Research Article

Human-induced hydrological changes in Lake Aoki and their influences in limnic environment

D.P. Adhikari*

Department of Geology, Tri-Chandra Campus, Tribhuvan University, Kathmandu, Nepal

Abstract
The hydrological regime of Lake Aoki, central Japan has been altered when electric power plants started draining water to and from the lake since AD 1954. The use of lake water drops its level during winter and early spring and exposes the littoral sediments on the surface. In order to examine how these changes have affected the lake environment, a 23 cm long sediment core from Lake Aoki was investigated for its lithology, sedimentation rate, and total organic carbon (TOC) flux. The sediment below 10 cm was olive black silty clay, and it abruptly changed to grayish olive clayey silt above, corresponding to the timing of the hydrological perturbations (1954). The sedimentation rates were 5 mg cm^{-2} yr^{-1} and 85 mg cm^{-2} yr^{-1} before and after 1954, respectively, and the TOC content was more than eightfold higher in the post-1954 sediments. The large increase in sedimentation rate was resulted from the combine effects of high sediment load in the artificially added water and remobilization of littoral sediments during lake level lowering in early spring, whereas the elevated TOC flux was attributed to higher biological productivity stimulated by the continuous supply of additional nutrients to the lake via interbasianl mixing of water.

Key words: Biological productivity, Carbon flux, Hydrological regime, Littoral sediment, Sedimentation rate

Introduction
All lakes are subject to a variety of extrinsic and intrinsic forcing variables that regulate the subsequent history of the lake, such as climate, watershed bedrock composition, tectonic and volcanic activity, vegetation, aquatic biota, and human activities (Cohen, 2003). Paleolimnologists reconstruct the history of changes in these variables using lake sediment archives (e. g., sediment granulometry, organic geochemistry, fossils, stable isotopes etc.) as they are both repositories and source of information about lake history. Both modern and historical data show that lake systems are undergoing profound changes because of local and global human impacts (Cohen, 2003). On local scale, paleolimnologists have documented the chronologic alteration of the lake system due to human activities such as deforestation along with climate change (Curtis et al., 1998; Hodell et al., 1995). Human-induced hydrological changes in Lake Aoki can be a good example to learn how such changes can affect sedimentary and biological processes in lakes.

As a limnological proxy, sediment grain-size variation could provide information about the power of transporting and reworking media at the depositional site. During the times of low lake level, deposits that were previously accumulated along the margins of a lake might be eroded and redeposited in the deeper part of the lake. Changes in lake size and water depth are considered to be the main factors affecting the variability in sediment grain-size distribution and properties (Adhikari, 2011a).

Nutrient availability and water circulation largely control the biologic productivity of lakes. The biologic productivity in lake water affects the amount of organic residue in the sediment through food-chain and decomposition process, so that high productivity corresponds to high flux of organic materials in sediments (Adhikari & Kumon, 2001). Another important factor that controls lake productivity is water temperature. High water temperature makes living beings more active and enhances production of biogenic materials except for extremely high temperatures (Adhikari et al., 2002).

Total organic carbon (TOC) is often taken as an indicator of productivity, particularly when TOC concentrations can be converted into fluxes (Cohen, 2003). The underlying assumptions are that original productivity is quantitatively

*Corresponding author, email address: adhikaridp@ntc.net.np

reflected as the amount of biomass that sinks to the lake floor, and that this biomass is proportionately degraded after burial. Nitrogen (N) is sedimented in lakes from both terrestrial and lake-derived organic matter. Aquatic organic matter derived from phytoplankton is richer in N with lower C/N ratios than the terrestrial organic matter (Nakai & Koyama, 1987). Many studies have shown that the C/N ratio is a useful tool for distinguishing long-term transitions from terrestrial to algal-input dominance in lake sediment organic matter (Meyers & Ishiwattari, 1995).

Study area

A narrow intermontane valley extending N-S from Hakuba to Omachi City, near the northern Japanese Alps in central Japan, hosts a series of three fresh-water bodies, Lake Aoki, Lake Nakatsuna, and Lake Kizaki, which are collectively known as the 'Nishina Three Lakes' (Fig. 1). Lake Aoki, the northernmost lake and the object of this study, is intermediate in size (1.86 km^2); however, it is the deepest (58 m) among the three lakes with the largest water volume ($53940 x 10^3$ m^3) (Adhikari et al., 2002). Despite its large dimensions, streams draining the catchment are few and small. Amount of total natural inflow into the lake is estimated at 0.58 m^3 s^{-1} (Watanabe et al., 1987).

