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Diatom assemblage in the 24 cm upper sediment associated with human activities in Lake Warna Dieng Plateau Indonesia

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A B S T R A C T

Lake Warna is a small shallow crater lake on the Dieng Plateau, Central Java, the second highest plateau in the world after Nepal. A 24 cm sediment core was extracted from Lake Warna to reconstruct environmental changes in the Lake and its catchment from preserved diatom assemblages. Diatoms are microalgae in the Bacillariophyte that have silicious cell walls that can be preserved in sediments. As diatom species are sensitive to water quality changes in the assemblages upcore reflect changes in lake condition. Sediment cores were collected from two sites, sliced at 1 cm intervals for diatom analysis and bulked across 3 cm for^{210}Pb radiometric dating. Examination of diatoms in a 24 cm sediment core from Lake Warna reveals clear correlation with human activities in the catchment area over the past 124 years. The record is divided into 2 zones based on sustained changes in the diatom assemblages. The lowest zone Zone I (21–15 cm, estimated 1935–1954) was dominated by *Frustulia crassinervia* (Brebisson ex W. Smith) Ross, Gomp*h onema parvulum* (Kutzing) Kutzing, Pinnularia valdetolerans Mayama & H. Kobayasi, P. viridis (Nitzsch) Ehrenberg, and *Aulacoseira distans* (Ehrenberg) Simonson. Zone II (15–0 cm, estimated 1980–2013), the uppermost zone was dominated by *P. viridiformis* Krammer, *P. latevittata* Cleve, *E. monodon* var. *tro p ica* (Hustedt) Hustedt, S. seminulum Grunow, *P a crosphaeria* W. Smith. *E. zygodon* Ehrenberg, P. gibba Ehrenberg, and *P. viridiformis* Krammer. The 15 cm core from TW3 commenced sediment accumulation 114 years ago and is divided into 2 zones as well. Zone I (15–7 cm, estimated 1901–1981) was dominated by *Brachysira brebissonii* R. Ross, *G. parvulum* (Kutzing) Kutzing, *E. monodon* var. *tropica* (Hustedt) Hustedt, *E. zygodon* Ehrenberg and *S. seminulum* Grunow. Zone II (7–0 cm, estimated 1981–2006) was dominated by *P. viridiformis* Krammer, P. gibba Ehrenberg, Pinnularia viridis (Nitzsch) Ehrenberg, *Sellaphora bacillum* (Ehrenberg) Mann, *S. seminulum* Grunow, and *Stauroneis* sp. These assemblages reflect ongoing acid, clear water conditions for the time represented by the cores. The recent rise in *S. seminulum* Grunow reflects recent lake eutrophication likely owing to the accelerated agricultural and urban development in the lake's catchment in recent decades.

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1. Introduction

The Dieng Volcanic Complex, called the Dieng Plateau, hosts the highest village on Java, located in the Wonosobo and Banjarnegara Regencies, on the slopes of the active Sindoro and Sumbing Volcanoes. The Dieng Plateau, the second highest plateau in the world after Nepal, has many surface manifestations of hydrothermal activity, including hot lakes, fumaroles/solfatara, mud pools, altered rocks, and hot springs. Dieng Plateau is also rich in geothermal resources and is subject to lethal outbursts of gas. The many temples on the Plateau attest to the long establishment of ancient Indian Hindu culture that established a firm footing in Java from about AD 400 (van Bergen et al., 2000). The Dieng Plateau is 14 km long and 6 km wide and geologically consists of late Quaternary to Recent volcanic cones and explosion craters. There are 3 major volcanic activities resulting in volcanic rocks comprising Old Dieng, Adult Dieng, and Young Dieng (Sukhyar, 1994). During the second episode, a number of stratovolcanoes emerged within the depression, producing basalts, basaltic andesites and pyroxene-andesites. Pyroclastic fall deposits, believed to have been erupted from all of these volcanoes, blanket the Dieng and Batur depressions. They are collectively referred to as the 'Dieng tephra' for which dating yielded an age of 16,770 years. A parasitic eruption centered on the southern slope contains an 800 m wide and $>$ 150 m deep crater lake (Telaga Menjer), which is used for hydroelectric power and irrigation. Pangonan and Merdada are two stratocones east of Nagasari. The latter has a crater lake which is used for drinking water by local villagers. This crater, which has been partly filled by a biotite-andesite lava from the third episode, contains a colored lake, Lake Warna (van Bergen et al., 2000).

The high sulfur content, and possibly other elements, causes this lake's colorful state which ranges from blue to yellowish-green, and sometimes brownish, especially when exposed to sunlight. The color is a reflection of sunlight by sediment/rock at the bottom of the lake or refraction from fine sediments within the water. Red and yellow colors are a reflection of the sulfur deposits, and the white color comes from the deposition of limestone rocks and quartz. Now however, the only color visible is mostly blue on account of the sediment surface (Soeprobowati et al., 2017). In terms of chemical composition, Lake Warna is the most interesting crater lake in the Dieng area. The original shape of the crater has been modified by a lava flow and now the water occupies $<$1 km^2. Gas bubbles with a sulfurous odor can be seen rising to the lake surface. The water has a pH of about 3 (van Bergen et al., 2000) to 5 (Soeprobowati et al., 2017) which may fluctuate depending on seasonal conditions. The lakes chemistry is unusual with high concentrations of sulfate and chloride. Strong emissions of CO_2-rich gas are variable but have been intense enough to occasionally kill animals, warranting the closure of a path on the north side of the lake (van Bergen et al., 2000).

