The Diatom Stratigraphy of
Rawapening Lake, Implying Eutrophication History

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Abstract: Problem statement: The use of diatoms to reconstruct past ecological conditions in lakes is well established. Diatoms are microscopic algae that forms siliceous frustules which allow them to preserve well in sediments. Rawapening Lake is one of 15 Indonesian lakes identified as 2010-2014 National Priority Lakes. Naturally, Rawapening is a tectono-volcanic lake. In the early 1900s, the sole outlet of the lake, Tuntang River, was impounded for hydroelectricity, irrigation and fisheries. Since then Rawapening had become a semi natural lake. The main problem of Rawapening Lake is blooming of water hyacinth that reduce lake function. This research was conducted in order to reconstruct the nutrient history of Rawapening Lake, Java. **Approach:** Sediment samples were taken from four sites and were sliced every 0.5 cm for diatom analysis and bulked across 2-5 cm for ^{210}Pb radiometric dating of sediment. Diatom analysis consisted of three steps: the digestion process to separate the diatoms from the sediment; preparation and mounting of diatom residues onto slides and identification-enumeration. **Results:** The diatom-inferred condition of Rawapening Lake may be divided into four phases represented by zone 1 (1967-1974), zone 2 (1974-1983), zone 3 (1984-1990) and zone 4 (1990-2008). The predominance of *Synedra* from 1967 to present indicates that Rawapening Lake has been fresh and meso-eutrophic throughout. Zone 1 is also characterized by *Fragilaria capucina* Desm, *Luticola goeppertiana* (Bleisch) Mann, *Mayamae atomus* (Kutzing) Lange-Bertalot, *Navicula radiosa* Kutzing, *Nitzschia palea* (Kutzing) W. Smith and in one site, *Tryblionella apiculata* Gregory, that reflect eutrophic, but clear waters. An increase in epiphytic *Gomphonema* spp. in zone 2 marks an increase in aquatic macrophyte plants, perhaps in response to high nutrient levels. This change is followed promptly by an increase in acidophilous *Eunotia* spp. reflecting high organic production. A transition to a diatom community dominated by planktonic forms occurs c. 1983. This community was initially dominated by more clear water, oligotrophic species such as *Discostella stelligera* (Cleve and Grunow) Houk and Klee and *Aulacoseira distans* (Ehrenberg) Simonsen, but transitions in 1990 to one dominated by *A. granulata* (Ehrenberg) Simonsen and ultimately *Aulacoseira ambigua* (Grunow) Simonsen. This is interpreted as a shift to a turbid water phase that has advantaged phytoplankton, at the expense of benthic or epiphytic taxa that require clear water. **Conclusion:** The dominance of *A. granulate* (Ehrenberg) Simonsen since the 1990s indicates the lake experienced hypertrophic conditions with pH > 9. A high proportion of the taxa in Rawa Pening sediments are not represented in the European data set, so the development of data set of tropical lakes is recommended to provide stronger inferences in local settings.

Key words: Eutrophication, Rawapening Lake, nutrient, diatom

INTRODUCTION

Diatoms are a dominant form of microalgae in all aquatic ecosystems. They contribute 20-25% of the primary production in many systems and they have an important role in the silica and carbon cycle (Mann, 1999). Different taxa have different levels of tolerance to environmental (water quality) variables, therefore, fossil diatom assemblages preserved in lake sediments reflect past environmental conditions effectively (Dixit

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et al., 2001; Gell *et al.*, 2007; Reid *et al.*, 1995; Reid and Ogen, 2009). In recent years diatom research has focused on the application of sedimentary assemblages to reconstruct past water quality conditions (Smol, 2008).

Rawapening Lake is a tectono-volcanic lake situated in the Central Java, Indonesia, 45 km to the south of the city of Semarang. It is a circular lake of ~ 2,000 Ha surface areas situated at 400 mASL. It is supplied by flows from 16 stream inlets, many of which are used for domestic water supply for the 17 villages surrounding the lake, or diverted for paddy field development. In the early 1900s its only outlet was impounded to ensure supplies for hydroelectricity development and to mitigate the risk of flooding downstream (GS, 2000).

The lake acts as a sink for pollutants released across the intensively used catchment and within the lake itself. Industrial, urban and agricultural development has increased the loads of fertilizers and metal pollutants to the lake. The development of the steep catchment slopes has resulted in increased turbidity in the inlet streams and increased sediment loads to the lake (EM, 2010). The present poor water quality of the lake precludes its use for water supply. Pesticide uses in paddy fields, the use of pellets to improve fisheries production and the excess fish catches, have further led to a decline in the available fishery.

From the 1930s the lake was invaded by water hyacinth (*Eichornia crassipes* (Mart.) Solms) and other aquatic invasives, *Hydrilla* and *Salvinia* (Goltenboth and Timotius, 1994; UNEP, 1999). Now, over 40% of the lake is covered with water hyacinth. The degraded state of this lake has drawn the attention of the United Nations Environment Program and Indonesian authorities and there is, within the Indonesian Environmental Regulatory Report Number 32 (2009), a directive to establish management plans for the lake to improve its water quality and amenity. The Bali Agreement of 2009, resulting from the actions of 9 ministries decided that Rawapening is 1 of 15 priority lakes for conservation over 2010-2014.

Research on paleolimnology in Indonesia is very limited (Hehanusa and Haryani, 2009). This research was conducted in order to reconstruct the diatom-inferred nutrient history of the Rawapening Lake to identify the drivers of eutrophication. The reconstruction of nutrients and habitat changes over time is interpreted in light of the known settlement and lake management history. Abrupt changes in condition coincident with specific events suggest a history of direct impacts on the lake's condition; whereas gradual changes suggest more diffuse and chronic impacts.

MATERIALS AND METHODS

Field sampling: In 2008 an intensive regime of diatom and water quality sampling was undertaken covering a range of substrates across the Lake. The water quality variables analyzed comprising dissolved oxygen, temperature, conductivity, turbidity and pH. A comprehensive bathymetric study was undertaken on Rawapening Lake in August 2008 (Fig. 1). Echo-sounding of the lake reveals extensive areas of less than 2 m depth but three deeper depocentres in the lake's west of up to 18 m depth. This was used to direct coring activities. At multiple core sites surface sediment samples and water samples were taken from which total nitrogen, total phosphorous, silica, lead, cadmium, chromium and copper were analyzed. The collected sediment cores ranged in length from 29-63 cm. These were sub sampled in fine resolution (0.5 cm) for diatoms.