The lake has topographic closures in the east, west and north (Fig. 2) and draws runoff from 9.2 km^2 area (Fig. 1). The peak elevation in the catchment area is about 1599 m with a maximum relief of 778 m. Bedrocks in the catchment area consist of Cretaceous granite, welded tuffs, Tertiary sedimentary rocks (Omine Formation), and Quaternary terrace deposits (Kosaka, 1983). Some of the main characteristic features of the lake are summarized in Table 1.

Lake Aoki has a main basin and a sub-basin which are separated by a steep slope (Fig. 3). The main basin has

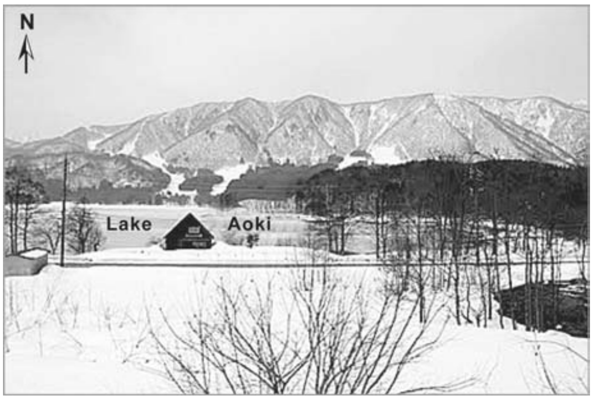

Fig. 2 Northern view of Lake Aoki and the surrounding area in winter. The area has experienced thick and widespread snowfall, and the peripheral part of the lake has undergone frozen

roughly a rectangular outline and reaches a maximum depth of about 58 m. It is symmetrically bounded by a steep bathymetric gradient to the north, south and west in the upper slope and a gentle slope merged to the basin plain in the foot slope. This gentle foot slope is wider in the axial ends of the basin than in the other two sides. The eastern one-third part of the lake appears gently sloping westward with a narrow flat area lying under the water depth of about 32.5 m and abutting one of the bathymetric highs in the south above the main basin (Fig. 3). This hanging portion of the lake is the sub-basin, which is bounded by steep gradient to the east and south, and gentle slope to the north.

Modern climate in the area is characterized by cold dry winters and moist hot summers. Annual average temperature during 1971-2000 varied from 8.3 °C to 10.5 °C, with an average summer temperature in the range from 18 °C to 21 °C and winter average temperature between 1.1 °C and -5.5 °C. Annual average precipitation for that period was 2000

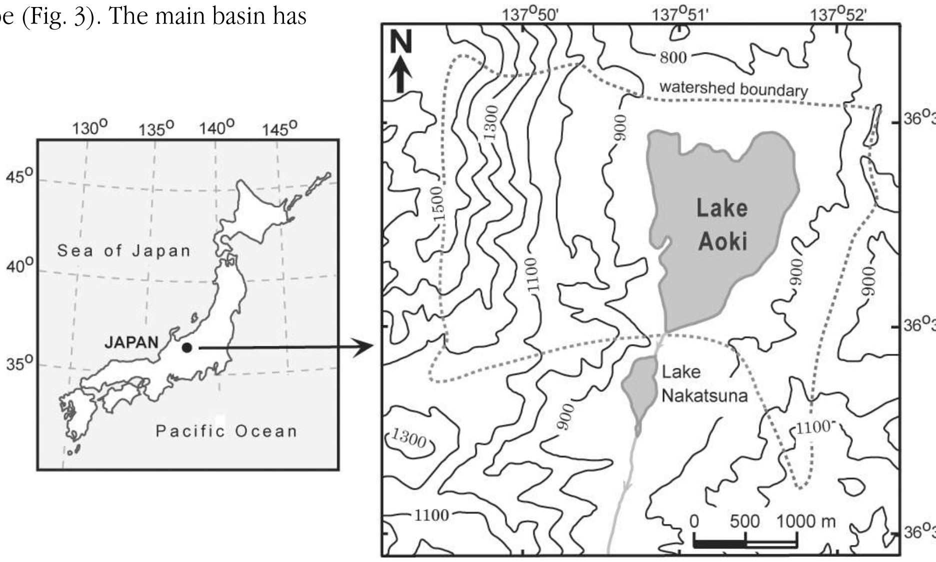

Fig. 1 Location of Lake Aoki and the topographic features around it. Lake Kizaki and Omachi City are to the south of the map. Topographic contours are at 100 m intervals (adopted from the topographic map, Geographical Survey Institute of Japan, Kamishiro, 1:25000)

