

Geochemical Study of Ecological Risk Potential of Heavy Metal Contamination in Urban Lake Sediment - Malaysia - from the Context of Ecological Disturbance Theoretical Tradition

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This study quantified the degree of heavy metal contamination and ecological risk potential from metals concentration in urban lake sediment. The analytical method involved six geochemical indices (enrichment factor (EF), geo-accumulation index (Igeo), contamination factor (CF), degree of pollution, modified degree of contamination, & pollution load index (PLI). Sediment samples were analysed using ICP-MS. The results revealed that EF and Igeo of trace elements were in the order of Pb > Cr > Cu > Mn > Ni, whereas the order of heavy metals was Na > K > Fe > AL. Na and Pb manifested the highest level of evidence for anthropogenic enrichment and geochemical anomaly. Based on CF, the sediment is heavily contaminated by Pb, Na, and moderately by Fe, K, AL. In the event of profound ecological disturbance, and resuspension of sediment contaminants to the water column, the contamination effects of Pb, Na, Fe, K, and AL on biota will range from heavy to moderate contamination. Assessment using PLI revealed that the sediment is in 80% of locations polluted and in a progressive state of deterioration by the metals. The overall degree of metal ecological risk potentials seems higher in the northern and southern outlet parts of the lake, especially during the dry season.

Keywords: Environmental Geochemistry; Geochemical Indices; Sediment Heavy Metal Contamination; Enrichment Factor; Geo-accumulation Index; Ecological Risk Potential; Ecological Disturbance; Lake Water Pollution in Malaysia; Sediment Quality Remediation; Geochemical Enrichment

Introduction

Sediments are an essential component of an aquatic ecosystem as they provide habitat and nutrients for both heterotrophic feeding benthic invertebrates and autotrophic food synthesizing organisms, thus contributing profoundly to the whole aquatic life survivability. The degree to which urban lake sediments sustain this aquatic primary productivity has remained a constant source of concern, since many studies show that bed sediment-associated metals not only present a direct risk to the benthic dwelling organisms but also pose a risk to the quality of water column overlying it (Casper et al. 2004; Comero et al. 2014). As a result, numerous research findings have established that heavy metal concentrations in sediment beyond the permissible limit lead to toxicity of aquatic life (Withanachchi et al. 2018; Sojka et al. 2019; Frankowski et al. 2009; Friberg et al. 1985; Karbassi et al. 2008). Notwithstanding that essential metals such as Fe, Al, K, Na, Mn, are important for biological life system, they can be stressors and toxic above normal concentration. On the other hand, the non-essential metals and trace elements such as Pb, Cr, Cu, and Ni can be very toxic at low concentration levels. Consequently, the European Union regulation has listed Pb among hazardous metals. Similarly, Cr and Ni were included in the United States Food and Drug Administration list of hazardous metals (Soliman et al. 2015). The risks of toxicity of metal accumulation in aquatic organisms are bolstered by the recalcitrance and non-degradable nature of metals (Addo et al. 2011, Loska and Wiechula 2003). Amongst groups of contaminants, heavy metals are of special concern due mainly to their environmental persistence, bio-geochemical recycling and ecological risk (Erol et al. 2016). However, bioavailability of metals and toxicity is heavily dependent on their ability to be mobilized in solution. Principal physical and chemical factors that influence the release and mobilization of metal from sediment to the water column include pH, organic matter, and oxidation-reduction potential (redox potential) (Frankowski et al. 2009; Oksu 2003). Hence, as the environmental conditions of sediments-bound metals change under these factors (Oksu 2003; Prica et al. 2008; Van Den Berg et al. 1999) argue that sediments may transform from the main sink of heavy metals to become secondary sources of contamination for the overlying water column. Lake sediments are the quintessence of heavy metals sink with highs of absorptive and storage capacity for the metals. This characteristic high storage capacity makes sediments an excellent medium for assessing heavy metals contamination in an aquatic ecosystem. Sediment's monitoring provides indicative markers of aquatic pollution and essential information for ecological risk assessment. As heavy metals often bear a relationship with anthropogenic activities (Long et al. 1995), knowledge of geochemical characteristics in pollution studies tells us

about the sources of the pollution (Nesbitt et al. 1996; Nath et al. 2000; Buccolieri et al. 2006) and helps detect evidence of anthropogenic effect on lake ecosystems (Arunachalam et al. 2014). The pollution index is a dominant tool for assessing, analysing and communicating sediment contamination risk information to decision makers and stakeholders involved in aquatic environment management and policy making. In this study we adopt the two most popular classes of pollution indices used in quantifying and analysing sediment contamination – vis-à-vis: (1) single indices and (2) integrated indices (Qingjie et al. 2008). Single indices are used to calculate and evaluate only one metal contamination, which includes the enrichment contamination factor, geo-accumulation, contamination factor (Qingjie et al. 2008). Integrated indices are used to calculate more than one metal contamination and are based on the single indices (Qingjie et al. 2008; Wei and Yang 2010). But while there are many studies on sediment ecological risk evaluation and quantification using sediment pollution indices, there is still a missing link in existing studies, since no studies yet have attempted to explain the evaluation and quantification of sediment ecological risk within the context of the ecological disturbance theoretical tradition. We argue that relating sediment quality evaluation with ecological disturbance makes a lot of sense because sediment contamination of the overlying water column will largely be influenced by the magnitude of ecological disturbance.

The lake we are investigating (popularly known as Varsity Lake) is located in Petaling Jaya, at the main entrance of Universiti Malaya, Malaysia. The lake is mostly used for recreational purposes such as canoeing and fishing as well as for educational purposes. It is also a habitat for many aquatic lives. One major ecological concern is that urban storm water is a major source of water supply for the Varsity Lake. Petaling Jaya is a highly urbanised area. Thus, most rainfall events generate a high volume of runoff and pollutant loads as they flow through heavily populated residential and commercial areas. There is profound evidence that urban storm water discharging into lakes and rivers constitute substantial sources of water pollution and sediment contamination (Livingston and Borja 1985; Tonderski 1996; Meng et al. 2007). As such, storm water constitutes a major ecological disturbance to sediment-bound metal contaminants because of their potential to mobilise and re-suspend contaminated sediments (Whalley and Aldridge 2000). In particular, urban storm constitutes more ecological disturbance to aquatic biota because it is inherently a potential source of anthropogenic heavy metal and nutrients. Besides, anthropogenic activity is the main source of aquatic sediments pollution (Troni et al. 2017) and urban lakes have become a major culprit. Despite reasonable literature on what is known about urban lake sediment contamination in other countries,

especially in the USA and Europe, there is little such data and information for Malaysian lakes and the Varsity Lake in particular. Even when the only study on Varsity Lake on water quality reported that the lake is polluted in terms of TSS, TDS, BOD, temperature, oil & grease and nitrate concentration beyond permissible standard limits (Ashraf et al. 2010), suggesting evidence of ecological disturbance, there have not been further studies to evaluate possible contamination of the underlying bottom sediment by heavy metals and risks to the lake aquatic system. This is even more important, as it is known that most of the pollutants reported (Ashraf et al. 2010) can increase the redox potential of the lake which could lead to mobilization of heavy metals in the sediment. Against this background and taking cognisance of the importance of the analysis for the academic community and the urban setting at large, this study seeks to (1) quantify and analyse the degree of the Varsity Lake sediment contamination and ecological risk potential of heavy metal concentration using geochemical parameters such as the enrichment factor, geo-accumulation, the contamination factor degree of pollution, and the modified degree of contamination and pollution load index; (2) determine the season and locations of the lake where the metal ecological risk potentials are higher; (3) determine the geochemical distribution and pathways of the contamination; (4) analyse the implications of the evaluation in the event of ecological disturbance.