Sediment subsamples were prepared following Last and Smol (2001), identified following standard texts (Krammer and Lange-Bertalot, 2010) and by comparison with the reference collections held at Diponegoro University and The University of Ballarat. Counts of a minimum of 300 valves were taken on a subset of samples. The software ERNIE (Juggins, 2001) was used to reconstruct nutrient histories of the lake. As each site had multiple substrate diatom samples, it was possible to reconstruct the changing nature of the aquatic habitat (e.g., lake shallowing; invasion of emergent and floating macrophytes; changing light regime) within Rawapening over recent time, independent of diatom-inferred nutrient changes. The fossil diatom assemblages are presented in the data management and drawing package C2 1.5.1 (Juggins, 2003).

Chronology: The 50 mm diameter cores taken from Rawapening were unlikely to provide sufficient sediment to allow for gamma analysis each centimeter so samples were bulked across 2-5 cm. Ten subsamples/core, each of 20-30 dry grams, were prepared for gamma spectrometry to derive ^{210}Pb ages for four cores. Particle size analysis was undertaken largely as a precaution given the site is in a steep catchment with high rainfall. This aids in the choice of age-depth model (CIC or CRS) used to derive sedimentation rates from each core.

Geochronology, based on the changes to the diatom biostratigraphy, especially major shifts in benthic, epiphytic and planktonic forms, enabled a broad chronology to be applied across cores. Subsamples were also taken for analysis of moisture and organic (LOI) content using standard loss-of-weight on drying and ashing methods.
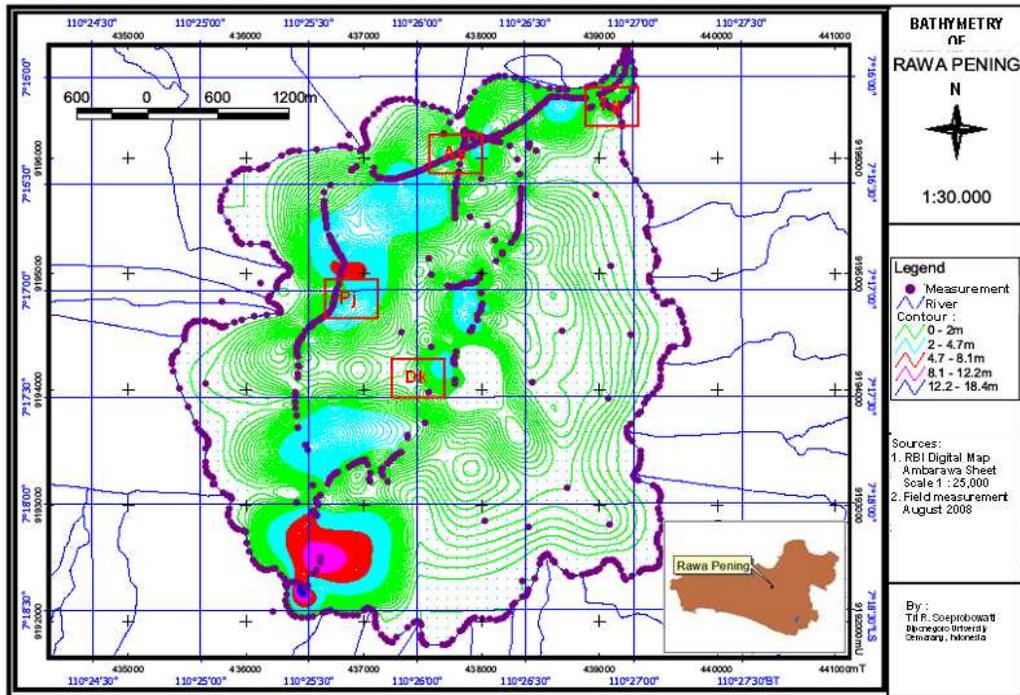
Fig. 1: Bathymetric map of Rawapening Lake and core length. As = Asinan, Tg = Tuntang, Dk = Dangkel and Pj = Panjang

RESULTS

Sediment core chronology-Rawapening: Fourteen sediment samples were used to establish the chronology of the 63 cm long Asinan core. The unsupported ^{210}Pb activities in the Asinan core exhibit an overall decreasing profile with increasing depth (Fig. 2). The basal sediment samples also showed activity suggesting the profile had not reached background and that the sediments were < 100 years old. The CRS model at Asinan core provided a mass accumulation rate of 1.26±0.05 g cm^{-2}/year to 60 cm depth equating to an age of 41±1.6 years (Table 1). The sedimentation rate using the CIC model however, was 1.155±0.113 g cm^{-2}/year, (r^2 = 0.937), suggesting an age of 48.6±4.8 years at 63 cm. Assuming 0 cm is equivalent to 2008 AD, the sediments at 63 cm were deposited in 1955-1964 (CIC model) or 1965-1969 (CRS model). The CRS model was used as a basis for the chronology accompanying the diatom stratigraphy graph.

Eleven sediment samples were analyzed to establish the chronology of the Tuntang core. The unsupported ^{210}Pb activities in this core exhibit an overall decreasing profile with increasing depth (Fig. 3), at least as far as 10.5 cm. The unsupported ^{210}Pb activities below 12.5 cm are close to being constant. The sediment below 12.5 cm may all be of the same age (due to rapid deposition); however, diatom changes

exist in the stratigraphy, suggesting continual, rather than episodic, accumulation. The CIC model reveals a mass accumulation rate of 0.13±0.01 g/cm^2/year (r^2 = 0.9926), allowing an age of 54.1±7.1 years (1947-1961 AD) for 33.5 cm depth. The CRS model provides a mass accumulation rate of 0.15±0.01 g/cm^2/year and an age of 38.5±1.9 years (1968-1971 AD) for 10.5 cm depth (Fig. 3 and Table 2).

The sample sizes processed for Dangkel"s core were very short (Fig. 4 and Table 3).