Table 1 Characteristic features of Lake Aoki

Latitude and longitude	36° 36' 32" N 137° 51' 14" E
Mean annual temperature (° C)	9.4
Mean annual precipitation (mm)	2022
Surface elevation (m)	822
Drainage basin area (km^2)	9.2
Maximum relief in the drainage basin (m)	778
Perimeter (km)	6.5
Maximum depth (m)	58
Average depth (m)	29
Water volume (x 10^3 m^3)	53940
Water residence period (days)	193
Lake type	oligotrophic

Note: Location as well as lake and catchment characteristics were determined from topographic and bathymetric maps, and partly referred from Saijo (2001) and Horie (1962).

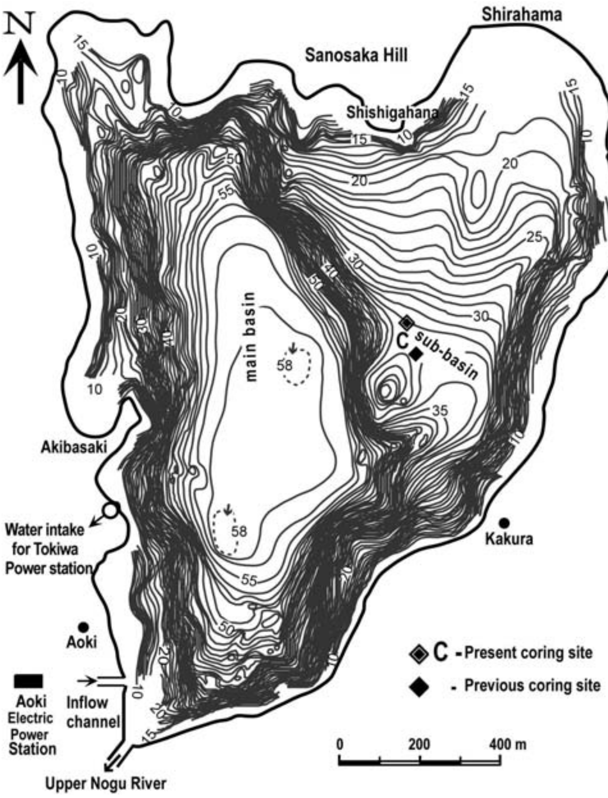

Fig. 3 Bathymetric map of Lake Aoki with the location of coring sites. Contours are at 1 m interval. Bathymetric map is modified after Inouchi et al. (1987)

mm, with a large variation from year to year (Adhikari & Kumon, 2001). The lake and the surrounding area experience more than 1 m thick snowfall in winter, making the mountain slopes suitable for skiing (Fig. 2). During winter extremes, peripheral part of the lake sometimes undergoes freezing for a few weeks, but complete ice bounding rarely occurs. The area produces abundant snow melt water in spring.

Modern hydrological changes

The hydrological system of Lake Aoki has been influenced by human activities. Since 1954, an artificial flow of 2.69 m^3 s^{-1} (annual average) has been diverted from a tributary of Kashima River (interbasinal) to Aoki Power Station for electric power generation, and the outflow after power generation joins the lake at its southern extremity close to the outlet sill (Fig. 3). The outflow is about 4.6 times larger than the total natural inflow from its catchment area and a few degrees colder than the lake water due to its high altitude origin. Since 1954, lake water has also been drained to Tokiwa Power Station through a tunnel for power generation (Fig. 3). This usage of lake water drops the lake level as much as 20 m during winter and early spring seasons and exposes littoral sediments on the surface (Fig. 4). This exposure has subjected the lake sediment to remobilization through the process of erosion and washing. To recover the lowered water level, abundant snow melt water containing a lot of silt and clay materials is added into the lake from outside of the natural catchment in spring. Surface outflow from Lake Aoki flows into Lake Nakatsuna to the south through the Upper Nogu River (Fig. 3).

