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Distributions of particulate and dissolved phosphorus in aquatic habitats of Peninsular Malaysia

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ABSTRACT

Particulate phosphorus was the dominant phosphorus species and accounted for 72 ± 5% of total phosphorus in coastal habitats, 63 ± 4% in estuaries, 58 ± 6% in lakes and 80 ± 7% in aquaculture farms whereas dissolved inorganic phosphorus (DIP) and dissolved organic phosphorus (DOP) were minor components. Correlation analyses (DIP vs Chl *a*; $R^2 = 0.407$, df = 31, $p < 0.001$) suggested phosphorus limiting conditions in lakes, which was corroborated with the highest alkaline phosphatase activity (APA) that fluctuated from 0.38 to 41.14 nmol L^{-1} min^{-1}. In contrast, APA was elevated in coastal habitats and estuaries only when DIP concentration decreased below 0.9 μM. Moreover size-fractionation experiment showed that the highest APA was detected in the 0.2–2 μm pico-size fraction. Our results suggested that the main APA in coastal habitats and estuaries was from phototrophic pico-eukaryotes and heterotrophic bacteria, and regulated largely by DIP availability.

1. Introduction

In the last 50 years, rapid population growth, extensive development and significant changes in land use are taking their toll on different aquatic habitats leading to increase eutrophication (Bennett et al., 2001; Rabalais et al., 2009). As a result, excessive nitrogen and phosphorus loading have increased remarkably throughout the years (Seitzinger et al., 2005; Chislock et al., 2013; Lee et al., 2013; Song et al., 2015). As nitrogen loading generally exceeds the input of phosphorus, it is more common to observe phosphorus depletion in estuaries and coastal waters around the world (Howarth and Marino, 2006; Elser et al., 2007).

Phosphorus is an important element for all living organism and plays an important role in many of the fundamental processes i.e. storage and transfer of genetic materials, cell metabolism and energy storage of cells (Karl, 2000; Paytan and McLaughlin, 2007). Generally, the phosphorus pool in aquatic habitats can be divided into three main compounds; dissolved inorganic phosphorus (DIP), dissolved organic phosphorus (DOP) and particulate bound phosphorus (Part-P) (Froelich et al., 1982; Karl and Björkman, 2001). Part-P is a complex intermediate compound where phosphorus derivatives are bound to the biogenic and non-biogenic particulate matter. In habitats with serious phosphorus limitation, biogenic Part-P (i.e., living and dead cells or plankton biomass) can be remineralized into DOP and can sustain the phosphorus cycle. In contrast, non-biogenic Part-P is generally bound on clay or rock fragments, and is less significant for biological processes (Paytan and McLaughlin, 2007; Meng et al., 2014).

Relative to Part-P, DIP is more commonly measured because it represents the bioavailable component of the phosphorus pool. Specifically, orthophosphate (HPO_4^{2-}) can be assimilated directly by a wide range of organisms without any additional expenditure of energy, and thus play a vital role in regulating different biological processes (Cotner and Wetzel, 1992). In contrast, DOP which is not directly available for biological activities, has received a great deal of attention as an alternative source of phosphorus in habitats with serious phosphorus limitation (Nausch and Nausch, 2006; Paytan and McLaughlin, 2007). With the use of phosphatase enzymes, HPO_4^{2-} from DOP can be hydrolytically cleaved and transformed into bioavailable phosphorus. A variety of phosphatase enzymes are capable of breaking down DOP compound for example C-P lyase, phosphodiesterase, pyrophosphatase