Dieng plantations over the years only used a monoculture system with potatoes as the main commodity. The slope of the land in Dieng area ranges from 35% to more than 45%, therefore, the farmers developed tillage systems terracing on contours as far as the tops of the hills. The erosion rate has reached 161 tons/hectare/year. About 7758 hectares of land has become critically unstable and has high erosion rates. In 2007, the Dieng area was 63.22% dominated by non-forest areas and this increased to 66.1% in 2010 (Mulyana, 2008). Lack of vegetation cover and the use of monoculture systems had induced sedimentation and damaged the ecosystems within this important watershed, such as Tulis and Serayu (Fig. 1, Pradana et al., 2015).

Lake Pengilon (Pengilon = mirror), located next to and connected to Lake Warna, is also notable. The two lakes host specific ecosystems that differ from other lakes. However, due to land use changes in the surrounding area both lakes are now facing environmental degradation. The land use in the surrounding area is dedicated to intensive agriculture with the main crops being vegetables, especially potatoes. Agricultural practices for plantation potato production use water from Lake Pengilon to irrigate the plants by pumping and irrigation. Agricultural practices expose soils to erosion, which contributes sediment to the lake via surface runoff. The volume of the lake is gradually decreasing due to water abstraction. Further, the overuse of fertilizer for agricultural production contributes nutrients to the lake leading to eutrophication (Sudarmadji and Pudjiastuti, 2015).

Diatoms are microalgae that can be found in most aquatic ecosystems. Their silicious cell walls are often well preserved in sediments so diatoms are particularly useful for reconstructing environmental history. Different species have distinct optima to given environmental variables, and they are taxonomically distinct allowing identification to species and sub species level (Smol, 2008). They are highly sensitive to variations in the aquatic environment so they can be used as bioindicators of lake conditions. The lake's sediment reflects the history of changes in the catchment area (Battarbee et al., 2011; Di et al., 2013; Tolkkinen et al., 2014; Gell and Reid, 2014). This history can be reconstructed by reference to the nutrient requirements or typical habitats of each fossil taxon, or by consideration of their relative species abundance.

Palaeolimnological studies offer an opportunity to understand past and present lake condition and so, from the inferred trajectory, to predict future conditions. Preliminary research was conducted on the water quality of Lake Warna over the period of 2014–2015. Diatoms are particularly sensitive to pH and the acidification of surface waters is known to negatively impact on aquatic organisms, reduce diversity, and induce shifts in community structure. Diatoms can act as an early detection mechanism for decreasing pH and so can flag the need for the implementation of mitigation measures.

Hustedt (1937–1939) found *E. septentrionalis* lived in acid waters (pH ca.3) of the sulfur-springs of Sumatra. Negoro reported these varieties occurring as epiphytes from many highly acidic environments in Japan (DeNicole, 2000). The presence of *E. septentrionalis* in Lake Warna may be on account of the influence of the sulfur springs as was recorded in Sumatra (Soeprobowati et al., 2017).

Studies on diatoms in Indonesian lake sediments have in general been very limited in the analysis to determine indicator species and the changes of relative abundance through time (Soeprobowati et al., 2018). Notable among these are Dama