Scope of study

Although the limnological study of Lake Aoki was started in 1907 (Tanaka, 1930), the first sediment-based research of this lake was conducted in 1987 with the extraction of two sediment cores (17 m and 28 m) by the Geological Survey of Japan for lithological descriptions (Inouchi et al., 1987). More recent studies on the sediments cores and geomorphic features around the lake (Adhikari, 2011b; Manaka et al., 1998; Ono et al., 2000) suggested that a landslide damming created the lake ca. 43 ka cal BP. Using separate sediment cores from Lake Aoki, Adhikari et al. (2002) reconstructed the climatic variability of the last 10 ka, and recently, Adhikari (2011c) investigated a 15 m long sediment core for diatom abundance and showed a sudden increase in diatom population in post-Glacial (Holocene) sediments, indicating the onset of warming period in central Japan ca. 13 ka cal BP. However, study aiming at understanding the impact of modern hydrological changes in the lake system has not previously been carried out despite its limnological significance. In this study, a 23 cm long sediment core from the sub-basin of Lake Aoki was investigated for its lithology, sedimentation rates, and total organic carbon (TOC) and total nitrogen (TN) contents to examine whether the hydrological changes imposed to the lake since AD 1954 have any influence on sedimentation and lake productivity. It was hypothesized that sedimentation rate is proportional to the volume of inflowing water, and its sediment reworking capacity and interbasianl mixing of water may lead to higher lake productivity.

Fig. 4 Northeastern view of Lake Aoki during water level lowering in early spring. Gravel covers coastal area as finer fractions wash out to the inner lake during the lowstand. Surface erosional marks are also evident

Materials and Methods

A 23 cm long sediment core was extracted from the sub-basin of Lake Aoki under 32 m water depth (Fig. 3) by using a gravity corer. Special care was taken to retrieve an undisturbed sediment-water interface at the core top. Sediment was recovered and split lengthwise in the laboratory, lithology was described on the cut surface, and colors were assigned using the Munsell soil color charts. The sediments were then sub-sampled at 0.5 cm interval for the determination of water content, apparent density, and total organic carbon (TOC) and nitrogen (TN) contents. The water content was measured as the difference in weight between freshly extruded samples before and after drying at 105 °C for 12 hrs. The apparent density was calculated as solid weight per unit volume based on dry weight and water content, postulating grain density as 2.65 g cm^{-3}.

Dried sediment samples were ground with an agate bowl, and digested with dilute HCl (3%) for 24 hrs to remove inorganic carbon fraction (carbonates). The samples were then dried on hot plate at 110 °C with addition of distilled water 3-5 times to remove the remaining HCl. Following the treatment, TOC and TN were measured using the dry combustion technique in a CHN corder (YANAKO MT-5, Yanagimoto Seisakusho Co., Inc), and their contents were expressed in dry weight percentage of the original sediments.

Depth-age relation of the sediment was established by using two known and one interpolated ages, and age of the sample horizons were derived by interpolating the reference ages. The average linear sedimentation rates were determined by using the age-depth relationships (Fig. 5b). To homogenize dilution effect that might have involved in percentage TOC content, TOC flux (amount per unit area per unit time) was calculated by using bulk sedimentation rate and percentage TOC content and expressed in mg cm^{-2} yr^{-1}.

Results

The sediment core is composed of olive black silty clay (7.5Y 3/2) below 10 cm and grayish olive (7.5Y 5/2) clayey silt above that horizon (Fig. 5a). The boundary was horizontal and sharp. Figures 6b and c show that sediment attributes such as TOC and TN contents, C/N ratios, apparent density, and TOC flux abruptly changed at a depth of 10 cm. Particularly, TN, apparent density, and TOC flux are increased and TOC is decreased in sediments above 10 cm.