Only 4 out of 36 samples were analyzed from the Panjang core. This core shows a slightly decreasing activity of unsupported ^{210}Pb with depth (Fig. 5 and Table 4). Analysis of more samples is required for the deeper part of the core, to ascertain whether the levels of unsupported ^{210}Pb activity reach background. Despite this, based on the analyses made, the CIC and CRS ^{210}Pb dating models were used to estimate sediment ages. The CIC model provided a weak result (r^2 = 0.6039) for a mass accumulation rate of 1.309±0.01 g/cm^2/year with 16-16.5 cm depth equal to 12.42±7.11 years (1988-2003 AD). Assuming constant sedimentation this would suggest the 32 cm core covers 24.54±7.11 years or was initially deposited in 1976-1990. The CRS model however, provides a strong relation (y = 0.6889x + 0.0751, r^2 = 0.9972). From this model the sediments at 16-16.5 cm date to 10.9±2.3 years and so were deposited between 1995 and 1999 AD (Table 4).

Diatom biostratigraphy of Rawapening Lake: The longest sediment core (63 cm) was from the Asinan site. The Panjang and Tuntang cores were 36.5 cm and 35.5 cm long, respectively, while that at Dangkel was 29 cm. The Asinan core can be divided into four zones based on a cluster analysis of diatom assemblages, whereas Tuntang and Panjang may be divided into 3 zones and Dangkel into 2 zones (Fig. 6-9). This discussion is based principally on the results of the Asinan site, as it yielded the longest core and was well dated, but it is also with reference to the other three cores.

Zone IV (1967-1974): The lowest zone is dominated by *Gomphonema parvulum* (Kutzing) Kutzing, *Luticola goeppertiana* (Bleisch) Mann, *Luticola mutica* (Kutzing) Mann, *Mayamaea* (syn:Navicula) *atomus* (Kutzing) Lange-Bertalot, *Nitzschia palea* (Kutzing) W.Smith and *Nitzschia umbonata* (Ehrenberg) Lange-Bertalot. These species are indicators of high nutrient concentrations confirming the enriched status of the Rawapening Lake from the base of this record. Other common taxa include *Fragilaria capucina* Desm, *Gomphonema gracilis* Ehr. and *Navicula radiosa* Kutzing which suggest alkaline conditions; however, the presence of *Eunotia pectinalis* (Kutzing) Rabenhorst var. *undulata* (Ralfs) Rabh suggest neutral to slightly acid conditions. *Synedra ulna* (Nitzsch) Ehrenberg is also a common species that persists to the upper sediments. This assemblage, with low representation of planktonic forms, is evident in the basal zone of the Tuntang core but not Panjang, supporting the dating evidence for the former holding the longest record. While a clear chronology is not available for the Dangkel core, the predominance of *Fragilaria capucina* Desm suggests it may date to the 1970s. The presence of *Tryblionella apiculata* (Gregory) as a common taxon is exclusive to this core.

Zone III (1974-1983): Zone 3 in Asinan is marked by declines in several eutrophic indicators and a marked increase in *Ulnaria* (syn: Synedra) *acus* (Kutzing) M.Aboel and the emergence of the oligotrophic plankton *Discostella stelligera* (Cleve and Grunow) Houk and Klee. Here the epiphytes *G. parvulum* (Kutzing) H.F.va Heurck and *Gomphonema. truncatum* Ehrenberg increase and *E. pectinalis* (Kutzing) Rabenhorst var. *undulata* (Ralfs) Rabh is replaced by *E. pectinalis* (Kutzing) Rabenhorst var. *pectinalis* Taf. In the Tuntang core *G. gracilis* Ehr. also increases. In the Dangkel core (Fig. 8) *G. gracilis* Ehr. is the most common dominant epiphyte and it cedes dominance to a diverse *Eunotia* flora. This transition is also evident in zone 2 of Tuntang core. On this basis, a reconstruction of pH of Zone II of Dangkel would suggest acidic conditions (less than pH 6) and to a lesser extent at Tuntang, with more neutral waters near Asinan.
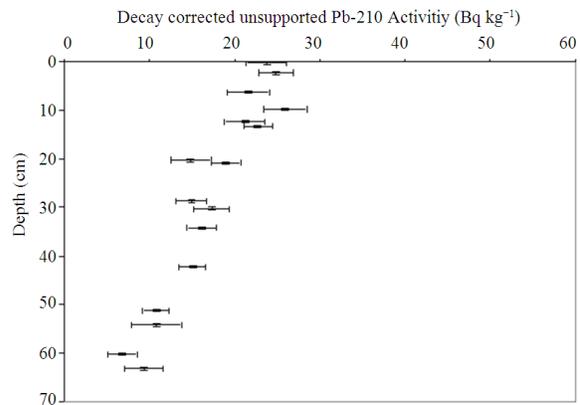

Fig. 2: Unsupported ^{210}Pb versus depth of the Asinan core, trend of a decrease decay

Table 1: Sample numbers, depths, bulk densities, cumulative masses and count dates, total ^{210}Pb, supported ^{210}Pb, decay corrected unsupported ^{210}Pb, CIC and CRS models calculated ages and mass accumulation rates of Asinan core. Constant Mass of accumulation rate of CIC e.i., 1.15 ± 0.11 g/cm^2/year R^2 = 0.94