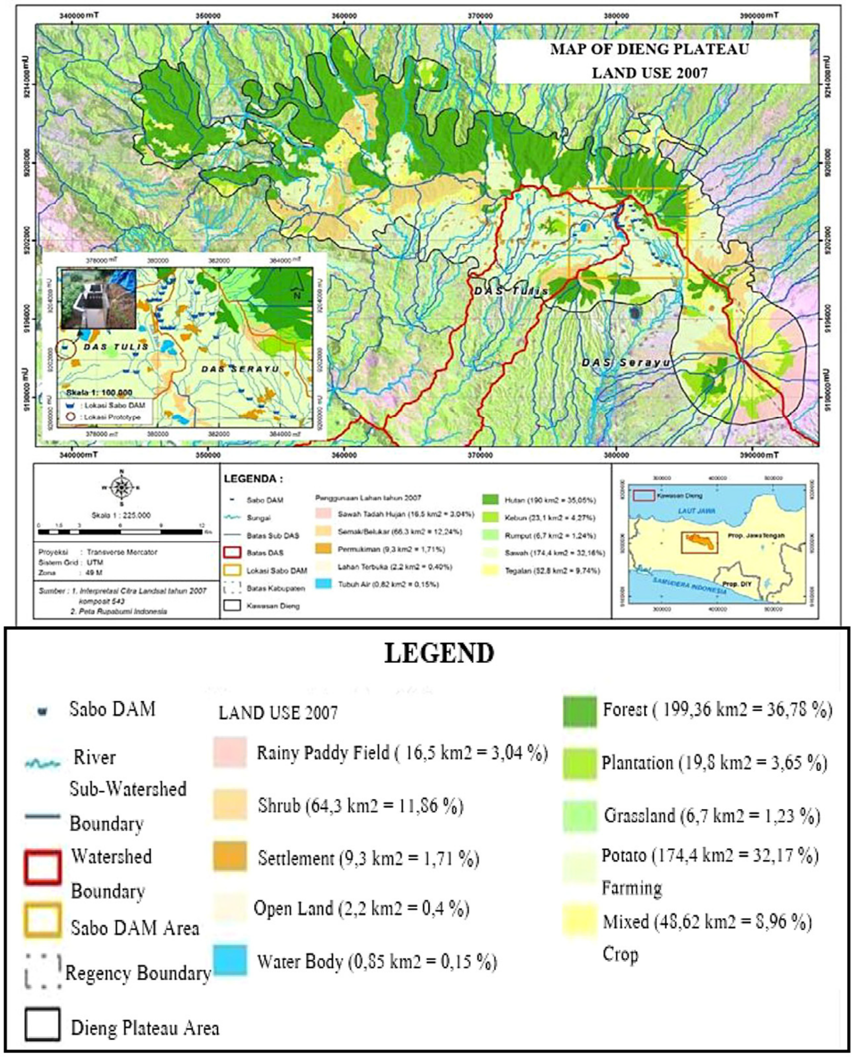

Fig. 1. Land use of Dieng Plateau (Pradana et al., 2015). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

et al. (2001) on Tondano, and Soeprobowati et al. (2012) on Rawapening. These studies have been devoted to long-term developmental trends in lakes and dealt with recent historical trends in diatom populations that might be correlated with the well documented changes in lake sediments. Diatom studies in sediments have not been made previously in Lake Warna. This research was conducted in order to study the past impact of human activities in the catchment area from one hundred years ago by the reconstruction of the ecological condition of the lake from diatom bioindicators preserved in the lake sediments.

2. Material and methods

Sediment cores were extracted from two sites within Lake Warna Dieng, in February 2015 (Fig. 2). Lake Warna Dieng contained shallow water (1–3 m) at the time of sampling. The core sites were selected as being representative of the few remaining depositional sites disturbed (TW2), and undisturbed (TW3), by agricultural activities. The selected sites were considered most likely to receive constant sediment deposition. The cores were kept intact and placed in half drain-pipes and wrapped in cling-film immediately after collection. The cores were sliced in 1 cm sections for diatom analysis and in bulked samples across 3 cm for dating, from the upper 24 cm.

Samples bulked over 3 cm increments were analyzed at the Center for Isotopes and Radiation Application, National Nuclear Energy Agency, Indonesia for radionuclide ^{210}Pb in two sediment cores to establish sediment accumulation rates, and so the core chronology. Total ^{210}Pb analyzes followed a standard method (Carroll et al., 1999; Theng et al., 2003; Lubis, 2006) whereby 5 g of sediment was spiked with ^{209}Po tracer and digested with a mixture of HCl, HNO_3, H_2O_2 and distilled water. Ascorbic acid was added to complex any iron present. ^{209}Po and ^{210}Po in solution was plated onto copper

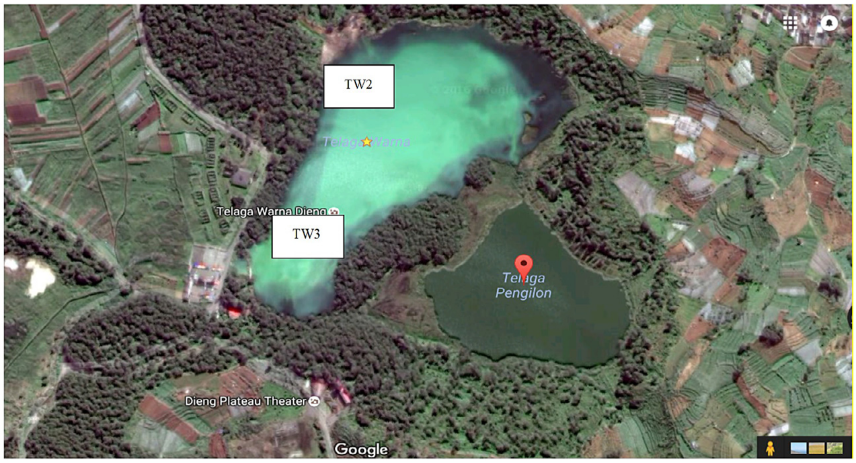

Fig. 2. Sites for coring sediment in Telaga Warna Dieng (Soeprobowati et al., 2017). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

disks for 10 min while stirring. ^{210}Po was assumed to be in radioactive equilibrium with ^{210}Pb. The measurement of activity was conducted using an alpha spectrometer equipped with a PIPS detector. For calibration of the detector, a point source of alpha emitters (^{238}U, ^{234}U, ^{239}Pu and ^{241}Am) was used while reference material IAEA-300 was used for controlling the method. Supported ^{210}Pb was calculated from the mean constant of concentration of ^{210}Pb at the bottom of the sediment core (Cossa et al., 2014). The excess ^{210}Pb was equal to the total ^{210}Pb minus the supported fraction. The depth-age profile was determined using the constant rate of supply (CRS) model that assumes a constant influx of unsupported, atmospheric ^{210}Pb to the site (Appleby, 2001).