Results of the analysis showed that the mean TOC content, which was about 4.7% below 10 cm sharply decreased to 2.23% above 10 cm (Fig. 6b). Similarly, mean TN content decreased to 0.18% from 0.34% below 10 cm. In both cases, the reduction was about twofold. Contrary to that, TOC flux abruptly increased to a mean of 1.75 mg cm^{-2} yr^{-1} above 10 cm from 0.2 mg cm^{-2} yr^{-1} below (Fig. 6c). With some drop

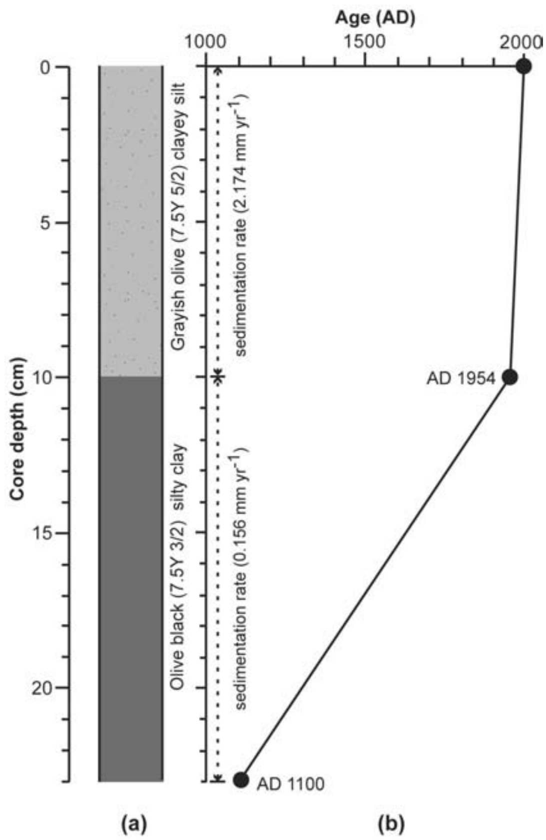

Fig. 5 (a) Lithology of the cored sediment, (b) Depth-age relationship of the sediments. Sedimentation rates before and after AD 1954 are also shown

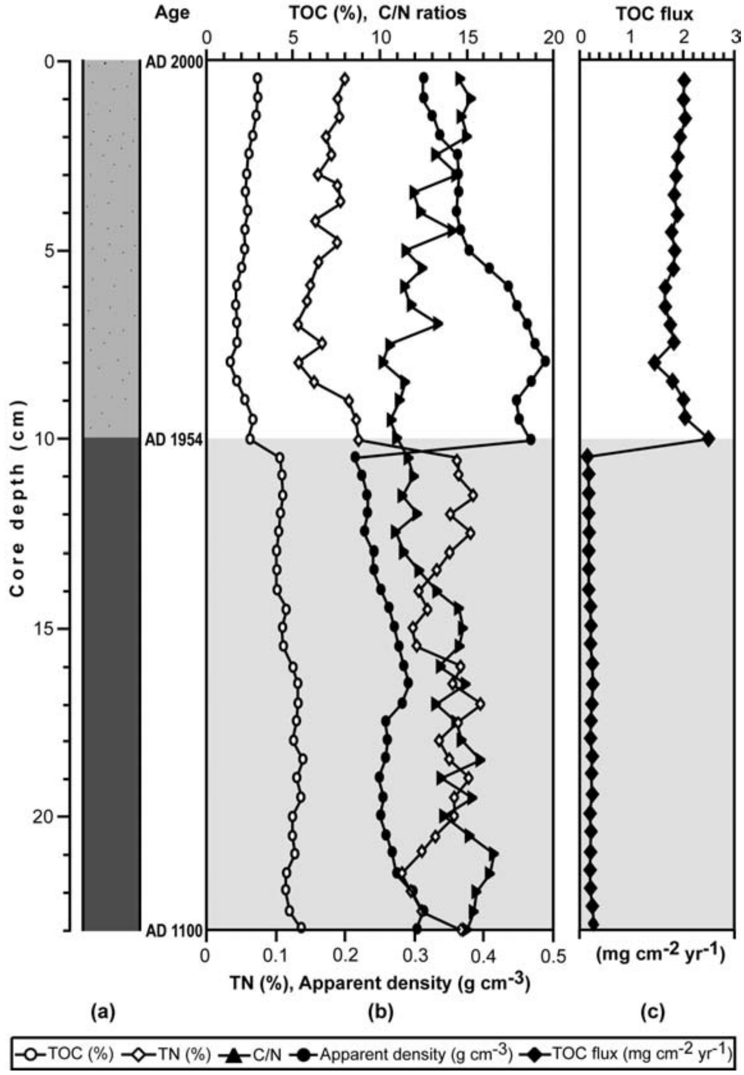

Fig. 6 (a) Lithologic column of the sediment, (b) Variation in total organic carbon (TOC) and total nitrogen (TN) contents, C/N ratios, and apparent density with depth, (c) Variation in TOC flux with depth. TOC and TN are in weight percent, and C/N is their ratio. The sharp color contrast in the sediment above and below 10 cm depth corresponds to the sharp break in TOC and TN contents, C/N ratios, and apparent density. The sediment spans a period of about 900 yrs

