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Status of Sediment Dynamics in Lake Takkobu of the Kushiro Mire, Japan, Associated with Forestry and Agricultural Development in the Watershed

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Fine sediment loadings from agricultural watersheds have led to habitat degradation in Lake Takkobu, northern Japan. Fifteen lake sediment core samples were obtained and analyzed to develop a chronology using physical sediment characters, ^{137}Cs, and tephra. The reconstructed sedimentation rates over the past ca 300 years suggested that sedimentation rates increased drastically after land use development. With a natural sedimentation rate of 0.1-1.1 mm year^{-1} until 1898, lake sedimentation accelerated to 0.6-12.8 mm year^{-1} after 1898. The sedimentation rates after land use change, such as forestry, river engineering works, and agricultural development, were about 6-12 times higher than that under natural conditions, leading to accelerated lake shallowing over the last ca 100 years. Sedimentation rates between 1898 and 1963 differed with location in the lake because of spatial variation in the sediment flux from the contributing rivers and their watersheds. The sedimentation rate in the southern zone between 1898 and 1963 was significantly higher than that in the middle and northern zones, reflecting active sediment production associated with forestry for charcoal production and canal construction for transportation in the southern watersheds and wetlands. The sedimentation rate after 1963 did not vary among the three zones, because decreasing sedimentation was found in most of the southern sites whereas an increasing trend was observed in the middle and northern sites. This result can be explained by shallowing of lake-bottom morphology with sedimentation and the resultant reduction of sediment retention capacity in the southern zone. Moreover, the sedimentation rate at sampling sites close to river mouths increased by 5–32 times compared with natural rates before 1898. The Kushiro River, into which Lake Takkobu drains under regular flow conditions, further contributed to an increased sedimentation rate, because water from the Kushiro River flows back into Lake Takkobu during floods.

Key words: Deforestation, Agricultural land, Sedimentation rate, Lake shallowing, Kushiro Mire

Introduction

The Kushiro Mire, the largest wetland in Japan, is home to diversity of wetland wildlife. However, excessive production and transport of suspended sediment and nutrients are evident in association with deforestation, pasture development, and stream channelization (Nakamura et al., 1997, 2002a, 2004). There are three lakes on the eastern side of the mire. In recent years, local residents have noticed a change in the colour of the lake water, progressive shallowing in most of the lakes, and a rapid degradation of the fish populations and aquatic plant communities. The main cause of these changes is assumed to be an excessive influx of fine sediments and associated nutrients from the surrounding cultivated region (Takamura et al., 2003; Ahn et al., 2006; 中村 et al., 2003). However, the relationship between the long-term sedimentation rate and land-use development has not been well characterized to date.

Fine sediments are produced from the watershed and can accumulate in geomorphic storages such as lakes and marshes. The sedimentary record preserved under depositional environments, such as lakes, reservoirs, and river floodplains, is a valuable basis for reconstructing longer-term sediment response (Walling et al., 1998, 2003; Owens et al., 1999; Ahn et al., 2006). In these studies, sediment profiles have been dated using radiochronological methods using ^{137}Cs and ^{210}Pb and well-preserved volcanic ash (tephra) to interpret the sedimentation history.

Under natural conditions, a constant, low sediment flux from the contributing watersheds is gradually accumulated in lakes and reservoirs (Foster et al., 1985; Dearing 1992; Foster and Lees, 1999; Walling et al., 2003; Yeloff et al., 2005). However, the sedimentation rate varies with location, exhibiting a high spatial

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variability in lakes and reservoirs due to human disturbance. There are few studies examining the spatial variability of sedimentation rate in lakes and reservoirs associated with historical changes in land use (Foster et al., 1985; Dearing, 1992; Yeloff et al., 2005). To prevent further degradation of lake ecosystems, especially lakeshore ecotones, I need to understand the spatial variability of land use effects on lake sedimentation. Ahn et al. (2006) were reconstructed the sediment yields at Lake Takkobu in the Kushiro Mire over the last ca 300 years and clarified the influence of land use change on the sediment yields. This study was undertaken at Lake Takkobu in the Kushiro Mire to clarify sediment dynamics over the last 300 years. In particular, I focus on spatial variability of sedimentation rate in the lake with reference to land use alteration in contributing watersheds.

Materials and Methods

Study area The Kushiro Mire (194 km^2) lies in eastern Hokkaido, northern Japan, and drains into the Kushiro River. The Kushiro district is in the Pacific coast climate zone, with an annual mean air temperature of 5.6℃ over the period from 1910 to 2005. The annual mean precipitation is 1075 mm, with a range of 705–1704 mm.