Depth sediment sample (cm)	Dry bulk density (g/cm³)	Cumulative dry mass (g/cm²)	Count date	Total ^{210}Pb (mBq/g) or (Bq/kg)	Supported Pb-210 (mBq/g) or (Bq/kg)	Unsupported ^{210}Pb Corrected to reference date 15-Jan-09 (mBq/g) or (Bq/kg)	Calculated CIC Ages (years)	Calculated CRS Ages (years)	CRS model Mass Accumulation Rates g/cm²/y
0,0-0,5	0,56	0,1±0,1	20-Jan-09	48,0±1,6	24,2±1,8	23,7±2,4	0,1±0,1	0,1±0,2	1,5±2,7
2,0-2,5	0,90	1,6±0,2	22-Mei-09	51,6±1,0	27,0±1,7	24,9±2,0	1,4±0,2	1,0±0,5	1,5±0,7
6,0-6,5	0,61	4,6±0,2	20-Jan-09	43,6±1,9	22,0±1,6	21,6±2,5	4,0±0,4	3,0±0,8	1,5±0,4
9,5-10,0	1,34	8,0±0,2	22-Mei-09	47,7±1,9	22,1±1,6	25,9±2,5	7,0±0,7	5,4±0,9	1,5±0,3
13,0-13,5	1,33	12,7±0,2	22-Mei-09	42,9±1,1	20,3±1,2	22,8±1,7	11,0±1,1	9,2±1,0	1,4±0,2
20,5-21,0	0,69	20,3±0,2	22-Mei-09	39,5±1,2	20,7±1,3	19,0±1,8	17,6±1,7	15,3±1,2	1,3±0,1
28,5-29,0	0,65	25,7±0,2	22-Mei-09	37,0±1,1	22,2±1,4	15,0±1,8	22,2±2,2	19,4±1,3	1,3±0,1
34,0-34,5	0,70	29,4±0,2	22-Mei-09	36,5±1,2	20,6±1,3	16,1±1,8	25,5±2,5	22,3±1,3	1,3±0,1
42,0-42,5	0,69	35,0±0,2	22-Mei-09	32,3±0,9	17,4±1,2	15,1±1,5	30,3±3,0	27,3±1,4	1,3±0,1
51,0-51,5	0,92	42,2±0,2	22-Mei-09	30,1±0,9	19,5±1,3	10,8±1,6	36,6±3,6	33,6±1,5	1,3±0,1
54,0-54,5	0,89	44,9±0,2	20-Jan-09	37,8±2,1	27,0±2,0	10,8±2,9	38,9±3,8	35,8±1,5	1,3±0,1
60,0-60,5	1,39	51,8±0,2	22-Mei-09	30,5±0,7	23,8±1,5	6,8±1,7	44,8±4,4	41,0±1,6	1,26±0,05
63,0-63,5	1,52	56,1±0,2	20-Jan-09	36,9±1,2	27,5±1,9	9,4±2,3	48,6±4,8		

Table 2: Sample numbers, depths, bulk densities, cumulative masses and count dates, total ^{210}Pb, supported ^{210}Pb, decay corrected unsupported +Pb, CIC and CRS models calculated ages and mass accumulation rates of Tuntang. core. Constant Mass of accumulation rate of CIC e.i., 0.13±0.01 /cm^2/year R^2 = 0.99

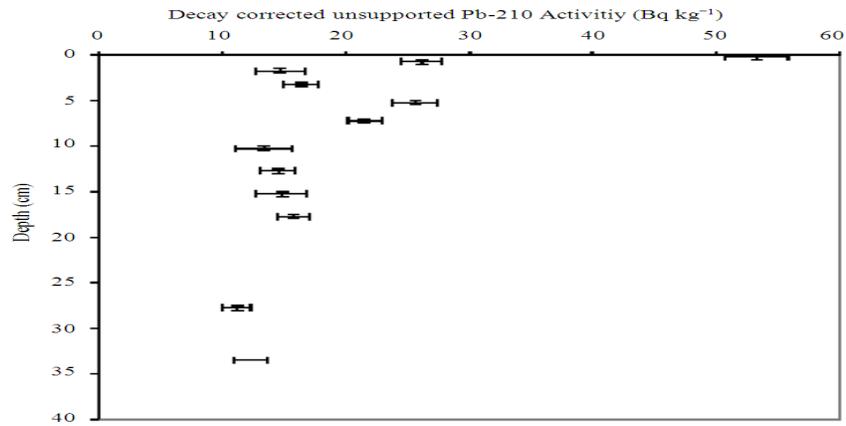| ANSTO ID	Depth (cm)	Dry Bulk Density (g/cm^3)	Cumulative Dry Mass (g/cm^2)	Count date	Total Pb-^{210} (mBq g^{-1}) or (Bq/kg)	Supported Pb-210 (mBq/g/) or (Bq/kg^1)	Unsupported^{210}Pb Corrected to reference date 12-Jan-09 (mBq/g) or (Bq/kg)	Calculated CRS Ages (years)	CRS model Mass Accumulation Rates g/cm^2/y
L148	0.0-0.5	0.47	0.1±0.1	15-Jan-09	68.4±2.2	15.1±1.2	53.3±2.5	0.2±0.3	0.5±0.6
L508	0.5-1.0	0.73	0.4±0.1	21-Jul-09	42.5±1.2	6.7±1.1	26.2±1.7	0.9±0.4	0.5±0.2
L509	1.5-2.0	1.01	1.3±0.2	21-Jul-09	34.0±1.3	19.5±1.5	14.7±2.0	1.9±0.6	0.7±0.2
L401	3.0-3.5	0.64	2.5±0.2	22-May-09	33.2±0.8	17.0±1.1	16.4±1.4	3.0±0.7	0.8±0.2
L149	5.0-5.5	0.59	3.8±0.2	15-Jan-09	39.2±1.4	13.6±1.1	25.6±1.8	4.6±0.8	0.8±0.1
L402	7.0-7.5	0.60	4.9±0.2	22-May-09	34.9±0.9	13.6±1.1	21.5±1.4	6.4±0.9	0.8±0.1
L150	10.0-10.5	0.63	6.8±0.2	15-Jan-09	37.0±1.4	23.7±1.7	13.3±2.2	8.6±1.0	0.8±0.1
L403	2.5-13.0	0.79	8.6±0.2	22-May-09	31.9±0.7	17.5±1.1	14.5±1.4	10.5±1.1	0.8±0.1
L151	15.0-15.5	0.74	10.5±0.2	15-Jan-09	37.2±1.3	22.5±1.6	14.8±2.1	12.7±1.1	0.8±0.1
L404	17.5-18.0	0.66	12.2±0.2	22-May-09	31.0±0.9	15.4±1.0	15.8±1.3	15.0±1.2	0.8±0.1
L405	27.5-28.0	0.86	19.8±0.2	22-May-09	23.8±0.7	12.7±0.9	11.2±1.1	25.4±1.4	0.8±0.1
L406	33.5-33.5	0.54	23.9±0.2	22-May-09	24.4±1.0	12.2±0.8	12.3±1.3		

