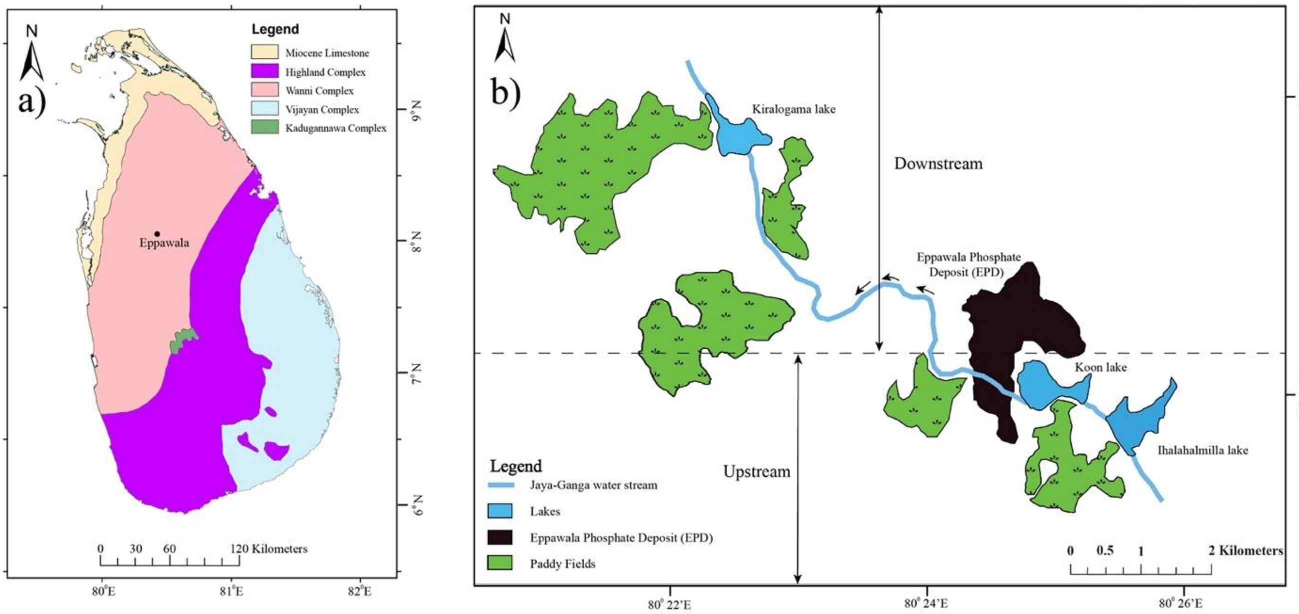

Fig. 1: a) Geological litho-tectonic complexes of Sri Lanka (Source: [16]) and b) study area (Source: [17])

The Eppawala Phosphate Deposit (EPD) in Sri Lanka was first discovered by the Geological Survey Department in 1971, which is located in the Precambrian Wanni Complex (Fig. 1(a)) [13]. The EPD is adjacently located to three lakes, namely, Ihalahalmillalake (L1), Koon lake (L2) and Kiralogama lake (L3) (Fig. 1(b)). Therefore, lake sediments, especially downstream lake sediments, have been continuously receiving phosphate-bearing materials via fluvial transport by Jaya-Ganga (also known as Yodha ela) as soluble and particulate forms due to the physical erosion and chemical weathering of the deposit [3], [14]. This continuous process increased P_2O_5 content and phosphate solubility in the downstream lake sediment column and eventually increased the potential of lake sediments being an alternative phosphorus source [15]. To assess the true potential of lake sediments as an alternative phosphorus source, this study is mainly aimed to determine the average sedimentation rate (ASR), mass accumulation rate (MAR) and phosphorus accumulation rate (PAR) in lake sediments around EPD.

2. Study area

Eppawala phosphate deposit (EPD), the major phosphate deposit in Sri Lanka, is located in the North Central Province. It is known as the largest phosphate deposit in Sri Lanka with an estimated reserve of about 60 million metric tons [18]. This deposit consists of a secondarily developed thick phosphate-rich regolith (covered about 20 km2 with a thickness of 50 m) on top of a carbonatite bedrock. The regolith mainly contains minerals such as chloro-fluoro-hydroxyapatite, fluoroapatite, and carbonate-fluoroapatite. During progressive weathering conditions under tropical climates, these primary apatite minerals dissolve and recrystallize, forming secondary minerals such as millisite, crandallite, and wavelite [19], [20].