at 10 cm, C/N ratios fluctuated between 11 and 16 in the lower part and between 10 and 15 in the upper part (Fig. 6b). The apparent density markedly increased from a mean of about 0.25 g cm^{-3} below 10 cm to 0.40 g cm^{-3} above that, and after attaining a maximum value of about 0.5 g cm^{-3} at 8 cm, it gradually decreased upward (Fig. 6b).

Discussion

The marked difference in sediment color and grain-size above and below 10 cm depth (Fig. 5b) is considered to indicate the influence of modern hydrological changes that have been imposed to the lake by mixing artificial flows since AD 1954. The age of the sediment at 10 cm is therefore AD 1954. A separate sediment core retrieved from a nearby location in the sub-basin (Fig. 3) contained an intercalation of Kikai Akahoya (K-Ah) volcanic ash of 7.3 ka cal BP (Machida & Arai, 1992) at 1.24-1.25 m depth (Adhikari et al., 2002). Interpolation of age from the volcanic ash gives a bottom age of the core at AD 1100 (Fig. 5b), and the core sediment, therefore, represents a history of about 900 years.

The three age-depth tie points [core top (AD 2000), 10 cm (AD 1954), and 23 cm (AD 1100)] yield linear sedimentation rates at 0.156 mm yr^{-1} before AD 1954 and 2.174 mm yr^{-1} after that time with bulk sedimentation rates of 5 mg cm^{-2} yr^{-1} and 85 mg cm^{-2} yr^{-1}, respectively (Fig. 5b). Therefore, the linear sedimentation rate after 1954 is ca. 14 times higher than sedimentation rate before AD 1954. The pre-AD 1954 sediments transported to the lake by small natural inflow of water were much finer in grain-size than the grain-size of the post-AD 1954 sediments (Adhikari et al., 2002).

The large increase in sedimentation rates in the upper 10 cm of the core (Fig. 5b) is attributed to the combination of three separate processes that are being active in the lake after the hydrological changes in AD 1954. First, the artificial flow (outflow from power generation) has been supplying additional sediments, mostly of silt-size particles, to the lake (Fig. 7b), especially in early spring when the area gets abundant snowmelt water. The snow melts induced surface erosion or shallow slope failure due to ground saturation or their combination would make sediment particles available to transport. Second, the exposure of lake sediments on the surface during low lake level in winter and early spring seasons subject the materials in the littoral zone to erosion (Fig. 4) from rain, snow, and inflowing streams. Since the proximity of coring site from the lake shore controls the process of sedimentation (Adhikari, 2011d), some of the sediments derived from the erosion get transported to the deep water (e. g., coring site) through the process of sediment focusing. Third, as in the first process, melt waters that have been diverted to refill the lake also supplies additional sediments to the lake.