Diatoms were chosen as a primary palaeolimnological tool. Diatom extraction was conducted following the procedure of Battarbee et al. (2001), whereby the subsamples are digested in 10% HCl and subsequently 10% H_2O_2 with multiple washes in distilled water between stages. Samples were mounted onto slides and a minimum of 300 diatom valves were identified per slide under 1,000x magnification with oil immersion using a compound microscope (Soeprobowati et al., 2016a). The diatoms were identified to species level where possible, whereas the others were identified to genus level following standard texts (Sonneman et al., 2000; Krammer and Lange-Bertalot, 2004a, 2004b, 2004c; Krammer and Lange-Bertalot, 2010; Taylor et al., 2007; Karthick et al., 2013; Bahls, 2017). Guiry and Guiry (2018) was used for consulting taxonomy and nomenclature. The counts of diatom valves were expressed as relative abundance. Species with a relative abundance less than 1% were not included in the analysis and the remaining assemblage was graphed using the software package C2 version 1.7.7 (Juggins, 2016). The diatom assemblages were positioned into statistically significant clusters by Bray Curtis Clustering performed using PAST (Paleontological statistics software package for education and data analysis) version 2.17c (Hammer et al., 2001; Hammer, 2017).

3. Results

Seventeen sediment samples were used to establish the chronology of the 72 cm long TW2 core, and 16 sediment samples were used to establish the chronology of the 65 cm long TW3 core. The unsupported ^{210}Pb activities in the TW2 core exhibited an overall decreasing profile with depth (Fig. 3). The unsupported ^{210}Pb activities below 30 cm (TW2) and 18 cm (TW3) are close to being constant, showing that the activity had reached background and that the sediments below these levels were deposited $>$100 years ago. This also indicates that the sediments in the upper 24 cm were deposited in the last 124.9 years (deposited since the year 1891) for TW2. Meanwhile, the sediment in the upper 12–15 cm of TW3 were deposited in the last 114 years (deposited since the year 1901) Tables 1a and 1b).

Diatoms were well preserved in the lake sediments with most valves being entire or many valves were fragmented or dissolved. A total of 62 diatom species were identified from TW2 and 47 diatom species were identified from TW3. The identifications were made by comparing the species descriptions in published floras and comparing the morphometrics of valves measured down the microscope (length, width, striae density etc.) to the published ranges. Where any valves observed from the Warna sediments did not clearly match the features of published species they were assigned affinity status.

Based on the cluster analysis, basically the two cores of TW2 and TW3 can be divided into 2 zones, upper (Zone II) and bottom (Zone I), that are separated with a blue line in Fig. 2. Within the upper zones there were sub zones with red color (Figs. 3 and 4). For TW2, the zonations are: **Zone I (21–15 cm, estimated 1935–1954)**, the lowest zone was dominated by *Frustulia crassinervia* (Brebisson ex W. Smith) Ross, *Gomphonema parvulum* (Kutzing) Kutzing, *Pinnularia valdetolerans* Mayama & H. Kobayasi, *P. viridis* (Nitzsch) Ehrenberg, and *Aulacoseira distans* (Ehrenberg) Simonson. **Zone II (15–0 cm, estimated 1980–2013)** can be divided into 2 sub zones IIb (9–0 cm, estimated 2003–2013), the uppermost zone was

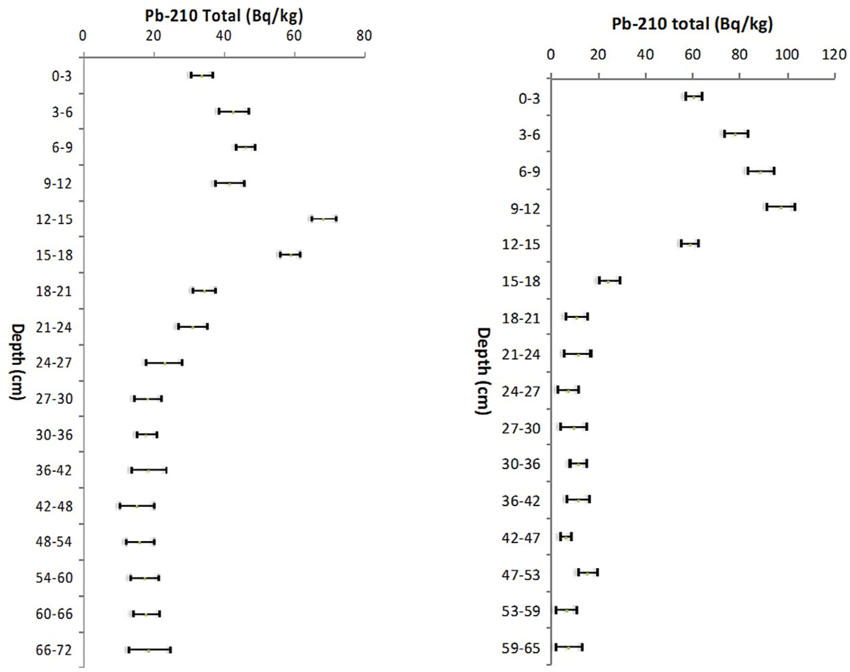

Fig. 3. Total ^{210}Pb versus depth of the TW2 core (left) and TW3 core (right), decay trend.

Table 1a
Age estimates determined from 210Pb analysis in TW2.