Jaya-Ganga is a man-made water canal flowing across the EPD for thousands of years. Based on the location of the EPD, this water stream feeds two upstream lakes, namely, Ihalahalmilla lake (L1) and Koon lake (L2), and one downstream lake, namely, Kiralogama lake (L3) (Fig. 1(b)). These three lakes are the only lakes found in the vicinity of the EPD. Dushyantha et al., [12] reported that P_2O_5 enrichment is evident in surface sediments of L3 (Fig. 2), whereas Dushyantha et al., [9] revealed that P_2O_5 content in core samples of L3 is also high. Furthermore, according to Dushyantha et al. [9], the solubility of phosphate in surface and core sediments in L3 is significantly high compared to the corresponding solubility values in EPD. In addition, Dushyantha et al. [9] also divulged that phosphate-bearing minerals such as fluorapatite, crandallite, and millisite derived from the EPD have been continuously accumulated in the sediment column of L3.

3. Methodology

A total of three sediment core samples (one core sample from each lake) were taken reaching the bedrock at locations where the surface sediment phosphate concentrations showed the highest value at each lake (Fig. 2) [22]. Since wave actions are negligible in these lakes, post depositional sediment disturbances are minimal in the sediment columns [23]. A boring machine, model D50 with a 5cm diameter (inner diameter) metal rod attached to the core head, was

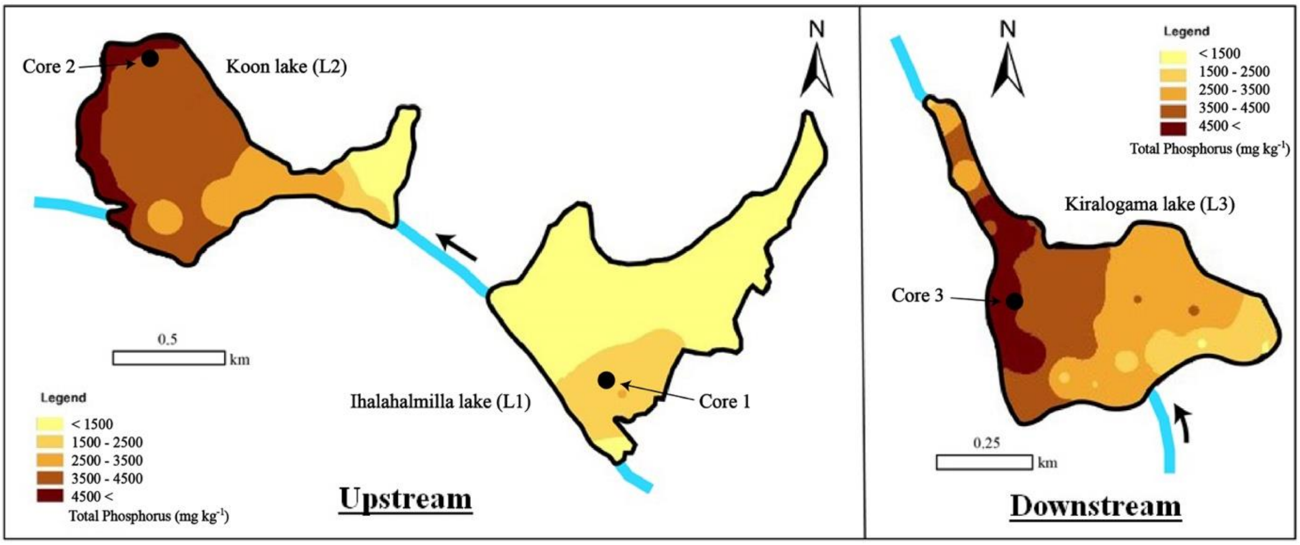

Fig. 2: P_2O_5 distribution in surface lake sediments in L1, L2 and L3, and locations of core samples (Source: [9])

used for core sampling. This coring method made minimal disturbances to the sediment-water interface during sampling [24]. Then, core samples were divided vertically into two sections (Fig. 3). One section was sub-sampled by slicing into 1 cm slices, whereas the other section was kept frozen to use as a reference.

Fig. 3: Vertically divided two sections of a core sample.