Fitting Heavy Metal Contamination within an Ecological Disturbance Component of Ecological Theory

Ecological disturbance has long remained a major threat and challenge to ecological integrity of many aquatic communities. As a result, ecological disturbance has been historically recognised as a restructuring and rebalancing force in ecological theories (Dayton 1971; Connell 1978; Resh et al. 1988). In keeping with this premise, most early and existing studies have focused on the dynamics and mechanisms of ecological disturbance in ecosystem structure, functioning and biodiversity (McDonnell and Pickett 1990; Bengtsson et al. 2000; Attiwill 1994; Jones and Syms 1998; Pickett et al. 1989) as well as on ecological succession, exotic invasions and abundance (Vitousek 1990; Turner et al. 1998). A few works related to the effects of forces of ecological disturbance on heavy contamination of benthic communities can also be found (Lake et al. 1989; Sousa 2001; Eggleton and Thomas 2004; Stark 1998; Roberts 2012; Hedge et al. 2009). But no studies have attempted to relate interpretation or implication of ecological disturbance-induced sediment contamination to sediment ecological pollution indices. Moreover, there is a missing link in existing studies on sediment quality evaluations. Many studies have carried out sediment quality evaluations using sediment geochemical parameters

(sediment quality indices); but no study has explained the evaluation within the context of ecological disturbance. This study argues that relating sediment quality evaluation with ecological disturbance is important because the extent of sediment contamination of overlying water column will largely be influenced by the magnitude of ecological disturbance. There is a plethora of definitions on ecological disturbance. Pickett and White (1985) defined it as “any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability or the physical environment”. For Lake (2000), a disturbance takes place when potentially damaging force applies to a habitat occupied by a population, community, or ecosystem and the magnitude of such forces may be to the extent that organisms may be killed or displaced, or depleted. On the other hand, Rykiel Jr (1985) described disturbance as a cause agent which results in perturbation, stress or effect change on the system state, and then denoted four descriptive categories of disturbance: destruction, dis-composition, suppression and interference. As a result, various forms of ecological disturbances effects are discernible: the lethal effect where the dominant effect is massive mortality and reduction in quantity of existing biotic lives; biotic life dis-composition effect which results in relatively low biological life reduction through selective elimination and displacement; suppression effect from inhibited energy flow; and biotic life stress effect, which is stress-induced disturbance resulting from biological life deviation from its natural state. Overall, the perturbative effect of disturbance may be transitory (temporary) after which normalcy resumes, or permanent or long-lasting (Rykiel Jr. 1985).

For the purpose of this study, ecological disturbance is defined as a perturbative disequilibrium force exerting on the ecological habitat – benthic sediment that leads to mobilization, resuspension and bioavailability of heavy metal contaminants (as well as PCBs and PAHs) which can result in different degrees and magnitudes of mortality or stress effects on the habitat biotic life structure and functioning. This definition presupposes that ecological disturbance by heavy metal contamination is hardly direct. It is often precipitated by agents or trigger forces of disturbance. The trigger forces of heavy metal contamination of benthic sediment may be categorised into (a) physical disturbance, resulting from mechanical forces such as wind and tidal movements, sediment dredging and waste discharge, boating traffic, flooding, storm runoff, combined sewer overflow, erosion deposition; (b) physiological disturbance, comprising the lethal effects caused by biochemical reactions influenced by temperature, light or salinity and state of anoxia; and (c) biological disturbance, representing perturbation or stress effects of burrowing and trampling activities of some organisms. Varsity Lake and urban lakes in

general are at the risk of exposure to these trigger agents of ecological disturbance. Interaction among these three trigger forces of ecological disturbance can produce a series of chain reactions that can lead to mobilization, resuspension and bioavailability (MRB) of heavy metal in overlying water columns and eventual bioaccumulation in biotic organisms. The MRBs are influenced by change environmental factors such as temperature, PH, salinity, redox potential, organic carbon content (Weltens et al. 2000). However, the extent of influence of these factors depends on the partitioning characteristics and binding strength of the metals to the bed sediment (Yuan et al. 2004).

In line with other ecological disturbance studies, ecological disturbance-induced heavy metal contamination can be assessed by the disturbance regimes attributes, such as frequency, magnitude or severity intensity. In other words, in the context of Varsity Lake and benthic sediments in general, the frequency and intensity of the trigger forces of ecological disturbance greatly affect the extent of disturbance-induced heavy metal contamination. High magnitude frequently occurring disturbance events are likely to cause more contamination effects than low magnitude frequently occurring disturbance events. Nevertheless, short-term high magnitude disturbance to the sediment can cause severe large-scale contamination effects. For example, a single day to 4 days of dredging of a lake can lead to sediment plume with a wide geographical spread beyond the dredging site and can remain in resuspension for many hours or days after dredging has stopped. The sediment plume can simultaneously act as a physical stressor to biotic lives through increased turbidity and reduced visibility and as a chemical stressor through hypoxia-related oxygen depletion. Similarly, infrequent intermittent combined sewer overflows discharging into a lake can cause huge heavy metal mobilization and resuspension. In the same vein, intermittent wet season urban storm water loaded with excess nutrients such as nitrogen and phosphate can cause frequent hypoxia conditions of oxygen deficiency that can sometimes have a severe stress effect for benthic organisms. As Handy (1994) pointed out, intermittent exposure can be more toxic to an aquatic community than continuous exposure. Heavy propeller boats trafficking in shallow lakes can also lead to multiples resuspension and a release of metals within a short period of time. In general, the amount of metal that could be potentially released to water columns and bioavailable is influenced by the frequency, magnitude of duration of resuspension, amount of contaminants, the reactivity of each metal and the biotic response (Stark 1998; Eggleston 2012). A study by Saulnier and Mucci (2000) revealed that in dredging disturbed anoxic sediments, Fe was released into the dissolved phase within the first hour of sediment resuspension, while Mn was released in solution within seven

days of resuspension, thus potentially making the metals bioavailable.