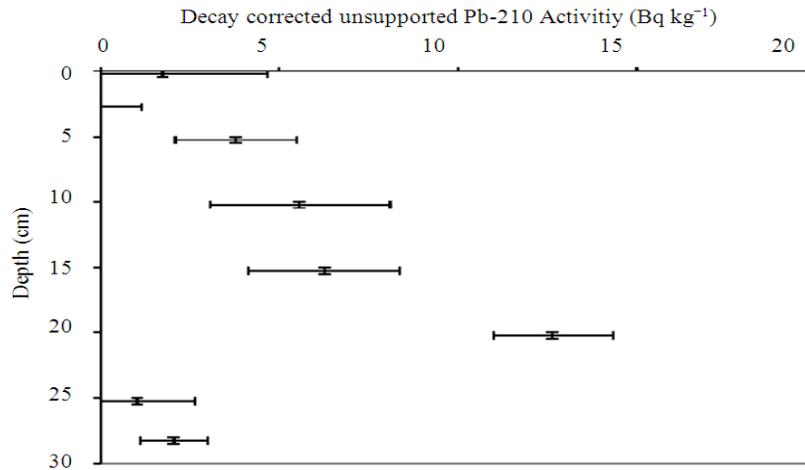Fig. 3: Unsupported ^{210}Pb versus depth to the Tuntang core

Fig. 4: Unsupported ^{210}Pb versus depth for the Dangkel core

Table 3: Sample numbers, depths, bulk densities, cumulative masses and count dates, total ^{210}Pb, supported ^{210}Pb, decay corrected unsupported ^{210}Pb of Dangkel core

Depth sediment samples (cm)	Dry Bulk Density (g/cm³)	Cumulative Dry mass (g/cm²)	Total Pb-210 Count Date	Pb-210 (mB/q/g) or (Bq/kg)	Supported to reference (mBq/g) or (Bq/kg)	Unsupported 210 Pb corrected date 12-Jan-09 (mBq/g) or (Bq/kg)
0,0-0,5	0,13	0,03±0,03	16-Jan-0909			
2,5-3,0	0,16	0,40±0,04	16-Jan-09			
5,0-5,5	0,12	0,75±0,04	16-Jan-09			
10,0-10,5	0,14	1,40±0,03	16-Jan-09	Activities of Po-210 and Ra-226were below detectable limits		
15,0-15,5	0,14	2,09±0,03	16-Jan-09			
20,0-20,5	0,19	2,89±0,04	16-Jan-09			
25,0-25,5	0,14	3,71±0,04	16-Jan-09			
28,0-28,5	0,90	5,27±0,05	16-Jan-09			

Table 4: Sample numbers, depths, bulk densities, cumulative masses and count dates, total ^{210}Pb, supported ^{210}Pb, decay corrected unsupported ^{210}Pb, CIC and CRS models calculated ages and mass accumulation rates of Panjang core. Constant Mass accumulation rate of CIC e.i. 1.309 ± 0.01 g cm^{-2}/year $R^2 = 0.6039$

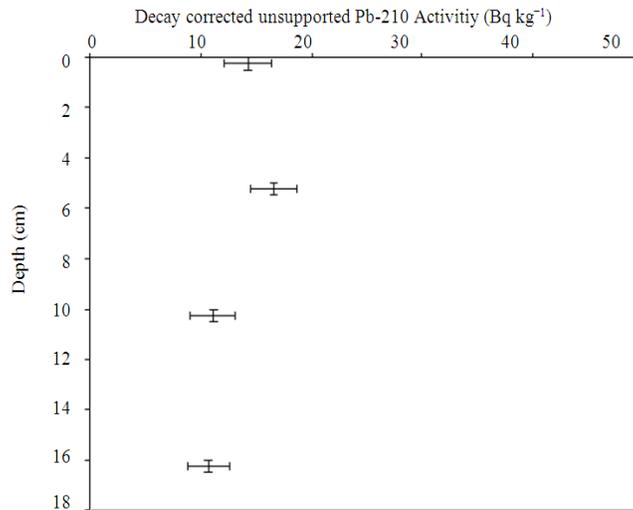| Depth sediment samples (cm)	Dry bulk density (g/cm³)	Cumulative dry mass (g/ cm)	Count date	Total Pb-210 (Bq/kg) or (Bq kg⁻¹)	Supported Pb-210 mBq/g) or (mBq/g)	Unsupported ^{210}Pb corrected to reference 12-Jan-09 (mBq/g) or (Bq/kg)	date Calculated CRS ages (years)	Calculated CIC ages (years)	CRS model mass accumulation rates g/cm²/y
0,0-0,5	1,00	0,3±0,3	15-Jan-09	38,1±1,3	23,9±1,6	14,2±2,1	0,19±0,22	0,16±0,39	1,55±3,74
5,0-5,5	1,00	5,3±0,3	15-Jan-09	40,4±1,3	23,8±1,6	16,6±2,1	4,01±2,31	3,68±1,72	1,43±0,67
10,0-10,5	1,00	10,3±0,3	15-Jan-09	36,2±1,0	25,1±1,8	11,1±2,0	7,83±4,49	7,16±2,02	1,43±0,40
16,0-16,5	1,00	16,3±0,3	15-Jan-09	33,4±0,9	22,7±1,7	10,7±1,9	12,42±7,11	10,89±2,30	1,49±0,32

Fig. 5: Unsupported ^{210}Pb versus depth Panjang core

Zone II (1984-1990): In Zone II of Asinan, eucentric diatoms (*Aulacoseira* spp.) increase at the expense of all others, except for *S. ulna* (Nitzsch) Ehrenberg. While *A. granulata* (Ehrenberg) Simonsen is considered a meso-eutrophic species, *D. stelligera* (Cleve and Grunow) Houk and Klee and *A. distans* (Ehrenberg) Simonsen are more common in oligotrophic, clear waters. This transition to plankton is accompanied by the decline in benthic and epiphytic taxa. The transition to plankton is marked by *D. stelligera* (Cleve and Grunow) Houk and Klee and *A. distans* (Ehrenberg) Simonsen at Tuntang also, but not at Panjang or Dangkel. The rise in *A.*

granulata (Ehrenberg) Simonsen is common to all four cores but the chronology would suggest this timing of this change varies.