Dushyantha et al., [9] reported the P_2O_5 content and the phosphate solubility along the core samples (Fig. 4,5,6). In this context, three representative sediment samples (S1 at the depth of 12.2 cm in core 1, S2 at the depth of 11.1 cm in core 2 and S3 at the depth of 44.9 cm in core 3) were selected based on the P_2O_5% distribution along the core samples and subjected to radiocarbon dating via Accelerator Mass Spectrometry (AMS) method at International Chemical Analysis Inc., Florida, USA. All three samples were accurately and precisely calibrated at the laboratory during the dating process.

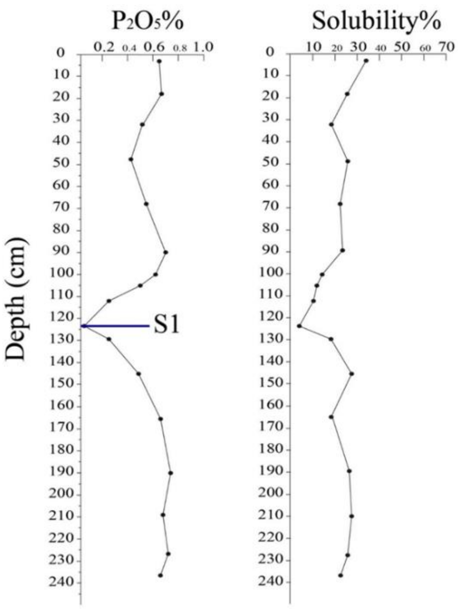

Fig. 4: Distribution of P_2O_5% and phosphate solubility along the core 1 (Source: [9]) and the location of S1 sample collected for dating core samples (Source: [9])

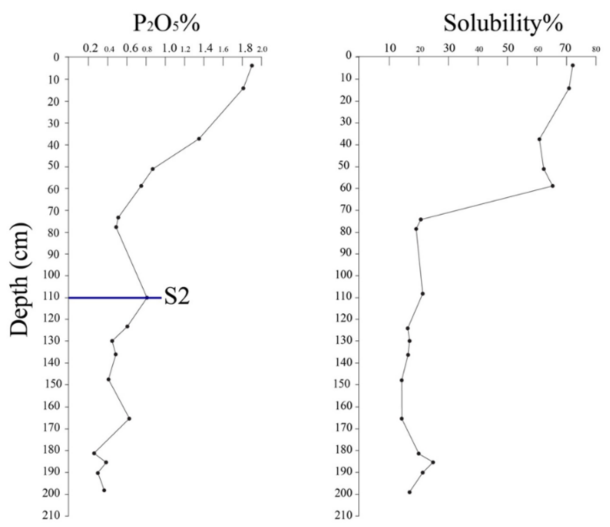

Fig. 5: Distribution of P2O5% and phosphate solubility along the core 2 (Source: [9]) and the location of S2 sample collected for dating.

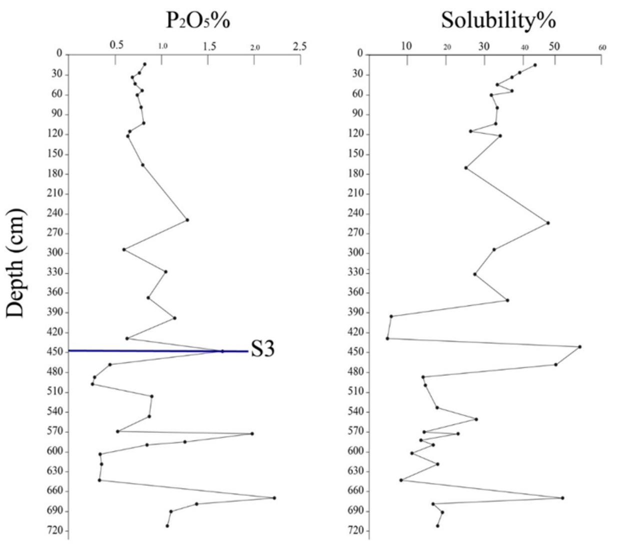

Fig. 6: Distribution of P2O5% and phosphate solubility along the core 3 (Source: [9]) and the location of S3 sample collected for dating.

4. Results and discussion

Table 1 shows the radiocarbon dating results of sediment samples (BP –Before Present). Based on the above dating results, average sedimentation rates (ASRs) of upstream and downstream lakes were calculated according to Eq. 1 [25] which are illustrated in Table 2.