The notion that the interpretation of ecological disturbance explicitly requires quantitative reference baseline conditions or values makes pollution indexes relevant. As Rykiel Jr. (1985) argues, the effect of ecological disturbance can only be determined by comparison with a reference state that can be used to assess ecological impact. Rykiel Jr. (1985) further stressed that without a defined reference state (quantitative baseline values), the occurrence of a disturbance, perturbation or stress cannot be detected or measured. In a similar tone, Villnäs (2013) stressed that a reference state must be defined in order to interpret the meaning of ecological disturbance. We argue here that in sediment quality evaluation; pollution indexes (such as the enrichment factor, geo-accumulation index contamination factor, degree of contamination, potential ecological risk index, pollution load index) can at least indirectly provide bases for gauging and interpreting steady state and possible deviation from it following a potential ecological disturbance event. By exemplifications, the sediment pollution index for enrichment factor (EF) ranges from no enrichment ($EF \leq 1$, class1) to extremely severe enrichment ($EF > 50$, class7). An aquatic benthic sediment evaluated as having no enrichment from anthropogenic input in heavy metal contamination may signal a steady state. This is because in the event of any ecological disturbance leading to resuspension of sediments, there may be little or no bioavailable anthropogenic-sourced heavy metal. From the perspective of environmental geochemistry, this may imply a geochemical background level where there may not be any manifestation or evidence of geochemical anomaly. On the contrary, sediment evaluated as being in the class of extremely severe enrichment from anthropogenic input in heavy metal contamination may signal a potential state of extreme instability. This is because in the event of any ecological disturbance leading to resuspension of sediments, there may be large bioavailable anthropogenic-sourced heavy metals. From the perspective of environmental geochemistry, this may translate into a high-intensity geochemical anomaly. Also, the sediment pollution index for the contamination factor of a single element ranges from non-contamination ($C_f < 1$, class 1) to very heavy contamination (> 6 , class 5). A sediment contamination factor of trace metals (Pb, Mn, Cu, Ni, Cr) assessed as non-contamination may well suggest a steady state, as in the event of resuspension caused by ecological disturbance, the metals will not be present for bioavailability, though biotic organisms may still be affected by physical stress from turbidity if the resuspension is high. On the other hand, if the contamination factor of the trace metals were assessed to be in the range of very heavy contamination [class 5], the sediment resuspension by ecological disturbance can greatly increase bioavailability 'ceteris paribus'. Similarly, the sediment pollution index

for the potential ecological risk index ranges from low potential ecological risk ($RI < 95$) to very high ecological risk ($RI > 380$). In this regard, sediment-bound heavy metals which are overall evaluated to fall under low potential ecological risk could imply a stable ecological state because in any event of resuspension by disturbance, the heavy metals will pose a low ecological hazard to the aquatic community. But if the heavy metals are overall evaluated to fall under a very high ecological risk, it may as a consequence suggest a sediment ecology that is in very high instability because at any event of resuspension by disturbance, the heavy metals will pose a very high ecological hazard to the aquatic community. The pollution indices will not provide a direct measure of bioavailability but certainly can provide bases for making an intelligent guess or hypotheses of bioavailability of heavy metals in the event of ecological disturbances.

Materials and Methods

Study Area

Varsity Lake is located at latitude $30^{\circ} 25' 27.52''$ N and longitude $101^{\circ} 25' 53.89''$ E and at an altitude 558 m above average sea level. The lake is situated at the main gate of the University of Malaya, bordering 250.6 m length, 85.3 m width and a depth of 6m. Overall, Peninsular Malaysia has the characteristic monsoon climate with two wet seasons related to the Southwest Monsoon (SWM), which occurs from May to September and the Northeast Monsoon (NEM) that takes place from November to March. The highest rainfall is observed during the transition period between the NEM (December to March) and SWM (June to September). Temperatures range from 21°C to 32°C (Wong et al. 2009). The precipitation patterns however vary slightly among that states. Petaling Jaya and Kuala Lumpur record heavier rainfall in the months of November, December, October, September, March and April. While lighter rainfall is recorded in the months of January, February, May, June, July and August. December has the highest mean monthly rainfall of 314mm, which represents about 14% of the mean annual rainfall. On the other hand, February receives the lowest mean monthly rainfall of 115mm, which accounts for only about 5% to the mean annual rainfall (Wong et al. 2009). In this study, a sample of heavy metals were taken in September, October and December to represent and characterize the wet season, and in May, June and February to characterize dry season.

Geochemical Sampling and Analysis

Ten sampling positions were selected based primarily on their proximity to sources of water inlets and outlets of the lake as well as locations within

the lake central and lake bay (close to the main road). The locations cover the northern, southern and central part of the lake. The lake is deeper at the southern outlets area of the lake. As the study requires repeated sampling at same location, GPS was used to identify and provide precision for each of the 10 sampling locations (Table 1). All sediment samples were taken using a Lamotte stainless bottom sediment grab sampler. The samples were immediately transferred into prewashed polythene bags, sealed and labelled. The sediments samples were dried in an air-circulating oven at 70C, ground and sieved through a < 2mm mesh sieve before the analysis. For the analysis, about 0.25g of the sediment was transferred into a granite vessel and treated with 2.5mL of hydrofluoric acid and 2.5 mL nitric acid. After a microwave-assisted digestion and cooling, the digested solution was filtered using Whatman filter paper.

TABLE 1
Sampling positions

Serial No.	Position		
	Latitude	Longitude	Close Proximity to:
Location 1	03 07 11. 14242	101 39 22. 46321	Proximity storm water inlets 1
Location 2	03 07 10. 78242	101 39 23. 06321	Proximity storm water inlets 2
Location 3	03 07 10. 36242	101 39 23. 86321	Proximity storm water inlets 3
Location 4	03 07 09. 70242	101 39 25. 06321	Proximity storm water inlets 4
Location 5	03 07 09. 58242	101 39 26. 66321	Within the lake central 1
Location 6	03 07 09. 76242	101 39 27. 16321	Within the lake central 2
Location 7	03 07 09. 28242	101 39 29. 96321	Lake bay (close to main road)
Location 8	03 07 08. 26242	101 39 29. 96321	Proximity to water outlet 1
Location 9	03 07 09. 46242	101 39 30. 96321	Proximity to water outlet 2
Location 10	03 07 09. 70242	101 39 31. 26321	Proximity to water outlet 3

The filtered sample was transferred into a 50mL volumetric flask, filled with de-ionized water and stored in plastic containers ready for analysis. After the digestion process, the geochemical analysis of the heavy metal concentrations was carried out using Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