Depth (cm)	Estimated date (year)	Calendar age	Sediment accumulation rates (gr/cm^2 y)
0–3	2.4 ± 0.1	2013	0.31 ± 0.013
3–6	6.9 ± 0.2	2008	0.18 ± 0.005
6–9	12.4 ± 0.2	2003	0.13 ± 0.002
9–12	18.3 ± 0.9	1997	0.13 ± 0.007
12–15	34.7 ± 1.3	1980	0.04 ± 0.002
15–18	60.9 ± 2.6	1954	0.03 ± 0.001
18–21	81.9 ± 6.8	1933	0.03 ± 0.003
21–24	124.2 ± 16.0	1891	0.02 ± 0.002

Table 1b
Age estimates determined from 210Pb analysis in TW3.

Depth (cm)	Estimated date (year)	Calendar age	Sediment accumulation rates (gr/cm^2 y)
0–3	10.8 ± 0.6	2004	0.10 ± 0.005
3–6	21.1 ± 1.3	1994	0.05 ± 0.003
6–9	33.7 ± 2.0	1981	0.031 ± 0.002
9–12	62.8 ± 3.8	1952	0.015 ± 0.001
12–15	113.7 ± 6.6	1901	0.008 ± 0.001

dominated by *P. viridiformis* Krammer, *P. latevittata* Cleve, *E. monodon* var. *tropica* (Hustedt) Hustedt, *S. seminulum* Grunow, and *P. acrosphaeria* W. Smith. Sub zone IIa (15–9 cm, estimated 1997–1980) was dominated by *E. zygodon* Ehrenberg, *S. seminulum* Grunow, *P. gibba* Ehrenberg, and *P. viridiformis* Krammer. Diatoms asssemblages in 1891 differed to that in other layers owing to the dominance of *F. saxonica* Rabernhorst in these layers.

For TW3, the 2 zones are: Zone I (15–7 cm, estimated 1901–1981), above Zone I of TW2 that was dominated by *Brachysira brebissonii* R. Ross, *G. parvulum* (Kutzing) Kutzing, *E. monodon* var. *tropica* (Hustedt) Hustedt, *E. zygodon* Ehrenberg and *S. seminulum* Grunow. Zone II (7–0 cm, estimated 1981–2006), just below the Zone II of TW2, was dominated by *P. viridiformis* Krammer, *P. gibba* Ehrenberg, *P. viridis* (Nitzsch) Ehrenberg, *Sellaphora bacillum* (Ehrenberg) Mann, *S. seminulum* Grunow, and *Stauroneis* sp.

The interesting note from the diatom stratigraphy from TW 2 and TW3 is that the population of *P gibba* tended to increase in the uppermost sediment in contrast with *P. viridiformis* Krammer and *G. parvulum* (Kutzing) Kutzing that tended to decrease in the uppermost sediment (see Fig. 5).

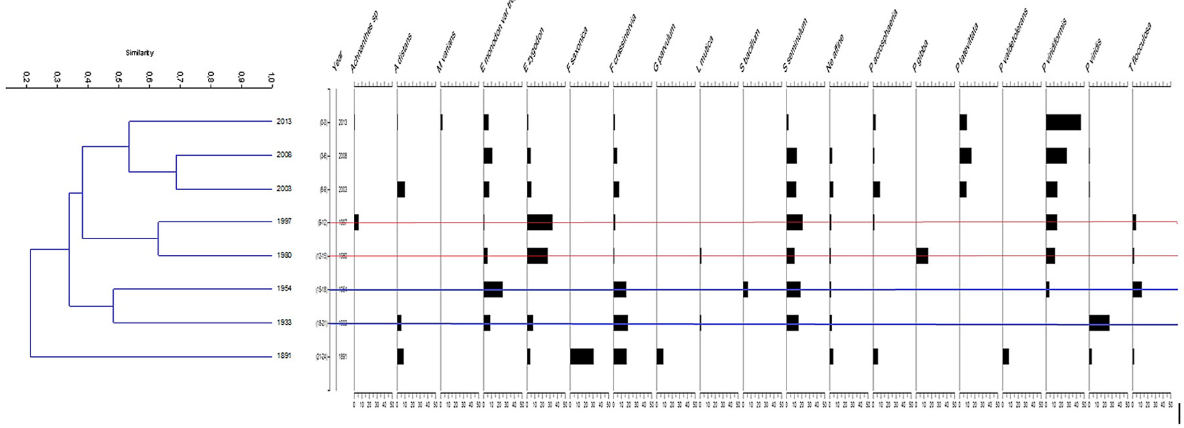

Fig. 4. Lake Warna diatom fossil record (TW2). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

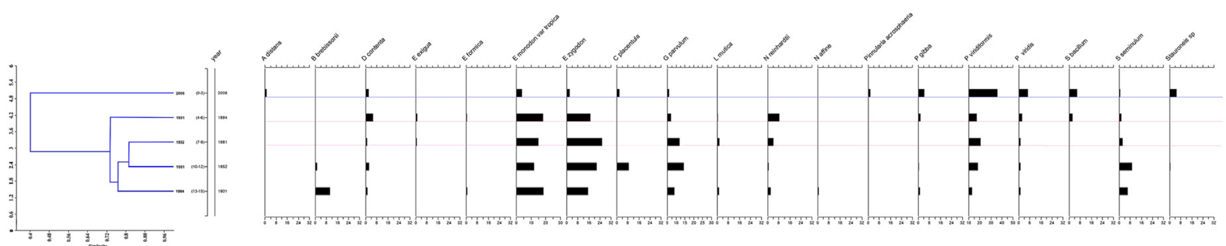

Fig. 5. Lake Warna diatom fossil record (TW3).