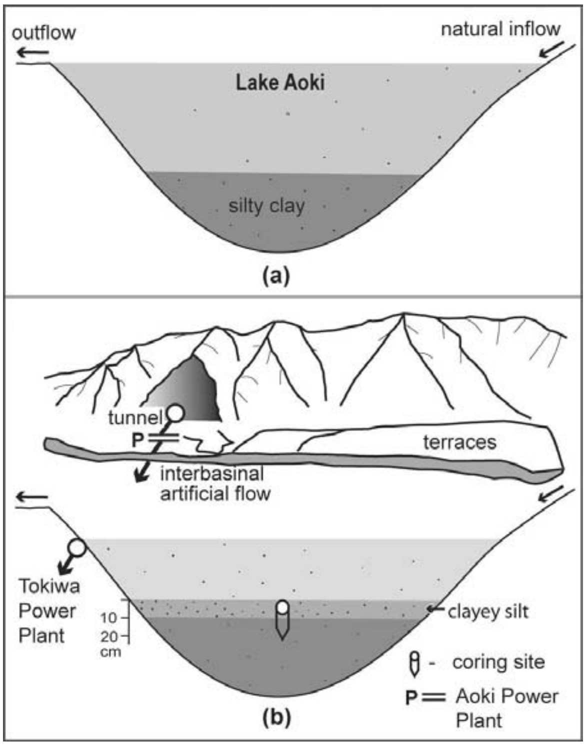

Fig. 7 Schematic illustrations showing sedimentation of: (a) Silty clay before AD 1954 with natural little water inflow, (b) Clayey silt after the artificial mixing of the outflow from the Aoki Power Plant in AD 1954 and the subsequent draining of water from the lake for power generation at the Tokiwa Power Plant. Draining water from the lake lowers the lake level during winter and early spring. The mixed water is 4.6 times larger than the total natural inflo w, and naturally it has higher capacity to carry more silt-size particles to the coring site

Similar to their roles for higher sedimentation, all the three processes have also contributed to the sediment coarsening after AD 1954. As the lake size becomes smaller at lowstand, the distance from shore line to the focusing center gets shortened and the sediments at the coring site become coarser (Fig.7b). However, the outflow from power generation (Fig. 7b), which is as much as 4.6 times the total natural inflow from its catchment area, contributes much sediments because higher discharge can carry larger particles due to its higher energy. The higher apparent density after AD 1954 (Fig. 6b) is the reflection of sediment coarsening, and the gradual upward decrease in the density after reaching maximum around AD 1960 might have suggested that the availability of coarse particles have decreased with time.

The abrupt increase in TOC flux after 1954 (>8 times) (Fig. 6c) can be attributed, partly, to the supply of larger amount of nitrogen (N) and phosphorous (P) into the lake following the introduction of artificial flow (outflow from power generation and snow melt diversion to raise the lake water level), which is 3-4 times higher than that of before 1954 (Omachi City Office, 1983). This flow adds nutrients continuously to the lake water, and induces vertical water circulation in part as well. These conditions, despite the mixing of cold water, have supported large biological productivity compared to that of before AD 1954. Similarly, during lake level lowering, organic materials from the exposed lake sediments (Fig. 4) could easily wash out to the inner lake and redeposit. This reworked organic material would be another contributing source for higher TOC flux in the sediment. The combination of higher sedimentation rate and lower TOC and TN contents after AD 1954 (Fig. 6b) clearly suggests a noticeable dilution effect caused from the increasing amount of inorganic materials supplied into the lake. The TOC flux is regarded as the true representation of the organic matter content in the sediment as the dilution effect is homogenized.

Organic matter in lake sediments may be derived from lake planktons and terrestrial plants. Generally, nonvascular aquatic plants have C/N ratios less than 8 whereas vascular land plants, which contain cellulose, have C/N ratios above 30 (Nakai & Koyama, 1987). The range of C/N ratios, i. e., 11-16 before AD 1954 and 10-15 after that (Fig. 6b), in Lake Aoki sediment, therefore, suggests that lake planktons are the major source of the organic matters in the sediments in association with minor contribution from terrestrial plants. It strengthens the above interpretation that the elevated TOC flux in the sediment after AD 1954 is largely due to proportionally higher contribution (input) of organic materials from lake plankton as the lake productivity increased following the hydrological changes.

Conclussion

Lake Aoki has experienced profound hydrological changes including strong water circulation and lake level lowering during winter and early spring after the diversion of a large interbasianl flow into it and subsequent draining of its water for power generation in AD 1954. Investigation of a 23 cm long sediment core from the sub-basin of Lake Aoki revealed that the hydrological changes have significantly increased sediment grain-size, sedimentation rate, and carbon flux in the sediment. The high sediment load in the artificially added water and remobilization of the littoral sediment during low lake level are the main contributors for higher sedimentation rate. Similarly, the continuous supply of additional nutrients to the lake from artificially added water has supported large biological productivity, which in turn increased the carbon flux in the sediment. This study provides an opportunity to understand how human-induced hydrological changes can alter the entire limnological process. It is likely that, the lowering of lake/reservoir level from various types of human activities, in combination with impending climate change and active geological processes, would give rise to the similar changes in lake/reservoir environment in the Himalayan region too, which could be detrimental to the environment and economy.

Acknowledgements

This paper contains part of the works undertaken by the author during his Ph. D. research at Shinshu University, Japan. F. Kumon supported the works in various ways. Comments by Dinesh Devkota, Nepal and Ghanashyam Neupane, USA are gratefully appreciated.