Quantification of the Degree of Sediment Contamination Using Geochemical Indices

Geochemical contamination indices are particularly important when researchers (as in this study) not only want to detect the presence and scale of a geochemical environmental anomaly manifested in the form of anthropogenic enrichment but also want to know the aggregate or composite influence of single heavy metal on the overall sediment quality. In other words, contamination indices are mostly useful when a researcher fundamentally wants to know both the single contamination

risk posed by each metal and the composite ecological risks posed by a series of metals to sediment. It was against this logic that Mahato et al. (2014) noted that heavy metal contamination indices are useful tools for quantifying aggregate influence of each heavy metal on the overall water quality. Thus, the analytical method involves three single pollutant indices vis-à-vis the enrichment factor, geo-accumulation, the contamination factor and three integrated pollutant indices involving the degree of pollution, modified degree of contamination and pollution load index. In environmental geochemistry, determination of geochemical anomaly and detection of anthropogenic influences on the environment requires the use and application of the geochemical background concentration, which is defined as the element concentration reflecting natural processes and thus not influenced by human activities (Dung et al. 2013; Matschullat et al. 2000). The geochemical background concentration allows the distinction of polluted areas from unpolluted ones and is useful for assessing the extent of human activities and the fate (mobilization, migration, and deposition/uptake of substances in the environment) of elements (Gałuszka 2007). Quantifications of geochemical contaminations using enrichment factors and the geo-accumulation index particularly require the geochemical background as an enrichment factor and the geo-accumulation index are used mainly to evaluate whether observed mean concentrations represents the geochemical origin and background level contamination or anthropogenic origin and contaminated level (Frañčišković-Bilinski 2007; Rubio & Nombela 2000).

The enrichment factor (EF) is a contamination index primarily used to evaluate the extent of metal contamination and for assessing the degree of anthropogenic input in heavy metal pollution. Thus, EF helps to differentiate between metal derived from anthropogenic sources and those originating mainly from natural weathering processes. Put differently, EF is applied to differentiate between the anthropogenic and geochemical content of elements (Relić et al. 2019). Low values of EF indicate a geochemical origin of elements while high values of EF indicate a significant anthropogenic origin of elements (Sakan et al. 2011). Effectively, EF is a concentration ratio of a measured metal in studied sediment to a normalizing referenced background metal such as Al and Fe. The essence of the normalized enrichment factor is to compensate for the natural variability of major heavy metals and trace elements in sediments in order to detect and quantify any anthropogenic metal contributions to pollution (Loring 1991). The enrichment factor is mathematically expressed as:

$$EF = \frac{\left(\frac{C_n}{C_{ref}}\right)_{sample}}{\left(\frac{B_n}{B_{ref}}\right)} \quad (1)$$

Where C_n is the concentration of a particular element ‘n’ in the sample being studied, C_{ref} is the concentration of the referenced element in the sample used as normalizing metal, B_n the natural background concentration of element ‘n’ while B_{ref} is the natural background concentration for the referenced normalization metal. For our study, the chosen normalizing metal is Fe. As Daskalakis and O’Connor (1995) pointed out, a major advantage of Fe as a normalizer is that its geochemistry is very much related to that of many trace metals and its natural concentration in sediment tends to be uniform. Moreover, many studies on sediment contamination have used Fe as their enrichment normalizer (Zhanget al. 2007; Amin et al. 2009). AL would have been a very good alternative but because it not as an effective normalizer in sediment with metamorphic sediments (which is possible in the case of this study) as it has potential in this circumstance to make poor correlation with heavy metal (Baeyens et al. 1991). Because background values of heavy metals are not available for our study area, we adopt (Turekian and Wedepohl 1961) pre-industrial world average shale metal content values such as Pb (20) Cu (45); Cr (90); Ni (68); and Mn (850). EF values between 0.5 and 1.5 indicate that the given metal is entirely derived from crustal materials or natural weathering processes, whereas EF values higher than 1.5 suggest that a significant portion of the metal comes from non-crustal materials and the sources are more likely to be anthropogenic (Zhang and Liu 2002).

TABLE 2
Sediment Pollution Indices - Enrichment Factor, Geo-accumulation Index, Contamination Factor, Degree of Pollution, Modified Degree of Pollution and Pollution Load Index

Indices	Index range, Class and Intensity of Contamination				
EF	EF ≤ 1, no enrichment [class1]; 1 < EF ≤ 3, minor [class2]	3 < EF ≤ 5, moderate [class3]; 5 < EF ≤ 10, moderately severe [class4]	10 < EF ≤ 25, Severe enrichment [class5]	≤ 4 I _{geo} < 5, Strongly to very strongly [class5]	> 5, very polluted strongly [class6]
I _{geo}	I _{geo} < 0, unpolluted [class 0]; ≤ 0 I _{geo} < 1, unpolluted to moderately polluted [class1]	≤ 1 I _{geo} < 2, moderately polluted [class 2]; ≤ 2 I _{geo} < 3, moderate to strongly polluted [class3]	≤ 3 I _{geo} < 4, strongly polluted [class4]	≤ 4 I _{geo} < 5, Strongly to very strongly [class5]	> 5, very polluted strongly [class6]
C _f	C _f < 1, non-contamination [class1]	≥ 1 C _f < 2 Light contamination [class2]	≥ 2 C _f < 3, moderate contamination [class3]	≥ 3 C _f < 6, heavy contamination [class4]	> 6, very heavy contamination [class5]
C _d	< 8 C _d low	≥ 8 C _d < 16, moderate	16 C _d < 32, relatively high	C _d > 32, very heavy
mC _d	mC _d < 1.5, Nil to very low degree contamination	1.5 ≤ mC _d < 2, low degree; 2 ≤ mC _d < 4, moderate degree	4 ≤ mC _d < 8 high degree; 8 ≤ mC _d < 16 very high degree	16 ≤ mC _d < 32 extremely high degree	mC _d ≥ 32 ultra-high degree contamination
PLI	PLI < 1 denotes no pollution or baseline pollution		PLI > 1 denotes pollution or increasing pollution		

The indices of geo-accumulation and the contamination factor are often used to assess and quantify the degree of heavy metal contamination. In the geo-accumulation index (I_{geo}), the measured concentration of metal is compared with the geochemical background concentration of the same

metal with a correction constant of 1.5. The constant is incorporated in the assessment to account for possible fluctuations in background data due to a lithogenic effect and to detect any small anthropogenic influence (Muller, 1969). The geo-accumulation index is mathematically expressed as:

$$I_{geo} = \log_2 \frac{C_n}{1.5 B_n}, \quad (2)$$

Where C_n is the concentration of the examined metal in the sediment, B_n is the geochemical background value of a given metal in the shale (Turekian and Wedepohl 1961) and the factor 1.5 is used to account for the possible variations in the background values.