Lake Takkobu is a small lake with an area of 1.3 km^2 and drains a 26.2 km^2 watershed into the Kushiro River at the eastern margin of the Kushiro Mire (Table 1 and Fig. 1). It was formed about 3,000 years ago by sea regression (Ministry of the Environment, 2003; 小疇 et al., 2003). The maximum water depth measured in this investigation was 1.6 m (Table 1). Under high flow conditions, the Kushiro River drains back into Lake Takkobu because the water elevations of Lake Takkobu and the Kushiro River are almost equal. Lake Takkobu is surrounded by hills to 100 m high. The lithology of the Takkobu area consists of tuff and unconsolidated gravel deposits. Lake Takkobu is surrounded by wetlands with dominant plant species such as reed (*Phragmites australis*), alder (*Alnus japonica*), and willow (*Salix sachalinensis*). Moreover, the headwaters of the Takkobu watershed are comprised of planted forest (*Larix leptolepis*) and indigenous forest (*Quercus mongolica* var. *grosseserrata*).

Table 1. Site characteristics of Lake Takkobu.

Mean depth (m)	1.0
Max. depth (m)	1.6
Lake area (km^2)	1.3
Watershed area (km^2)	26.2
Lake to watershed ratio	1:20
Dominant present-day land use	Coniferous/pasture
Average D50 particle size (㎛)	25

Land use history The first settlement in the Kushiro district was founded in the 1880s (小疇 et al., 2003). Forestry, to produce charcoal, has occurred in the Takkobu watershed since the 1880s. Because there was no transport system in the area, a canal was constructed at the southern part of the wetland in 1898 (Fig. 1) to ship charcoal from the headwaters via Lake Takkobu and the Kushiro River to the town of Kushiro (Ahn et al., 2006; 釧路町史編纂委員会, 1990). The indigenous forests were clear cut, and wetland margins in the southern watershed were claimed as pastures for horses. A major conversion of natural floodplains to cattle pastures occurred in the 1940s. Agricultural laws established in the 1960s have promoted further land consolidation (Nakamura et al., 2004). Since then, a full-scale promotion of the dairy industry has taken place (Ministry of the Environment, 2003), which promoted the construction of agricultural drainage networks in the southern wetland areas. Although reforestation with *L. leptolepis* aimed to recover forest resources, forestry and agricultural development have continued (Table 2).

Field surveys and laboratory analysis In order to reconstruct recent history of lake sedimentation, sediment cores were collected from 15 lake sites between 2003 and 2004 (Ahn et al., 2006). These sampling sites were classified according to their location in the lake. Three out of the 15 sites were located in the lake center (C1–C3), and a further seven sites were located about 150 m from the lakeshore (L1–L7). One sampling site was located near the inflow of the Takkobu River (T), and another was placed at the lake outflow (O). The remaining three sites were located at the inflow of small streams (S1–S3) (Fig. 1). All core samples were dissected into 1 cm thick slices and were preserved in sealed containers at −10℃ before being prepared for subsequent analysis (Ahn et

Table 2. Land use development in the surrounding watersheds.

Land use	Watershed (km^2)					
	Takkobu River	T1	T2	T3	T4	Kushiro River
Forest	13.9	0.5	0.9	0.5	0.4	866.4
Wetland	0.2	0	0	0.1	0	101.5
Farm land	1.2	0	0	0	0	344.5
Urban land	0.6	0.1	0	0	0	60.5
Barren	0	0	0	0	0	125.2
Total	15.9	0.6	0.9	0.6	0.4	1498.1

al., 2006).

Physical characteristics of the sediment, such as water content, dry bulk density, and organic matter content, were recorded at intervals of 1 cm. Water content and dry bulk density were calculated after drying for 24 h at 105℃. The organic matter content was determined from ignition loss after heating 3–4 g samples at 550℃ for 4 h.

Aerial photographs from the years 1947, 1977, 1985, 1993, and 2004 were used to analyze changes in land use in the watershed.

Establishing core chronologies and sedimentation rates Sedimentation associated with land use change can be reflected in changes of the physical characters of lake sediment. For example, agricultural activity, deforestation, and road construction can lead to an increase in inorganic sediment (Gurtz et al., 1980), coarse sediment particles, bulk density, and a decrease in water content (Ahn et al., 2006). I defined these synchronous physical variables as “signals” (for further details see Ahn et al., 2006).

^{137}Cs concentration was used to estimate sedimentation rates in the lakes. The peak concentration profile was found in the 1963 surface (Foster and Lees, 1999; Walling et al., 2003). The ^{137}Cs content of the cores for Sites O and T was measured over 3 cm intervals because the two tephra layers were situated at greater depths, whereas the ^{137}Cs content of the cores from the other sites were measured over 2 cm intervals. ^{137}Cs concentrations were assayed by gamma spectrometry at 662 keV using an HPGe detector coupled to a multichannel analyzer.