4. Discussion

During 1891 to 2015, the accumulation rates of sediment in TW2 increased from 0.02 to 0.31 gr/cm^2 yr^{-1}, whereas from 1901 to 2015, the accumulation rate of sediment in TW3 increased from 0.008 to 0.1 gr/cm^2 yr^{-1} (Tables 1a and 1b). The average accumulation rates in TW2 (0.11 gr/cm^2 yr^{-1}) was almost 3 times higher than in TW3 (0.04 gr/cm^2 yr^{-1}). This is likely as TW2 is located closer to agricultural activities on the nearby land, and TW3 is located in a less disturbed area. Land clearance events increased sharply in the 1970s, when the intensification of agriculture was the main national priority program (Pradana et al., 2015). As an impact, forests were converted into agricultural fields, mostly for potatoes.

The diatom valves were relatively abundant in the upper layers, but relatively rare in the lower layers, and mostly well preserved, although several large specimens of *Pinnularia* were broken. *S. seminulum* Grunow *was* found in all layers and zones with variable abundance that tended to increase in the upper zone, in contrast to *N. affine* that was found in almost all layers in low abundance. The presence of known eutrophic indicators such as *S. seminulum* Grunow (Zelazna-Wieczorek and Mamainska, 2006), signified that Lake Warna might have entered a nutrient enriched state from 1980 to present (Fig. 4).

S. seminulum Grunow is a small, freshwater benthic diatom (10.5 μm long and 3.9 μm wide). *S. seminulum* Grunow is previously known as *Navicula seminulum* Grunow, an important dominant species in benthic communities (Mann et al., 2008; Wetzel et al., 2015). As it is a clear indicator of eutrophic conditions it is critical to ensure the accuracy of its identification and to distinguish from other similar small naviculoid species. The specimens examined here comply with the description given by Wetzel et al. (2015) as:

> *The valves are linear-lanceolate to broadly lanceolate, with clearly convex margins (inflated in the middle) and protracted, broadly rounded, slightly rostrate ends (Figs. 158–172). The frustules are 9.8–16.5* μm *long and 3.4–4.4* μm *wide* ($n = 30$), *and in girdle view they are rectangular. The valve face is at and the mantle very shallow. The striae are markedly radiate and also arcuate, especially towards the apices, where they are also denser; they are uniseriate, or sometimes partially biseriate but only near the axial area (Figs. 295, 296, 298, 301). The areolae are small and round and each is occluded by a hymen lying across its internal aperture (Fig. 300). The axial area (sternum) is linear-lanceolate, with an irregular border, and is central or apparently very slightly displaced towards the secondary side (Figs. 295–298). The central area is bordered by three shorter striae and is usually butter y-shaped, but the size and shape vary. The raphe branches are slightly undulate externally and*

displaced towards the secondary side of the sternum; internally they are liform and straight. The proximal (central) part of each raphe branch curves gently towards the primary side externally and the central raphe endings are slightly drop-like. Internally, the raphe branches remain slit-like as they approach the center and are bent towards the primary side. Beyond the helictoglossa, a larger foramen-like (pit) can be seen (Figs. 295, 300, 301) at the poles. Distal raphe endings strongly curved onto the mantle, towards the secondary side (Figs. 295–298).

Over the last 100 years, Lake Warna has been known for its acidic clear water. *Sphagnum* is dominant in the bed of the lake, and, owing to the water clarity, benthic diatoms were also dominant compared to planktonic diatoms. Several planktonic species, such as *A. distans* (Ehrenberg) Simonson, and *M. varians* C. Agardh were found sporadically in several layers but with low numbers. Some species of *Eunotia* and *Pinnularia* that were found are acidophilus, so Lake Warna remained acidic throughout. One of the most widely distributed taxa in acid lakes is *P. acoricola*. Hustedt described it from sulfate rich waters in Java in 1935, and fossil specimens of *P. acoricola* var. *lanceolata* Hustedt was found in Lake Toba, Sumatra (Hustedt, 1935). A trend of increasing abundance and diversity of *Pinnularia* spp. from Zone II indicates that the pH was acid to neutral (Sonneman et al., 2000; Hobbs et al., 2009). This is supported by the results of the modern water quality which recorded pH values in the range of 2.2 to 5.35 from 2014–2015.

Lake Warna is a geothermal lake that releases air bubbles to the surface of the lake. This indicates that the region still experiences magmatism activity, that is a hydrothermal process that emits vapors containing sulfur. This ensures that Lake Warna is an acid lake with pH below 5. Lakes with pH $<$ 4 are typically dominated by acidophilus diatom species, such as *Eunotia paludosa* and *E. veneris* (Sonneman et al., 2000), many species in the genera *Eunotia, Pinnularia, Nitzschia,* and *Frustulia* as well as *Achnanthidium minutissima* (DeNicole, 2000). In Lake Rawapening, *E. bilunaris, E. minor, E. monodon* (Hustedt) Hustedt, and *E. pectinalis var. pectinalis* found in abundance indicates a pH of less than 6 or neutral (Soeprobowati et al., 2012). In the case of Lake Rawapening, temperature, phosphate and calcium were the modern parameters that were found to influence the diatom assemblage (Soeprobowati et al., 2016b).