The contamination factor was suggested by Hakanson (1980) for use in quantifying the magnitude of contamination by a single metal. The contamination factor (CF) is the ratio derived from dividing the total concentration of a particular metal in the sediment by the background value or baseline reference, often referred to as concentration in uncontaminated sediment. For the contamination factor of single element, the equation is given as:

$$C_f^i = \frac{C_o^i}{C_n^i} \quad (3)$$

Where – C_o^i is the single metal content in studied sediment, and C_n^i the background level of the metal. The degree of contamination was also proposed by Hanson (1980) to determine the magnitude of contamination by a series of metals in sediment. It is an integrated ecological contamination index used to assess the overall contamination risk attributable to a series of elements. As such, the sum of contamination factors for all elements examined is used to depict the degree of contamination (C_d). Hence, this formula:

$$C_d = \sum C_f^i \quad (4)$$

The calculation of C_d as proposed by Hanson (1980) is nevertheless restricted to seven metals and PCB (organic contaminant). Owing to this restriction, Abraham (2005) proposed the modified degree of contamination that has also become popular as an indicator of degree of contamination in sediment ecological risk evaluation. It is calculated as the sum of all the contamination factors in a particular site or sample divided by the number of contaminating heavy metals being analysed. The formula for a modified degree of contamination given by Abraham and Parker (2008) is written as:

$$mC_d = \frac{\sum C_f^i}{n} \quad (5)$$

Where n is the number of contaminating heavy metals being analysed, which in the case of this study is 9.

The Pollution Load Index (PLI) was incorporated into the study to provide an estimate of the extent or status of metal contamination and the required action that ought to be taken. The PLI provides an assessment of the level of trace element pollution for the entire sampling site (Relićet al. 2019). Values of $PLI = 1$ shows that metal loads are within the baseline or background level, and values > 1 depict pollution and indicate progressive deterioration of the site quality by the metal (Cabrera et al. 1999). In accordance to Tomlinson et al. (1980), PLI is calculated as:

$$PLI = (CF_1 \times CF_2 \times CF_3 \times \dots \times CF_n)^{1/n} \quad (6)$$

Results and Discussion

Table 3 shows that among the five trace elements, Pb recorded the highest enrichment value. The average EF values of Pb, Cu, Cr, and Mn were found to be higher in the dry season and in 80% of the sites, the Pb EF could be classified as a minor enrichment, while in 20% of the locations (L1 and L4) they were moderately enriched. Based on Zhang and Liu (2002) criteria of $EF > 1.5$, a significant portion of Pb accumulation in the lake could be attributed to anthropogenic influence and greater than the geochemical background which denotes the presence of geochemical anomaly. The other trace elements had EF in the order of: $Cr > Cu > Mn > Ni$. The EF values of these four elements were below 1 or within the geochemical background level, which means the metals had no geochemical enrichment or anomalous contents.

Among the major heavy metals, Na recorded the highest EF that ranged from 1.21 to 11.93. In 80% of the locations, the average Na EF could be classified as moderately severe (class 4) for both dry season and wet season. However, in 20% of the locations (L5 and L6) in dry season, an EF that could be classified as severely enriched (class 5) by Na was observed. For K, although the average EF was higher in the dry season, the EF of k in both seasons is within the classification range of no enrichment with K. Nevertheless, in 50% of the locations (I3, L4 to L7) in the dry season and in 40% of the locations in the wet season (I3 to L6), the lake could be said to have minor enrichment with k. Al had the least EF. Except in location 1 where minor enrichment was observed, in 90% of the locations, there was no Al enrichment. Based on the geo-accumulation index (Table 4), Pb and Cr did not show any evidence of no contamination. In 100% of the locations studied, the Igeo for Pb ranged from 0.63 to 0.90, while Cr ranged from 0.10 to 0.22. As a result, sediment contamination by Pb and Cr is designated to fall within the range of uncontaminated to moderately contaminated. However, a closer look showed that the Igeo values were all greater than 0.5, which could be interpreted as

TABLE 3
Enrichment Factor

Loc		1	2	3	4	5	6	7	8	9	10
Pb	TM	2.57	2.07	1.98	2.60	1.89	1.77	1.65	1.62	1.53	1.54
	DM	2.31	2.28	2.06	3.10	2.03	1.89	1.69	1.56	1.51	1.52
	WM	3.19	1.87	1.89	2.20	1.74	1.64	1.60	1.68	1.56	1.57
Mn	TM	0.08	0.06	0.05	0.05	0.04	0.04	0.04	0.05	0.05	0.05
	DM	0.07	0.06	0.06	0.07	0.05	0.04	0.04	0.06	0.05	0.06
	WM	0.12	0.06	0.05	0.04	0.04	0.04	0.04	0.05	0.04	0.05
Cu	TM	0.50	0.42	0.41	0.46	0.44	0.40	0.37	0.32	0.31	0.31
	DM	0.45	0.51	0.43	0.46	0.51	0.44	0.41	0.33	0.31	0.31
	WM	0.62	0.33	0.38	0.46	0.38	0.35	0.33	0.31	0.30	0.32
Ni	TM	0.04	0.07	0.02	-0.05	0.02	0.03	0.04	0.04	0.04	0.04
	DM	0.05	0.05	0.02	-0.11	0.02	0.04	0.04	0.03	0.04	0.04
	WM	0.04	0.08	0.02	-0.01	0.03	0.02	0.04	0.04	0.05	0.04
Cr	TM	0.51	0.44	0.44	0.41	0.41	0.41	0.43	0.42	0.44	0.41
	DM	0.46	0.49	0.49	0.42	0.49	0.48	0.48	0.42	0.43	0.42
	WM	0.63	0.38	0.39	0.40	0.35	0.35	0.38	0.42	0.44	0.41
K	TM	1.51	1.69	2.03	2.46	2.23	2.13	1.97	1.42	1.59	1.20
	DM	1.44	1.79	2.07	2.19	2.43	2.23	2.18	1.31	1.40	1.33
	WM	1.69	1.58	2.00	2.67	2.04	2.02	1.76	1.56	1.82	1.05
AL	TM	0.83	0.65	0.70	0.73	0.60	0.59	0.06	0.62	0.65	0.64
	DM	0.59	0.57	0.69	0.69	0.62	0.59	0.58	0.52	0.54	0.60
	WM	1.08	0.59	0.56	0.63	0.47	0.49	0.51	0.61	0.65	0.56
Na	TM	3.05	3.08	4.17	6.66	9.15	5.47	9.41	5.67	2.14	1.28
	DM	1.61	2.42	3.48	6.22	11.93	5.69	11.66	6.16	1.22	1.21
	WM	7.92	4.61	5.72	8.30	4.07	5.24	4.53	3.86	4.50	3.52

TM = Total mean; DM = Dry season mean; WM = Wet season mean; Loc = Location

being in the transition zone of clear moderate contamination by Pb. Locations 1 and 2 registered the highest Igeo followed by locations 7, 8 and 10. This also implies that northern inlet part and the southern outlet part of the lake have higher Igeo than the middle lake. Both Pb and Cr have higher Igeo in the dry season.