Tephra dating is a common technique (Wilcox, 1965; Machida and Arai, 1983). Measurement of the refractive index of volcanic glass shards can be an effective tool for the identification of the origin of tephra (Nakamura et al. 2002b; 中村 et al., 2002). However, the glass of Holocene tephras tends to have a remarkably wide range of refractive indices, and thus the refractive index of untreated glass is not a practical indicator for identifying Holocene tephras. 中村 et al. (2002) noted that these differences and wide ranges in glass refractive indices are caused by hydration variation of the tephra glass; therefore, they suggested removing the effect of hydration by applying a dehydration procedure. The core from Site O contained two tephra layers, determined as Komagatake-c2 (Ko-c2, 1694) and Tarumae-a (Ta-a, 1739) (Ahn et al., 2006).

Chronologies were derived using signals corresponding to land use change, ^{137}Cs measurements, and tephrochronology. The average sedimentation rates were compared for four time periods (1694–1739, 1739–1898, 1898–1963, and 1963–2004) over the last ca 300 years and between their locations in the lake.

Statistical analysis Water mainly flows into the lake from northern large watersheds through the Takkobu River, and flows out of the lake from the southern outlet connecting with the Kushiro River (Fig. 1). To examine the spatial and temporal variability in lake sedimentation associated with water flows, sampling sites were grouped into northern, middle, and southern zones (Fig. 2). In order to compare the sedimentation rate among the three zones, I used Kruskal–Wallis one-way ANOVA in each period divided by the above chronological markers. I excluded Sites T and O from this analysis, because they are so close to large river mouths and thereby have high sedimentation flux from the contributing watersheds.

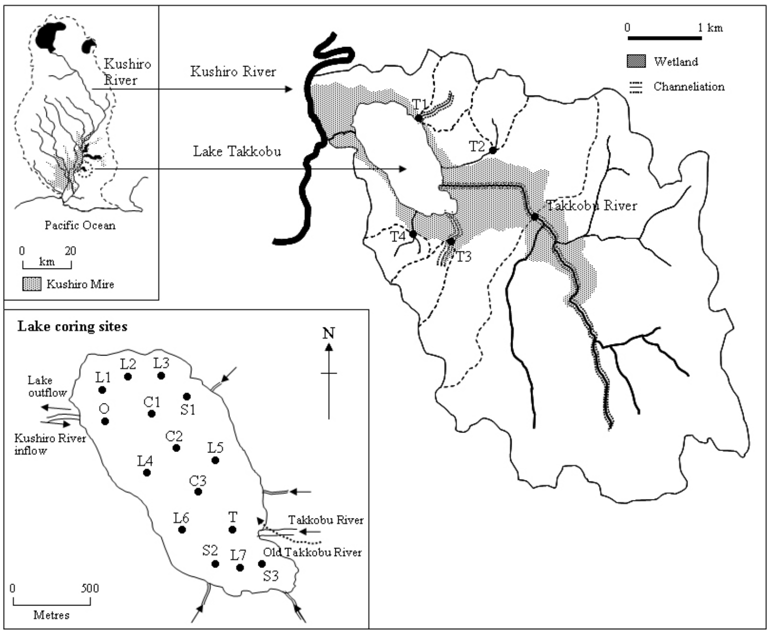

Fig. 1. Location of Lake Takkobu and the lake coring sites.

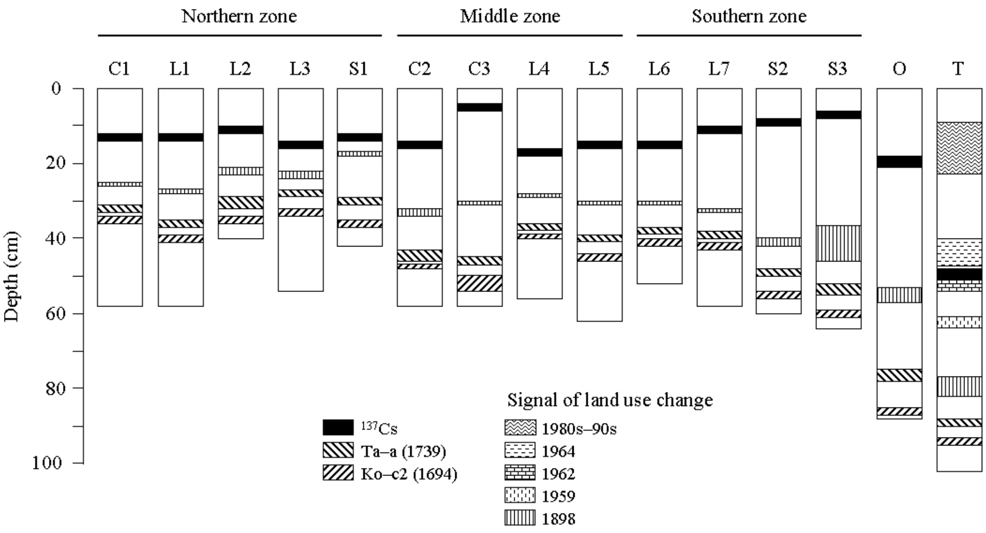

Fig. 2. The depth of ^{137}Cs peak, tephra and signal.