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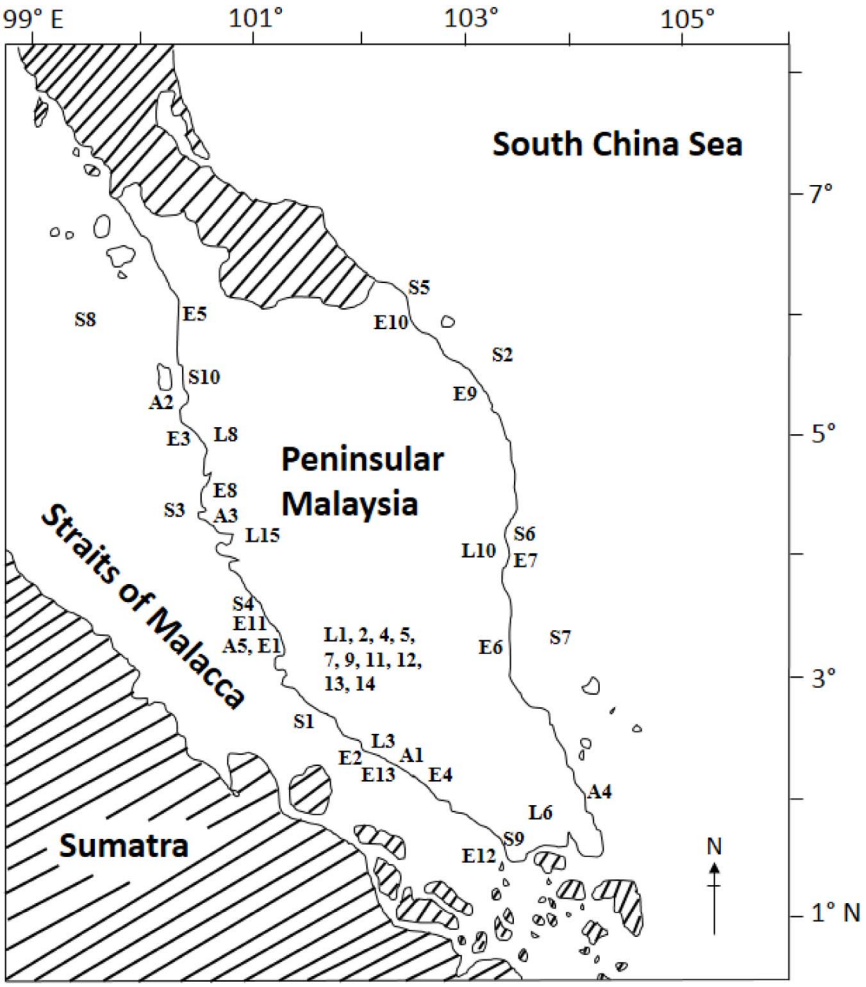

Fig. 1. Location of sampling stations. S, E, L and A denoted coastal, estuary, lake and aquaculture stations, respectively.

and 5′ nucleotidase. The best-studied of these enzymes is alkaline phosphatase which has been used as an indicator of phosphorus stress (Yoshimura and Kudo, 2011; Boge et al., 2012; Suzumura et al., 2012).

Alkaline phosphatase is found extracellular, either released through cell lysis or excretion. Depending on its lifespan and the condition of its surrounding environment, alkaline phosphatase can remain active outside of the cell and can be detected as free-living dissolved form (Li et al., 1998). Recent advancement had shown that both bacteria and phytoplankton could utilise DOP through alkaline phosphatase activity (APA) (Li et al., 1998; Hoppe, 2003; Dyhrman and Ruttenberg, 2006; Suzumura et al., 2012). Typically, APA is regulated by DIP concentration or to a lesser extent influenced by DOP concentration (Labry et al., 2005; Dyhrman and Ruttenberg, 2006). However, in many cases, this relationship is less significant because it also depends on the interaction between the physical, chemical and biological characteristics of an ecosystem (Garcia-Ruiz et al., 2000; Tanaka et al., 2006; Duhamel et al., 2010).

Reports on the distribution of phosphorus in the South-East Asia region have mainly focussed on DIP only (Suratman et al., 2008; Lee et al., 2013; Lim et al., 2015). Therefore, there is an obvious data gap with regards to DOP and Part-P measurements in this region (Karl and Björkman, 2015). For this present study, we wanted to complement our current understanding by characterising the spatial and temporal distribution of different phosphorus forms in the tropical waters of Peninsular Malaysia. For spatial distribution, we characterised the different forms of phosphorus across different habitats in Peninsular Malaysia (i.e. coastal, estuary, lake, and aquaculture) whereas for temporal variation, we characterised the different forms of phosphorus over a 12-year sampling period at two stations with lower and upper trophic states along the Straits of Malacca. We also carried out size-fractionation of APA in this study to relate the contribution of different size-fractions to total APA, and the importance of APA towards phosphorus cycling.

2. Materials and methods

2.1. Sampling

Surface water samples (≈0.1 m) were collected from different aquatic habitats located around Peninsular Malaysia i.e. coastal water (n = 10), estuary (n = 13), lake (n = 15) and aquaculture farms (n = 5) from 2012 to 2016 (Fig. 1) (Table 1). The lakes sampled were man-made urban lakes that also act as retention ponds for flood mitigation whereas for two of the stations (Stn E1: Port Klang and Stn S1: Port Dickson), samples from the year 2004 to 2015 were available for long-term analyses (n = 66 and n = 54, respectively). Samples for bacterial abundance were preserved on site with glutaraldehyde (1% final concentration) before storing all samples in an ice-box for further processing in the laboratory.

2.2. Environmental parameters

In situ measurements of water temperature and salinity were carried out with a conductivity meter (YSI 30, USA), whereas Secchi disc depth was measured to estimate water transparency. In the laboratory, water samples were filtered through pre-combusted (500 °C for 3 h) glass fiber filters (GF/F), and one filter was kept frozen for chlorophyll *a* (Chl *a*) analysis whereas another filter was kept for total suspended solids (TSS)