Zone I (1990-2008): This upper zone in Asinan is dominated by *A. ambigua* (Grunow) Simonsen, *A. granulata* (Ehrenberg) Simonsen and *U. acus* (Kutzing) M. Aboel. The abundance of *A. distans* (Ehrenberg) Simonsen is lower here than Zone II and *D. stelligera* (Cleve and Grunow) Houk and Klee decreases through this zone to the surface. Within this zone *U. acus* (Kutzing) M.Aboel. is common, but declines sharply at

5cm with a synchronous increase in *A. ambigua* (Grunow) Simonsen. This increase in *Aulacoseira* spp. is also evident in Dangkel (at 11 cm or c. 1990 AD in that core) and in Tuntang, where the rise in *A. ambigua* (Grunow) Simonsen is less marked. In Panjang *A. ambigua* (Grunow) Simonsen is common throughout but increases after 2001 AD, but *A. granulata* (Ehrenberg) Simonsen is less common after 1986 AD. Despite this, the shift to an *Aulacoseira*-dominated plankton is a lake-wide shift.

Zone II (1984-1990): In Zone II of Asinan, eucentric diatoms (*Aulacoseira* spp.) increase at the expense of all others, except for *S. ulna* (Nitzsch) Ehrenberg. While *A. granulata* (Ehrenberg) Simonsen is considered a meso-eutrophic species, *D. stelligera* (Cleve and Grunow) Houk and Klee and *A. distans* (Ehrenberg) Simonsen are more common in oligotrophic, clear waters. This transition to plankton is accompanied by the decline in benthic and epiphytic taxa. The transition to plankton is marked by *D. stelligera* (Cleve and Grunow) Houk and Klee and *A. distans* (Ehrenberg) Simonsen at Tuntang also, but not at Panjang or Dangkel. The rise in *A. granulata* (Ehrenberg) Simonsen is common to all four cores but the chronology would suggest this timing of this change varies.
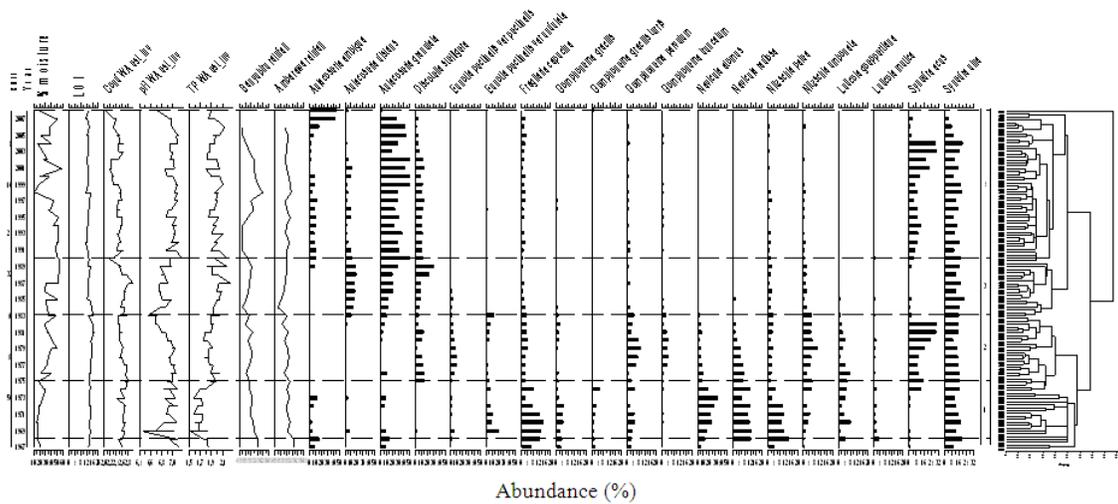

Abundance (%)

Fig. 6: Stratigraphic estimation of cores'year, moisture, LOI, reconstruction of conductivity, pH and TP, rainfall, diatom species, zonation and cluster of Asinan core, Rawapening Lake
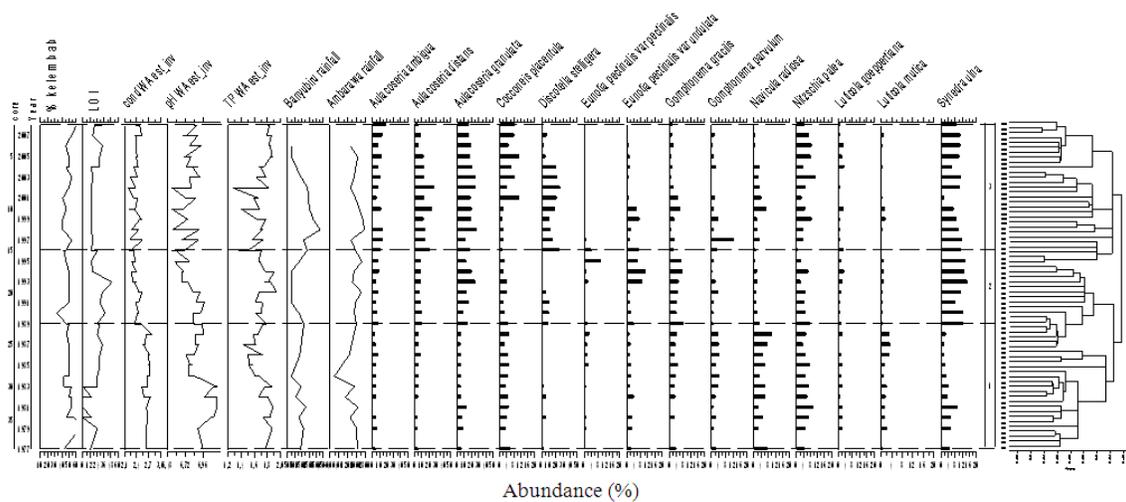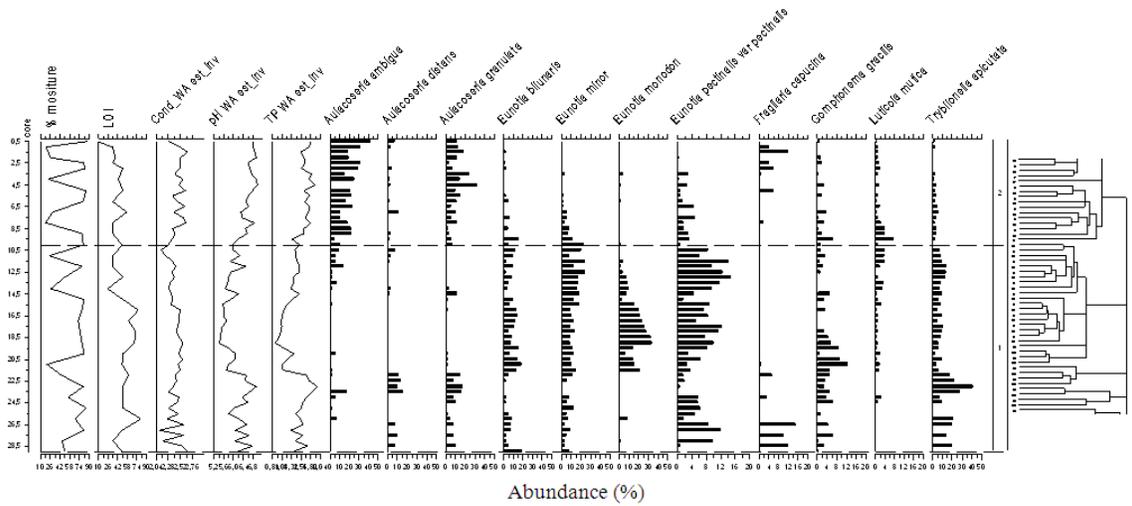