For heavy metals, the contamination was in the following order, Na > K > Fe > AL. As a result, Na recorded the highest Igeo. In 59% of the locations (L1 to L4, L9), the Igeo can be classified as (2) moderately polluted. In 20% (L6, L8) and 10% (L3), the Igeo is classified (3) moderately to strongly polluted and (4) strongly polluted respectively. Class 5 Igeo was observed in location 7, which in translation is strongly polluted to very strongly polluted by Na. The dry season recorded higher Igeo. In fact, clear evidence of strongly polluted (class 6) was observed in location 7 in the dry season. For K, Fe, and AL, Igeo were predominantly in the progression of unpolluted to moderately polluted contamination (class 1). The implication of ecological disturbance based on the enrichment factor and geo-accumulation index is that in the event of ecological

TABLE 4
Geo-Accumulation Index

Location		1	2	3	4	5	6	7	8	9	10
Pb	TM	0.9	0.88	0.75	0.65	0.77	0.75	0.82	0.82	0.76	0.81
	DM	1.02	1.0	0.78	0.66	0.74	0.75	0.79	0.81	0.78	0.79
	WM	0.78	0.76	0.72	0.63	0.79	0.76	0.84	0.84	0.74	0.82
Mn	TM	0.03	0.03	0.02	0.01	0.02	0.02	0.02	0.03	0.02	0.03
	DM	0.03	0.03	0.02	0.01	0.02	0.02	0.02	0.03	0.03	0.03
	WM	0.03	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.03
Cu	TM	0.18	0.18	0.15	0.11	0.18	0.17	0.18	0.16	0.15	0.16
	DM	0.2	0.22	0.16	0.1	0.19	0.17	0.19	0.17	0.16	0.16
	WM	0.15	0.13	0.14	0.13	0.17	0.16	0.17	0.15	0.14	0.17
Ni	TM	0.02	0.03	7.94	-0.01	0.01	0.01	0.02	0.02	0.02	0.02
	DM	0.02	0.02	8	-0.02	6.91	0.02	0.02	0.02	0.02	0.02
	WM	0.01	0.03	7.88	1.8	0.01	0.01	0.02	0.02	0.02	0.02
Cr	TM	0.18	0.18	0.17	0.1	0.17	0.17	0.21	0.21	0.22	0.22
	DM	0.2	0.21	0.19	0.09	0.18	0.19	0.22	0.22	0.22	0.22
	WM	0.15	0.16	0.15	0.11	0.16	0.16	0.2	0.21	0.21	0.21
K	TM	0.53	0.72	0.77	0.61	0.91	0.91	0.97	0.72	0.79	0.62
	DM	0.63	0.78	0.78	0.47	0.89	0.88	1.01	0.68	0.72	0.69
	WM	0.42	0.64	0.76	0.76	0.93	0.93	0.93	0.77	0.86	0.55
AL	TM	0.29	0.27	0.27	0.18	0.25	0.25	0.03	0.31	0.32	0.33
	DM	0.26	0.25	0.26	0.15	0.23	0.23	0.27	0.27	0.28	0.31
	WM	0.27	0.24	0.21	0.18	0.22	0.22	0.27	0.3	0.31	0.29
Fe	TM	0.35	0.42	0.38	0.25	0.41	0.43	0.49	0.51	0.5	0.52
	DM	0.44	0.44	0.38	0.21	0.37	0.39	0.46	0.52	0.51	0.52
	WM	0.25	0.41	0.38	0.29	0.27	0.46	0.53	0.5	0.47	0.52
Na	TM	1.07	1.3	1.58	1.65	3.71	2.33	4.64	2.89	1.06	0.67
	DM	0.71	1.06	1.32	1.34	4.36	2.25	5.41	3.2	0.63	0.63
	WM	0.53	0.72	0.77	0.61	0.91	0.91	0.97	0.72	0.79	0.62

disturbance, it is expected that Pb and Na are most likely to constitute the highest anthropogenic-sourced heavy metal contamination.

When the contamination status of the sediment was examined within the lens of contamination factor (Cif), it was clear that in 100% of the locations (Table 5), Pb contamination factor fell within the range that is classified as heavy contamination (≥ 3 CF < 6). Consistent with the geo-accumulation index, locations 1 and 2 in the northern area of the lake emerged as sites where the highest CF was observed, followed by 7 to 10 in the south. For Cr, a sign of minor contamination was recorded in 60% of locations (L1, L2, L7 to L10) in the dry season and in 40% of the locations (L7 to L10) in the wet season. Similar to Igeo, the average CF for Pb and Cr was higher in the dry season. The contamination factor of the heavy metals was in the order of Na > K > Fe > AL. For k, the contamination was in 90% of the locations in class 4, denoted as heavy contamination. The contamination factor of AL was in 80% of the locations within the range

TABLE 5

Contamination Factor for a Single (Cf) and Degree of Contamination for Multiple Metals (cd) and Pollution Load Index for Multiple Metals (PLI)

Location		1	2	3	4	5	6	7	8	9	10
		Cif									
Pb	TM	4.50	4.38	3.73	3.21	3.81	3.75	4.06	4.10	3.77	4.01
	DM	5.08	4.97	3.89	3.29	3.69	3.72	3.92	4.04	3.87	3.96
	WM	3.91	3.78	3.56	3.14	3.93	3.79	4.20	4.16	3.68	4.07
Mn	TM	0.15	0.12	0.10	0.06	0.09	0.09	0.11	0.13	0.12	0.14
	DM	0.15	0.13	0.10	0.07	0.08	0.09	0.10	0.15	0.14	0.15
	WM	0.15	0.12	0.09	0.06	0.09	0.10	0.11	0.11	0.10	0.13
Cu	TM	0.87	0.89	0.77	0.57	0.90	0.84	0.91	0.81	0.75	0.81
	DM	0.99	1.11	0.81	0.49	0.93	0.86	0.95	0.86	0.80	0.80
	WM	0.76	0.67	0.72	0.66	0.86	0.82	0.86	0.76	0.71	0.83
Ni	TM	0.08	0.14	0.04	-0.06	0.05	0.07	0.10	0.09	0.11	0.11
	DM	0.10	0.11	0.04	-0.11	0.03	0.09	0.10	0.08	0.11	0.11
	WM	0.05	0.17	0.04	-0.01	0.07	0.05	0.10	0.10	0.11	0.11
Cr	TM	0.89	0.92	0.83	0.51	0.83	0.87	1.05	1.06	1.07	1.08
	DM	1.01	1.06	0.92	0.45	0.88	0.94	1.10	1.09	1.10	1.11
	WM	0.77	0.78	0.73	0.57	0.78	0.80	1.01	1.03	1.05	1.06
K	TM	2.65	3.56	3.84	3.03	4.51	4.51	4.84	3.61	3.92	3.11
	DM	3.16	3.89	3.90	2.35	4.42	4.39	5.04	3.40	3.59	3.46
	WM	2.08	3.19	3.77	3.81	4.61	4.65	4.62	3.85	4.29	2.72
AL	TM	1.45	1.36	1.32	0.90	1.22	1.26	0.15	1.57	1.61	1.66
	DM	1.29	1.25	1.31	0.74	1.13	1.16	1.35	1.34	1.39	1.55
	WM	1.32	1.20	1.05	0.90	1.07	1.12	1.35	1.51	1.54	1.44
Fe	TM	1.75	2.11	1.89	1.23	2.02	2.12	2.46	2.54	2.47	2.60
	DM	2.20	2.18	1.89	1.07	1.82	1.97	2.31	2.59	2.56	2.60
	WM	1.23	2.03	1.89	1.43	2.26	2.31	2.62	2.47	2.36	2.60
Na	TM	5.34	6.50	7.86	8.23	18.51	11.61	23.10	14.39	5.29	3.34
	DM	3.54	5.27	6.57	6.66	21.72	11.20	26.97	15.97	3.12	3.15
	WM	9.73	9.34	10.80	11.85	9.20	12.08	11.88	9.54	10.62	9.13
Cd	TM	17.68	19.98	20.38	17.68	31.94	25.12	36.78	28.30	19.11	16.86
	DM	17.52	19.97	19.43	15.01	34.70	24.42	41.84	29.52	16.68	16.89
	WM	20.00	21.28	22.65	22.41	22.87	25.72	26.75	23.53	24.46	22.09
mCd	TM	1.96	2.22	2.26	1.96	3.55	2.79	4.08	3.14	2.12	1.87
	DM	1.94	2.22	2.16	1.67	3.85	2.71	4.65	3.28	1.85	1.87
	WM	2.22	2.36	2.52	2.49	2.54	2.86	2.97		2.71	2.45
*PLI	TM	1.04	1.16	0.96	-0.76	1.85	1.10	1.00	1.27	1.14	1.10
	DM	1.10	1.18	0.96	-0.74	1.04	1.12	1.37	1.26	1.08	1.11
	WM	0.94	1.26	0.93	-0.69	1.06	1.07	1.25	1.19	1.19	1.18