References

Adhikari, D.P. (2011a). Paleolimnology of Lake Yamanaka as reflected on particle-size distribution. *Bul. Dept. Geol. TU,* 14, 35-42.

Adhikari, D.P. (2011b). What does the Lake Aoki sediment record tell about its origin. *Bul. Nepal Geol. Soc,* 28, 98-104.

Adhikari, D.P. (2011c). Diatom abundance in Lake Aoki sediment as a proxy in demarcating the timing of the last Glacial-Holocene transition in central Japan. *Jour. Nepal Geol. Soc,* 42, 67-74.

Adhikari, D.P., Kumon, F., & Kawajiri, K. (2002). Holocene climate variability as deduced from the organic carbon and diatom records in the sediments of Lake Aoki, central Japan. *Jour. Geol. Soc. Japan,* 108, 249-265.

Adhikari, D.P., & Kumon, F. (2001). Climatic changes during the past 1300 years as deduced from the sediments of Lake Nakatsuna, central Japan. *Limnology,.* 2, 157-168.

Cohen, A.S. (2003). *Paleolimnology: The history and evolution of lake system,* Oxford University Press. pp 500.

Curtis, J.H., Brenner, M., Hodell, D.A., Balser, R.A., Islebe, G.A., & Hooghiemstra, H. (1998). A multi-proxy study of Holocene environmental change in the Maya lowlands of Paten, Guatemala. *Jour. Paleolim,* 19,139-159.

Hodell, D.A., Schelske, C.L., Fahnenstiel, G.L., & Robbins, L.L. (1995). Biologically induced calcite and its isotopic composition in Lake Ontario. *Limnol. Oceanogr,* 43, 187-199.

Horie, S. (1962). Morphometric features and the classification of all the lakes in Japan. *Mem. Col. Sci. Kyoto Univ,* B 24, 191-262.

Inouchi, Y., Yamazaki, H., & Shimokawa, K. (1987). Acoustic survey of Lake Aoki, Nagano Prefecture - a preliminary result. *Quatern. Res. Japan,* 17, 116-117.

Kosaka, T. (1983). A facies models for the sedimentation in the Marukiri-zawa syncline, central Omni Belt, Nagano Prefecture. *Jour. Fac. Sci., Shinshu Uni,* 18, 75-102.

Machida, H., & Arai, F. (1992). *Atlas of tephra in and around Japan,* Univ. Tokyo Press. pp 276.

Manaka, M., Kumon, F., & Inouchi, Y. (1998). Grain-size analysis on cores collected from the bottom of Lake Aoki, central Japan. *Geo-environ. and Geotech,* 8, 307- 12.

Meyers, P.A., & Ishiwatari, R. (1995). Organic matter accumulation records in lake sediments. In A. Lerman, D. Imboden, & J. Gat (Eds.), *Physics and Chemistry of Lakes (*pp. 279-328). Springer-Verlag, New York.

Nakai, N., & Koyama, M. (1987). Reconstruction of paleoenvironment from the viewpoints of organic constituents, C/N ratios and carbon isotopic ratio in the 1400 m core taken from Lake Biwa. In S. Horie (Ed.), *History of Lake Biwa (*553, 137-156). *Kyoto Univ. Contrib.*

Omachi City Office (1983). *Preservation of the natural condition of Nishina Three Lakes and the surrounding river system.* Omachi City Office, Japan. pp. 157*.

Ono, R., Kumon, F., Khobayashi, M., & Sakai, J. (2000). Late Quaternary sediments around Lake Aoki, Nagano, central Japan, and the origin of the Lake. *Quatern. Res,* 39, 1-13**.

Saijo, Y. (2000). Geography. In Y. Saijo, & H. Hayashi (Eds.), *Lake Kizaki (*pp. 3-11). Backhuys Publishers, Leiden, The Netherland.

Tanaka, A. (1930). *Limnological studies of the lakes in the northern part of Japanese Alps* (pp. 1036). Kokin Shoin, Tokyo.*

Watanabe, Y., Okino, T., & Sakurai, Y. (1987). Evaluation and discussion of the target level and curtailment of pollutant load for conserving the water quality in Nishina Three Lakes, *Bul. Environ. Conserv. Shinshu Univ,* 9, 34-49.

*: In Japanese, **: In Japanese with English abstract.