Abundance (%)

Fig. 7: Stratigraphic estimation of cores'year, moisture, LOI, reconstruction of conductivity, pH and TP, rainfall, diatom species, zonation and cluster of Tuntang core, Rawapening Lake

Fig. 8: Stratigraphic estimation of cores'year, moisture, LOI, reconstruction of conductivity, pH and TP, rainfall, diatom species, zonation and cluster of Dangkel core, Rawapening Lake
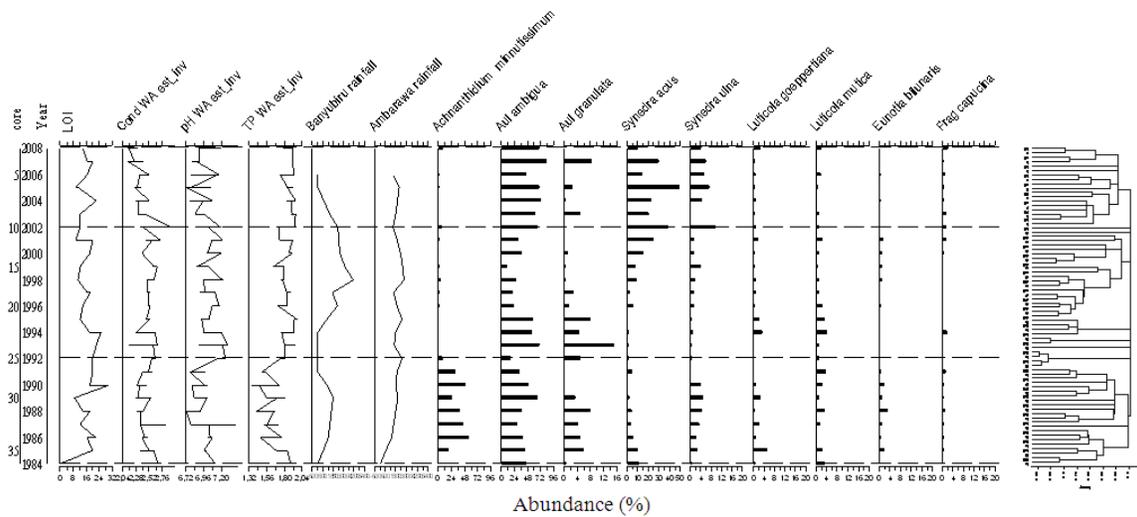

Fig. 9: Stratigraphic estimation of cores'year, moisture, LOI, reconstruction of conductivity, pH and TP, rainfall, diatom species, zonation and cluster of Panjang core, Rawapening Lake

Zone I (1990-2008): This upper zone in Asinan is dominated by *A. ambigua* (Grunow) Simonsen, *A. granulata* (Ehrenberg) Simonsen and *U. acus* (Kutzing) M.Aboel. The abundance of *A. distans* (Ehrenberg) Simonsen is lower here than Zone II and *D. stelligera* (Cleve and Grunow) Houk and Klee decreases through this zone to the surface. Within this zone *U. acus* (Kutzing) M.Aboel. is common, but declines sharply at 5cm with a synchronous increase in *A. ambigua* (Grunow) Simonsen. This increase in *Aulacoseira* spp. is also evident in Dangkel (at 11 cm or c. 1990 AD in that core) and in Tuntang, where the rise in *A. ambigua*

(Grunow) Simonsen is less marked. In Panjang *A. ambigua* (Grunow) Simonsen is common throughout but increases after 2001 AD, but *A. granulata* (Ehrenberg) Simonsen is less common after 1986 AD. Despite this, the shift to an *Aulacoseira*-dominated plankton is a lake-wide shift.

DISCUSSION

The ^{210}Pb age of the sediment cores indicates that the basal sediment of Rawapening Lake is less than 100 years old. The Constant Initial Concentration (CIC) and

Constant Rate of Supply (CRS) ^{210}Pb dating model used to calculate sediment ages compared well. Both models assume constant flux of unsupported ^{210}Pb at the sediment-water interface. The basic assumption of the CRS model is that the rate of supply of fallout ^{210}Pb to the core site is constant, reflecting the constant flux of ^{210}Pb from the atmosphere. The CIC (constant initial ^{210}Pb concentration) model assumes that sediments in the core all had the same initial unsupported ^{210}Pb concentration at the time they were laid down on the bed of the lake, regardless of differences in the sedimentation rate (Walling *et al*., 2003). For all four cores from Rawapening, the CRS model performed better than the CIC model, since the CRS model accounts for any variations in sedimentation rates over time, while the CIC model assumes a constant sedimentation rate for the period of time over which unsupported ^{210}Pb exhibits a decay profile.

The longest sediment core was from Asinan (63 cm), possibly related to the lowest erosion rate (40.18 ton/Ha) from the nearby catchment. The catchment areas near Panjang and Tuntang have middle-heavy erosion rates of 73.37-303.75 ton/Ha and 17.84-78.7 ton/Ha, respectively (GS, 2000).

Eucentric diatoms dominated (up to 70%) the modern flora of Rawapening Lake, consistent with the major influence of inlets/rivers (Asinan and Panjang). Meanwhile, in the centre of the lake, eucentric diatoms still dominated but in lower percentages (30% in Tuntang and 40% in Dangkel). Most of eucentric diatoms are planktonic, but are commonly found in the sediment (Sonneman, 1999; Soeprobowati *et al*., 2001).