The ASRs (mm yr^{-1}) of Ihalahalmilla lake (L1) and Koon lake (L2) are 0.575 and 0.529, respectively. However, the corresponding value of downstream Kiralogama lake (L3) is 2.190. This result reveals that the downstream lake experiences the highest ASR (about four times higher) than the upstream two lakes. Since core samples were collected only up to the bedrock (i.e. only the sediment column), sediment thickness gives an insight into the ASR of each lake [26]. The total depth of core 3 in L3 is 7310 mm, whereas the corresponding values of core 1 in L1 and core 2 in L2 are 2360 mm and 2020 mm, respectively. Therefore, it is justified that L3 has the highest sediment thickness as it has the highest ASR compared to the upstream two lakes.

Table 1: The radiocarbon dating results of three representative core sediment samples.

Sample	Sample depth (mm)	Age
S1	1220	2120 +/- 30 BP
S2	1110	2100 +/- 30 BP
S3	4490	2050 +/- 30 BP

$$ASR = \frac{Sediment\ Thickness}{Age} \quad \textbf{(1)}$$

Table 2: Average sedimentation rates of three lakes

Lake	Sediment thickness (mm)	Age	Average Sedimentation rate (mm yr^{-1})
L1	1220	2120 +/- 30 BP	0.575
L2	1110	2100 +/- 30 BP	0.529
L3	4490	2050 +/- 30 BP	2.190

However, it is crucial to acknowledge that before the construction of the lake, there might have been pre-existing soils or geological materials that are not solely attributed to the deposition from the mentioned fluvial processes. The construction of the lake altered the landscape, and the sediment cores were taken down to the bedrock to capture the entire sediment column post-construction. While the current study focuses on the sedimentation rates and phosphorus accumulation since the lake's formation, it is essential to recognize that the measured sediment thickness reflects the post-lake construction period. The sediment thickness observed in the cores is a result of both natural fluvial processes and any pre-existing geological materials that were present before the lake construction. It is acknowledged that low-level elevations often exhibit higher sedimentation rates. Therefore, the observed differences in sediment thickness and ASR are interpreted in the context of post-construction processes. Future studies could explore historical data or geological surveys to better understand the composition and thickness of sediments before the lake construction, providing a more comprehensive perspective on the geological history of the study area.

ASRs can be used to calculate the mass accumulation rate (MAR) of each lake. Therefore, the MAR (g m-2 yr-1) was computed as an average using the following Equation 2 [27].

$$MAR = (ASR) \times (ADSBD) \times 10^3 \quad \textbf{(2)}$$

Where;
ASR = Average Sedimentation Rate (mm yr^{-1}), and ADSBD = Average Dry Sediment Bulk Density (g cm^{-3})

The Average Dry Sediment Bulk Density (ADSBD) is assumed to be constant across the lakes. While it is generally true that sediment densities can be similar, we acknowledge that variations in sediment composition may lead to differences in density. The calculation of MAR using a constant density assumption provides a simplified means of estimating mass accumulation rates. Future studies could consider more detailed assessments of sediment density variations within and across lakes to refine the accuracy of MAR calculations.
Table 3 shows the MAR in upstream and downstream lakes.

Table 3: Mass accumulation rates of upstream and downstream areas.

Lake	Average Sedimentation rate (mm yr^{-1})	Average Dry Sediment Bulk Density (g cm^{-3})	Mass Accumulation Rate (g m^{-2} yr^{-1})
L1	0.575	1.34	771
L2	0.529	1.34	709
L3	2.190	1.34	2935

Since average dry sediment bulk densities are approximately the same in three lakes, the MARs of three lakes exhibit similar variations like in ASRs. Therefore, L3 shows the highest MAR over other two lakes.
Due to the disturbances of the land during the mining activities and natural weathering at EPD, soil and other finer materials are subjected to surface runoff and erosion during the rainy season. Therefore, these particles follow the hydraulic gradient and end up in Jaya-Ganga and subsequently transported to the downstream lake. In addition, during the mining activities such as blasting, transportation and crushing, dust is emitted to the air and eventually settled on the ground surface. These dust particles also enter to the Jaya-Ganga via surface runoff and eventually end up in downstream lake [3], [11]. Therefore, due to these entry paths of eroded particles caused by the ongoing mining activities and natural weathering at EPD, downstream lake (L3) experiences a high ASR and MAR.
MARs can be used to calculate the phosphorus accumulation rate (PAR) of each lake using Eq. 3 [28].

$$PAR = MAR \times P2O5\% \times 10^{-2} \quad \textbf{(3)}$$

In Eq. 3, P_2O_5% represents the average P_2O_5% from the top of the core to the location where the sample was collected for the dating. Table 4 contains results on the PAR in upstream and downstream lakes.