*PLI was calculated based on trace metals only (Pb, Mn, Cu, Ni, Cr)

of (class 2) moderately polluted. The Fe contamination factor, on the other hand, was in 90% of the locations in (class 3) moderate contamination. Na again constituted the highest contamination factor for heavy metals with 90% of the locations falling within the bounds of class 5, depicted as very

heavy contamination (> 6). The logical implication of ecological disturbance based on a contamination factor is that in the event of ecological disturbance and resuspension of contaminated sediments to water column, it is expected that Pb and Na are most likely to contribute highest to heavy metal contamination. The degree of contamination (Cd) by all the metals at each location was observed to range within the intensity of (17.68 to 41.84) relatively high to very heavy. The result from a modified degree of contamination showed that the lake sediment was in 30% of the sites in the class low of degree contamination and in 70% of the sites in the bounds of moderate degree contamination, but in the wet season all sites were in the range of moderate degree contamination. The pollution load index (PLI) was used to assess the summative ecological information on the overall degree of heavy metal toxicity at each sample location. Table 6 also shows that the value of PLI is slightly greater than 1 in 80% of the locations. This suggests that overall, pollution is greater than base level in 80% of the locations, hence contaminated. This provides the clearest evidence that the Varsity Lake sediment is polluted and signals that the sediment quality at these sites is in progressive contamination by the metals. The ramification for ecological disturbance on the basis of Pollution Load Index is that, in the event of ecological disturbance and resuspension of contaminated sediments to the water column, it is projected that overall, the 9 heavy metals investigated will in synergy have ecological hazard or toxicity stress effects on biotic lives.

The sources and pathways of the geochemical elements can be explained. The elevated concentration of Pb, Cr, and Cu may be attributed to construction activities in the University around the lake that make use of cements, paints, metal alloys, electroplating steel and aluminium as well as domestic garbage from student canteens and urban storm water runoff that empties into the lake. Principally, fabrication workshops in the engineering faculty near the lake could be significant sources of Cr, Pb, and Cu. Similarly, heavily trafficked automobile roads in close proximity to the University lake are likely major sources of heavy metals, particularly Pb. Studies by Cabrera et al. (1999), Christoforidis and Stamatis (2009), Duong and Lee (2011) and Liu et al. (2012) reveal that on roads of high vehicular traffic, heavy metals release from exhaust fumes, car oil leaks, tire wearing, brake disks and vehicles metal parts corrosion accounts for a significant portion of contamination load. In Hafen and Brinkmann (1996), Cu and Pb were among the heavy metals used to assess traffic contamination and their findings showed that the metal concentrations were very much influenced by traffic volume and decrease with increasing distance from the road. Similarly, the high concentration of Na could be attributed to food waste from student canteens that potentially contain high levels of salt. Moreover, Petaling

Jaya is notoriously known for acid rain. A study on the state of acid rain deposition in East Asia by EANET (2011) placed Petaling Jaya among the urban centres that are worst affected by acid rain. Acid rain precipitation accelerates the leaching of Na in soil and studies have shown that there is correlation between the amount of Na that can be released from the soil and rain acidity (Dai Zhaohua et al. 1995). Consequently, urban storm water discharging into lakes like the Varsity Lake may contain a high concentration of Na.

For the management of the sediment, there are two broad sediment remediation techniques: ex-situ and in-situ. Ex-situ remediation involves physical extraction (dredging) of the contaminated sediment and treatment at an off-site location, whereas in-situ remediation entails non-removal of the sediment and treatment of contaminants on-site - that is leaving and treating the contaminated sediment in place (in-situ). For the remediation mechanisms for the Varsity Lake, we recommend in-situ methods. As the lake sediment contamination is still generally not heavily contaminated, we recommend in-situ measures such as amendments, sand cap and phyto-remediation that are of immediate necessity for stabilization and immobilization of the heavy metal in the sediment. In the amendment metal immobilization strategy, the application of minerals such as apatite, zeolites, rock phosphate, lime; steel shot, or beringite can significantly reduce metal mobility and bioavailability in the sediment. This is because in the processes of either sorption or precipitation, these minerals have high cation exchange capacity to lower metal solubility, which culminates in reducing the metal mobility and bioavailability (Peng et al. 2009).

Sand cap strategy involves capping the sediment with clean sand, gravel or sediment so as to reduce the direct contact area between contaminated sediment and overlying water column. With minimal physical and chemical contact, mixing could be greatly reduced. As a consequence, higher sediment stabilization is attained and the transfer rate of metal in sediment is lowered. If sand capping is well designed, the placement of clean sand, gravel or sediment caps will not mar or mix with underlying sediments, and concentration of heavy metal in the water column could be reduced as much as 80% (Zoumis et al. 2001). Nonetheless, owing to the fact that sand cap remediation has little effect on metal immobilization, it is recommended that some minerals applied in an amendment strategy should be used in conjunction with the sand cap strategy to foster a heavy metal immobilization potential (Jacobs & Förstner 1999).