E. monodon var. *tropica* (Hustedt) Hustedt and *E. zygodon* Ehrenberg numbers sharply increased after 1980 and tended to decline in the upper layers of Lake Warna. Those *Eunotia* seem to be specific to acidic lakes, and, assuming their pH preference remains stable over time, these changes can be used to infer pH changes in Lake Warna. As their abundance fluctuated and shifted it is clear that recent inputs have influenced lake acidity. *E. monodon* var. *tropica* (Hustedt) Hustedt was the dominant species from 1980–1997 while *E. zygodon* Ehrenberg was dominant from 1997–2003. Their decline after 2003 may suggest that incoming nutrients have advantaged other species in recent times.

E. exigua (Brébisson ex Kützing) Rabenhorst is a cosmopolitan species that is found from tropical to arctic regions in lakes, ponds, bogs and hot springs (Joynt and Wolfe, 2001). The dominance of the acidobiontic taxon *E. exigua* (Brébisson ex Kützing) Rabenhorst in Lake Warna from 1991–2007 indicates a pH of 2–4 through this time (Hobbs et al., 2009). The acidic condition was also indicated by the dominance of *A. minutissimum* (Kützing) in uppermost centimeter of sediment (Soeprobowati et al., 2017).

F. saxonica Rabernhorst was dominant and only found in 1891, and *F. crassineervia* dominant in the following layers and tent to decrease from 1980. *Frustulia* Rabenhorst is a genus of phytobenthic diatoms, that are abundant in acidic habitats, such as *Sphagnum* peat bogs and many ephemeral habitats (Round et al., 2000; Wehr and Sheath, 2002; Siver and Baskette, 2004). The dominance of *F. crassineervia* indicated that, from 1891–1954, Lake Warna was oligotrophic. The two species are similar morphologically with small differences were correlated with environmental condition. Variation in the shape and size of valves has shown strong relationships with different types of peat land habitats (Kulichova and Fialova, 2016).

G. parvulum (Kutzing) Kutzing, *E. exigua* (Brébisson ex Kützing) Rabenhorst, and *E. minor are* only found in Zone 1 (1954–1933). *G. parvulum* (Kutzing) Kutzing is a cosmopolitan species (Abarca et al., 2014), mostly found in circumneutral and eutrophic waters (Kovacs et al., 2006; Karthick et al., 2013) but Zelazna-Wieczorek and Mamainska (2006) found *G. parvulum* (Kutzing) Kutzing in a pH of 3. *G. parvulum* (Kutzing) Kutzing is also reported as a common species in clean or metal contaminated systems (Ivorra et al., 2002).

The sediment core was separated into the relatively natural part (1891–1954 yr, lower layer: 24–15 cm) and the human disturbed part (1980–2013 yr, upper layer: 15–0 cm). The diatom abundance changes are abrupt in 1997. The use of fertilizer for intensive agricultural improvement since 1970s is likely to increase the nutrient loads in the Lake Warna that induced a eutrophic lake, indicated by an increase in *S. seminulum* Grunow since 1980 (Fig. 4). The deforestation and illegal logging combined to enable extensive monocultures of potatoes. As a result, there was high erosion and a reduced water supply (Sudarmadji and Pudjiastuti, 2018), and decreased land fertility that has impacted on potato productivity since 1997 (Pradana et al., 2015). This low land fertility is shown on the shift at 9 cm of diatom abundance from *S. seminulum* Grunow to *P.viridiformis* Krammer and *E. zygodon* Ehrenberg. This might suggest reduced nutrient inputs, or the onset of a secondary impact such as increased acidity or sediment input. The causes of these detected changes can be related to the changes in land use in the catchment area through reference to the chronostratigraphy and an interpretation of the historical record. The diatom record reveals continuous change through time and has enabled the impacts of changing land use practices on the lake's water quality to be identified. This trajectory indicates that the services provided by the lakes are at risk if effective management is not implemented.

Water quality monitoring of Telaga Warna commenced in 2014–2016. Lake Warna is an acidic eutrophic lake, with pH in the range of 2.2–5.35. In the dry season, the pH is about 2, and in the wet season, the pH is between 4 and 5. Today Lake Warna is eutrophic to hypereutrophic with the recorded total nitrogen concentration above 1.9 mg/L and total phosphorus