Table 4: Phosphorus accumulation rates of three lakes

Lake	Mass Accumulation Rate (g m-2 yr-1)	Average P2O5% in	Lake
L1	771	0.51	3.93
L2	709	0.94	6.66
L3	2935	0.76	22.31

Ihalahalmilla lake (L1) shows the lowest PAR among the three lakes in the area. The average P_2O_5% of the core sample in L1 is 0.51 up to the calculated depth of 1220 mm from the top, where dating has been carried out. The overall average P2O5% of this core is 0.52 (0.03-0.74) up to its total depth of 2360 mm. Therefore, similar PAR (i.e 3.93 g m-2 yr-1) can be expected for the total sediment column in the L1. Since L1 is located further upstream to the EPD, it is the least affected lake by the EPD. Therefore, PAR of the L1 can be considered as the background value of the area. In Koon lake (L2), although it accounts for the lowest ASR and MAR among the three lakes, PAR of L2 is considerably high compared to the L1. It is mainly due to high average P_2O_5% in the sediments, especially in the top 500 mm of the core sample (Fig. 6). This clearly exhibits that the top 50 cm of the core sample in L2 is highly affected by the EPD due to its closeness and variations in mining rates in recent ages. The dynamic nature of mining activities can introduce fluctuations in sediment composition, affecting the observed P2O5% values. Due to this high enrichment of P_2O_5 in top 500 mm of the sediments core, average P_2O_5% of the core sample in L2 is 0.94 up to the calculated depth of 1110 mm from the top. However, overall average P_2O_5% of the core sample in L2 is 0.65 (0.24-1.81) to its total depth of 2020 mm. Therefore, overall PAR of this sediment column in L2 could be less than 6.66 g m-2 yr-1.

Kiralogama lake (L3), the downstream lake, shows the highest PAR among the three lakes in the area. In addition, the PAR of L3 is more than five times higher than that of L1 and more than three times higher than that of L2. This elucidates that L3 has a significant PAR and considerable P2O5 content in the sediment column. Moreover, the average P2O5% of the core sample in L3 is 0.76 up to the calculated depth of 4490 mm from the top, where dating has been carried out. The overall average P2O5% of the core in L3 is 0.81 (0.26-2.22) up to its total depth of 7310 mm. Thus, overall PAR of this sediment column in L3 could be higher than 22.31 g m-2 yr-1. Therefore, it is evident that weathered and eroded phosphate-bearing materials liberated from the EPD yielded alluvial phosphates that has formed a placer accumulation in the downstream lake [3]. Moreover, Jaya-Ganga acts as a good fluvial transport medium for these materials during the mobilization. Since this accumulation in the L3 is a continuous process, downstream lake sediments have an economic value due to their capacity to host phosphate mineral resource.

5. Conclusions

Due to the mining activities and natural weathering at the EPD, finer materials are subjected to surface runoff and erosion during the rainy season. As a result, these materials continuously mobilize through Jaya-Ganga and subsequently accumulated in the downstream lake sediments. Therefore, downstream Kiralogama lake (L3) experiences a high ASR (2.19 mm yr-1) and MAR (2935 g m-2 yr-1) compared to the upstream Ihalahalmilla lake (L1) and Koon lake (L2). Similarly, L3 shows a significantly high PAR (22.31 g m-2 yr-1) compared to upstream two lakes. Therefore, the results reveal that downstream lake sediment column has a potential of forming an alluvial phosphate placer due to the long-term replenishment of phosphate-bearing materials. Since depletion of natural phosphorus sources is evident, downstream sediment column could be used as an alternative phosphorus source to extract phosphorus to cater the future phosphorus demand.

It is recommended to obtain more core samples and analyze them to quantify overall phosphate reserve in the alluvial placer in L3. However, there can be siltation issues in the downstream lake in the future due to the high MAR. Therefore, developing a novel extraction method with the amalgamation of extensive upgrade techniques is necessary to maximize the economic value of the downstream lake sediments and also to overcome the siltation issues in the future.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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