The predominance of *Synedra* from 1967 to present indicates that Rawapening Lake has been fresh and meso-eutrophic throughout. *Synedra ulna* (Nitzsch) Ehrenberg is a tolerant species, found in the Indonesian rivers and lakes with high organic content and so a total phosphorous content of 20-1,000 µg L^{-1} and pH of 5- 9 can be inferred from local records. The modern sampling of pH at Rawapening reveals it to fluctuate widely. Research in 1976 (Goltenboth, 1979) reported the pH of Rawapening Lake was 7.2-7.6. EPA-ERC Undip (1999), reported that the pH of Rawapening Lake was alkaline (7.5-8.8). In 2004 and 2005, the pH of the inlet and lake tended to neutral, except in the site around the spring and floating island where the pH was 9.52 (Soeprobowati *et al*., 2005). During field work for this study (2008), Rawapening had a pH of more than 11. Zone 1, the upper diatom zone in the lake sediments, was dominated by *Aulacoseira ambigua* (Grunow) Simonsen, *A. granulata* (Ehrenberg) Simonsen and *U. acus* (Kutzing) M.Aboel. This indicates that, from 1990 to present, Rawapening pH varied from 6.5- 9.

The deepest section of the Rawapening sediment sequence is dominated by mostly periphytic species, widely known to prefer eutrophic to hyper eutrophic conditions. For example, *Nitzschia palea* (Kutzing) W. Smith is epipelic or epiphitic diatom that is widely distributed in eutrophic waters (Dam *et al*., 1994; Gell, 1999; Gell *et al*., 2007; Soeprobowati *et al*., 2001; 2005). This is accompanied, or followed by, an increase in epiphytes *Gomphonema* spp. Prefer circumneutral to alkaline conditions while *Eunotia* spp. Tend to exist in circumneutral in acid waters. This site variation may reflect the variable accumulation of organic matter from dead macrophytes that would locally reduce pH, at least periodically. The transition from *Gomphonema* spp. to *Eunotia* spp. supports this notion of an increase in macrophyte cover (epiphytic diatoms) that induces more acidic waters suited to acidophilous taxa.

The most marked shift in the Rawapening sediment sequence is the transition to euplanktonic diatoms at the expense of benthic and epiphytic taxa at c. 1983 AD. Initially this transition was marked by increases in *A. granulata* (Ehrenberg) Simonsen , but also *D. stelligera* (Cleve and Grunow) Houk and Klee and *A. distans* (Ehrenberg) Simonsen. Such a shift to phytoplankton in eutrophic lakes is often stimulated by a reduction in the euphotic zone, possibly by an increase in the supply of clay and colloidal sediments. While the dating does not reveal changing sedimentation rates, increased human activity in the catchment may have lead to an increased flux in fine sediment that can remain in suspension impacting on the light regime. Such a state switch can occur independent of increases in total nutrient concentrations (Scheffer 1990; Scheffer *et al*., 1993) and this appears to be the case with basal core sediments supporting taxa with preferences for eutrophic waters. Typically, where the euphotic depth shallows, aquatic plants attached to the substrate decline and nutrients and sediments are further releases into the water column. This drive increases in phytoplankton which can continue to exploit the light that is confined to the surface waters (Reid *et al*., 2007). This sequence is evident in the diatom record from the Rawapening sediments that has ultimately come to be dominated by planktonic forms that are able to thrive in eutrophic, turbid and alkaline waters.

The reconstruction of nutrients, particularly of total phosphorus, was undertaken using a European data set. The diatom inferred total phosphorous concentration from the upper zone of the Asinan core was 20-200 µg L^{-1}). This range appears likely, given the evidence for its eutrophic state (Sonneman, 1999) from modern sampling. The poor representation of fossil taxa in the European data set has precluded a more robust reconstruction. Indonesia does not have yet an extensive diatom data set of nutrient or pH

reconstruction. Despite this, the European based reconstructions performed well, such as evidence for fluctuating pH.

Nevertheless, the development of Indonesian data set is essential to provide a data set of tropical diatoms that are local to the region. Its implementation will provide more accurate reconstructions compared to those attempted using a data set from another continent and climate zone.

It was predicted that Rawapening Lake would be filled with sediment (GS, 2000) as early as 2021, based on the remote sensing data (1972-2009) of land use changes in the catchment area of Rawapening Lake. This documented a decrease in the extent of paddy field plantations and crop dry land, followed by an increase in settlement. In 2009 the percentage of settlement was 19.03% of land and it is forecast to be 32.78% in 2099. The sedimentation rates suggest that a high percentage of Rawapening Lake remains stable. It indicates that the shallowing and sedimentation of the lake has not greatly reduced the lake as predictions would suggest, although the lake volume continues to decrease.

Co-management had been implemented in Rawapening (RCNDP UGM, 2000). The 2005-2010 action plan of Rawapening Development (CJPB, 2005) has been implemented to conserve Rawapening Lake, but its condition remains far from expectations due to a limited commitment to restoration. The record of change from lake sediments attests to a long history of elevated nutrient concentrations, but a shift to a less productive state from the 1980s through sediment input. Stakeholders, public and government bodies alike, have to be more integrated in the implementation of a program of co-management of the lake and catchment. Integrated and sustainable lake management needs to be developed, preferably based on the reconstructed past ecological condition using modern and fossil diatom assemblages, to understand trajectories and drivers of change, to predict changes in the future and the means to arrest state decline.

CONCLUSION

The condition of Rawapening Lake may be divided into 4 zones: zone 4 (1967-1974), zone 3 (1974-1983), zone 2 (1984-1990) and zone 1 (1990-2008). The dominance of benthic indicators of high nutrient status reveals that Rawapening has a long history of eutrophication. A rise in epiphytic and acidiphilous taxa suggests that high nutrients encouraged aquatic macrophytes that may have periodically caused reductions in pH. The abrupt change to euplanktonic taxa in the 1980s documents a state shift that passed initially though relatively clear water conditions, but

with a limited photic depth that reduced attached plants, to a turbid phytoplankton-dominated system. Rather than being linked to increased nutrients, this change is most likely driven by an increased flux of fine sediments that continue to advantage a food web based on phytoplankton rather that aquatic macrophytes.

ACKNOWLEDGMENT

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