Phyto-remediation is used to enhance natural attenuation of heavy metal contaminants in sediments. It involves the use of plants for sequestration, degradation and detoxification of toxic heavy metal. Unlike the

chemical remediation methods, this is an ecologically efficient alternative in which hydrophytes such as typha angustata and ipomoea are used in soil, lakes and wetlands remediation. This is because these hydrophytes have the ability to absorb and accumulate various heavy metals in high concentration in the roots zone through their phytochelatins and lothioneins actions (Suresh and Ravishankar 2004; Kumar et al. 2008).

A major limitation of the in-situ remediation method is that it has a lower treatment efficiency and lack of process control than the ex-situ method. It serves primarily for containment of contaminants. Though it improves the immobility of heavy metal in sediment, it does not lower the total metal content in sediment. The final outcome of the remediation technique is mainly demobilization of concentration into an inactive form. Thus, if environmental conditions change part, a portion of these immobilized metals may become active, mobilize and be released into the overlying water again. Owing to the fact that the ex-situ method involves dredging which disturbs the ecological balance that sustains aquatic organisms, ex-situ remediation is recommended in the future only if it is observed that sediment pollution has deteriorated to a level of being heavily polluted.

Conclusion

The environmental geochemistry of aquatic sediment provides a basis for quantifying, analyzing, interpreting and communicating potential contamination risks of sediment geochemical substances for decision makers. In this study, six environmental geochemical indices were used to quantify and explain the degree of ecological risk potential of heavy metal contamination of urban lake sediment. By extension, this was further explained within the context of the ecological disturbance theoretical tradition. The result showed that among the five trace elements, Pb recorded the highest enrichment value. In 80% of the sites, the Pb was classified as minor geochemical enrichment, while in 20% of the locations it was moderately enriched. As a result, a significant portion of Pb accumulation in the lake could be attributed to anthropogenic influence and thereby contains a geochemical anomalous Pb concentration. The enrichment factor of other trace elements was in the order of Cr>Cu>Mn>Ni, but they did not show clear evidence of metal enrichment or geochemical anomalous contents. The average enrichment factor of all the trace elements was found to be higher in the dry season. Among the major heavy metals, Na recorded the highest enrichment factor. In both dry and wet seasons, the average Na enrichment factor was classified as moderately enriched to severe, while in 20% of the locations in dry season, it was observed as severely enriched. Na accumulation could be primarily associated with anthropogenic influence since its geochemical content is at an

anomalous level, greater than the geochemical background limit. However, these results should be interpreted with caution as the calculations were based on pre-industrial world average shale values, and not on the local natural background values of heavy metals which are not available for our study area. Based on the geo-accumulation index, Pb and Cr showed evidence of contamination. Their Igeo values were in the range that could be interpreted to be in the transition zone of clear moderate contamination. In relating the implication to ecological disturbance, we hypothesize that, based on the geo-accumulation index, in the event of profound ecological disturbance, mobilization and resuspension of contaminated sediments, the intensity of contributions of Pb and Na to anthropogenic-sourced heavy contamination would be in the range of moderate contamination to very strong contamination respectively, while the anthropogenic impact of Cr, K, Fe, and AL will range from uncontaminated to moderate contamination. Based on the enrichment factor, in the event of ecological disturbance, Pb and Na will contribute highest to anthropogenic contamination in the magnitude of minor to moderately severe contamination and severe contamination respectively. From the perspective of environmental geochemistry, this may translate into minor to moderately severe geochemical anomaly. When the contamination status of the sediment was examined within the lens of contamination factor, it was clear that in 100% of the locations, Pb contamination fell within the range that is classified as heavy contamination. For Cr, a sign of minor contamination was recorded in 60% of the locations in the dry season and in 40% of the locations in the wet season. In relating the implication to ecological disturbance based on the contamination factor, we state that the sediment is not in a steady state and hypothesize that in relative terms, in the event of profound ecological disturbance and resuspension of contaminated sediments, Pb and Cr contributions to contamination would be in the range of heavy contamination, and minor contamination respectively, Na, K and AL in the class of very heavy contamination, heavy contamination and moderately contamination respectively, 'ceteris paribus'.

The overall integrated assessment of the degree of contamination by all the metals at each location was observed to range within the intensity of relatively high contamination to very heavy contamination. But when examined from the purview of a modified degree of contaminate, the lake sediment was in 70% of the sites in the bounds of moderate degree contamination. In depicting the overall status of metal contamination in the lake sediment, the Pollution Load Index revealed that in general, the pollution level is slightly greater than baseline level in 80% of the locations, indicating that, although not heavily polluted, it is typically polluted and in a progressive state of deterioration by the metals which require urgent intervention

to ameliorate the contamination. Based on the Pollution Load Index (PLI), we hypothesize that in the event of impactful ecological disturbance leading to mobilization and resuspension of contaminated sediments, overall all the heavy metals investigated (Pb, Cr, Cu, Mn, Ni, Na, K, Fe, AL) will in synergy have an ecological hazard or toxicity stress effect on biotic lives. Overall, the average enrichment factor, geo-accumulation index, contamination factor and Pollution Load Index were found to be higher in the northern inlet part (locations 1 and 2) and the southern outlet part of the lake as well as higher in the dry season. This also implies that the severity of ecological disturbance-induced contamination cum geochemical anomaly is expected to be in higher in the southern and northern outlet parts and in the dry season.

For the management and remediation of Varsity Lake sediment, we recommend the application of in-situ techniques such as amendments and sand cap, with phyto-remediation as a complement. Predicated on the finding that the overall level of contamination based on the Pollution Load Index is only slightly higher than the base line level, thus not yet heavily contaminated, in-situ remediation methods used for stabilization and immobilization of the heavy metal in the sediment should be given priority and immediate attention. Ex-situ remediation techniques are recommended in the future only if further studies indicate that the contamination has degenerated to a level of heavy pollution. The in-situ remediation techniques will enhance the resilience of the sediment to ecological disturbance. In terms of the contribution to knowledge, it is hoped that the methodology and outcomes of this study will have local and international significance, since as the sediment ecological risks quantification methods, the theoretical contexts, research findings, the generated hypotheses and the recommended remediation techniques will have both local and international appeals, particularly in the Southeast Asia region where there is a dearth of literature, studies and knowledge regarding sediment quality and ecological risks assessment. Thus, the study contributes to the advance of knowledge in the subject area. It is however recommended that future study in the subject area should incorporate metal speciation and isotope analytical methods for achieving a deeper understanding of geochemical tracing of anthropogenic influences.

Acknowledgement

The authors wish to express their sincere appreciation for the material support rendered by the Department of Geography and Department of Geology, University of Malaya during the period of the study. We are extremely grateful for the services provided by the lab assistants of the two departments.

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