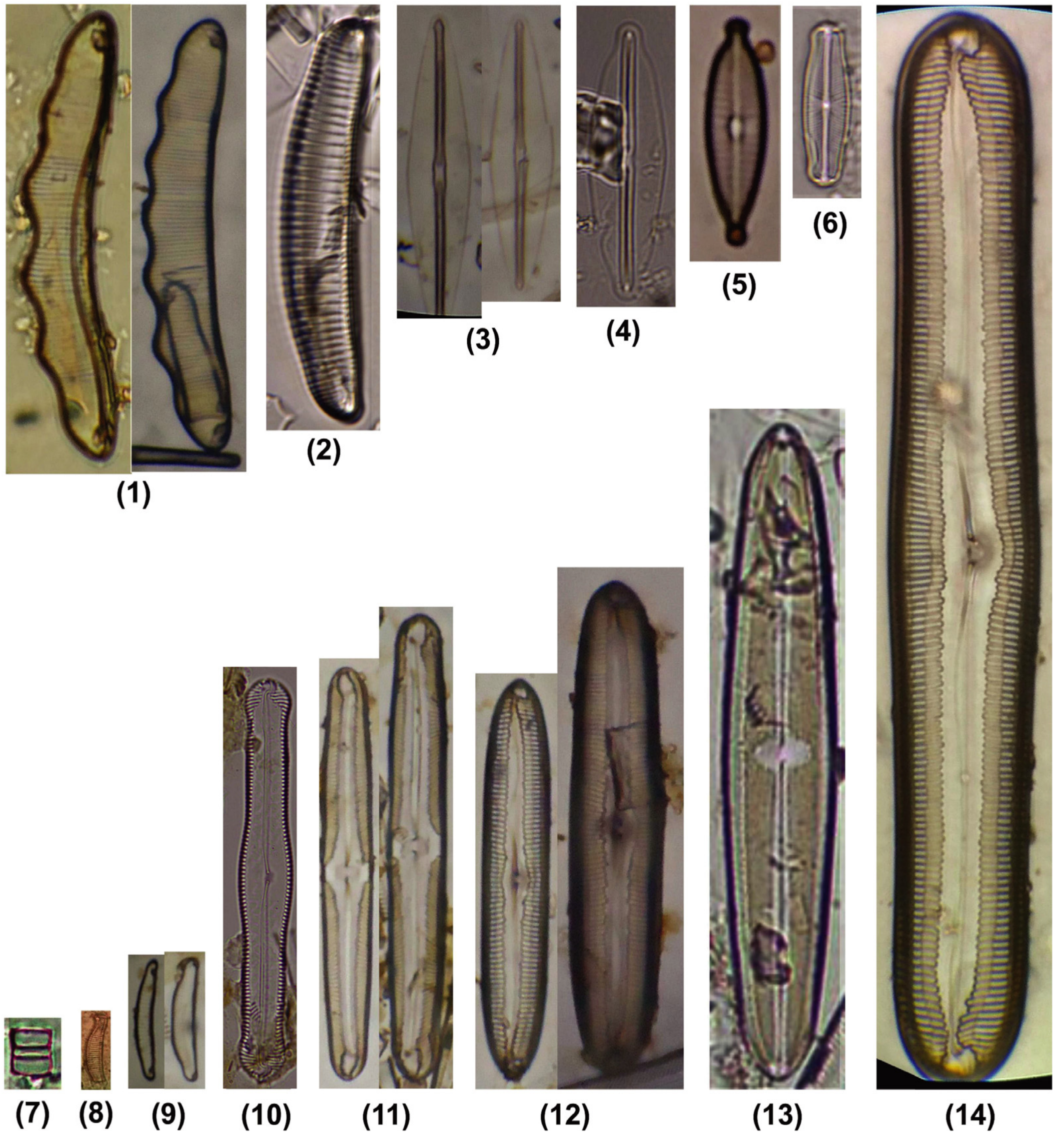

Plate 1. 1. *Eunotia zygodon* Ehrenberg. 2. *Eunotia monodon* Ehrenberg. 3. *Frustulia saxonica* Rabenhorst. 4. *Frustulia crassinervia* (Brébisson) Lange-Bertalot and Krammer. 5. *Gomphonema parvulum* Kützing. 6. *Sellaphora seminulum* (Grunow) D.G. Mann. 7. *Aulacoseira distans* (Ehrenberg) Simonsen. 8. *Eunotia exigua* (Brébisson ex Kützing) Rabenhorst. 9. *Eunotia minor Kützing. 10. Pinnularia acrosphaeria W. Smith. 11. Pinnularia gibba Ehrenberg. 12. Pinnularia viridiformis Krammer. 13. Neidium affine (Ehrenberg) Pfitzer. 14. Pinnularia viridis (Nitzsch) Ehrenberg.*

concentration above 0.1 mg/L. The recorded cadmium and lead content in Lake Warna was higher than the Indonesian water quality standard for agriculture, that was 0.01 and 0.03 mg/L, respectively

There is only little evidence of the changing conditions from these data owing to the short duration of the record (24 cm). But, as this is the only historical record available, the documentation of changing diatoms in the lake, as recorded in the sediment sequence, represents the only means by which the history of this lake can be reconstructed. This provides evidence of the trajectory of change as well as the variability of condition over time. It attests to the modern Lake Warna being different in condition to that evident in 1891. This then provides evidence that it has been impacted by human activity and flags the need to manage human impact to restore the condition of the lake. Paleolimnological studies in Indonesia are still limited (Soeprobowati et al., 2018). This study was initiated to provide evidence that sound lake management can be developed when the past condition is well understood. Other works, such as pollen analysis to determine crop pollen, XRF to determine erosion input, or stable isotope analysis — e.g. ^{15}N, would be useful to strengthen understanding to geode management options.

5. Conclusion

Based on diatom record from a 24 cm sequence of sediment from the upper section of a core taken from Telaga Warna has shown that human activities (deforestation and potatoes farming) in the catchment area have changed an acid oligotrophic lake into an acid eutrophic one. This is indicated by changes in the diatom assemblage from *Frustulia* spp. to *S. seminulum* Grunow. This initial result represents a baseline for further research for the development of appropriate management plans for the sustainable use of the lake (see Plate 1).

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