Results and Discussion

Changes in sedimentation rate over the last ca 300 years ^{137}Cs peaks and two volcanic ash layers were identified in all profiles (Fig. 2). In the 1880s, the Takkobu watershed had no transportation system. In 1898, the first large-scale development in the Takkobu watershed started with a 3 m wide × 300 m long canal built in the wetlands distributing to the margins of the lake (Ahn et al., 2006; 釧路町史編纂委員会, 1990). The signal identified at all sites could be attributed to the canal construction because it was the first large-scale project in this district (Fig. 2 and 3). The profile of Site T showed numerous signals reflecting the man-made disturbance history occurring in the vicinity of the mouth of the Takkobu River (Fig. 2 and 3). Drainage ditches were constructed in the wetlands of the Takkobu River watershed for land improvement in 1959, 1962, and 1964 (釧路町史編纂委員会, 1990). Forests covering large areas were harvested in the Takkobu River watershed between 1985 and 1993. The signal identified above the 1898 layer may originate from the construction of drainage ditches between 1959 and 1962. The elevated sedimentation rate after 1963 may be caused by the drainage engineering work in 1964 and deforestation in the watersheds from 1985 to 1993.

Human influence started with deforestation in the watershed of Lake Takkobu in the 1880s and intensified after 1898 (Fig. 3). Moreover, agricultural development and construction of drainage networks took place after the 1940s. Therefore, the sedimentation rates from 1694 to 1739 and from 1739 to 1898 reflect natural sedimentation rates. The period 1898–1963 is characterized by initial agricultural development with intensive agricultural development occurring during 1963–2004. Compared with the average natural sedimentation rate of 0.1–1.1 mm year^{-1} until 1898, initial and intensified development accelerated lake sedimentation by 0.6-5.8 mm year^{-1} and 1.5-12.8 mm year^{-1}, respectively (Fig. 4). The sedimentation rates estimated for the past ca 300 years in Lake Takkobu indicate that land use development increases sediment production in the watershed, contributing to the accelerated shallowing process of the lake.

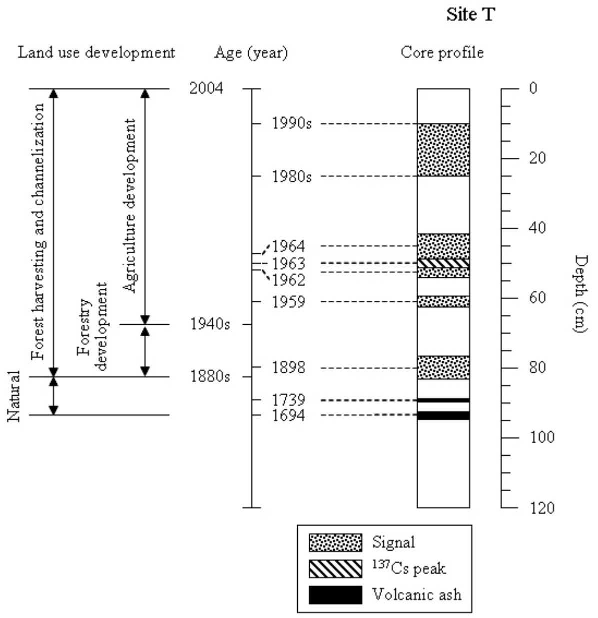

Fig. 3. Relationship between land use development and core profile at Site T as a representative example (Ahn et al., 2006).

Spatial variation in lake sedimentation Depth variation of ^{137}Cs peaks, signals, and the two volcanic ash layers suggested that there was a wide spatial variation in sedimentation rate in the lake (Fig. 2). The sedimentation rate between 1898 and 1963 was significantly different (p = 0.019, Kruskal–Wallis one-way ANOVA) among the three zones, whereas those in other periods were not (Table 3). The natural sedimentation rates in 1694–1739 and 1739–1898 were low and did not vary with location in the lake. The spatial variation in sedimentation rate and an elevated accumulation rate between 1898 and 1963 can be attributed to the initial agricultural development in the contributing watersheds. The sedimentation rate in the southern zone was higher than that in the middle and northern zones, reflecting accelerated sediment production associated with forest harvesting and canal construction (Table 3). Sites S2, S3, and L7, located in the southern zone, exhibited their highest sedimentation rate in 1898-1963 (Fig. 4), because these sites are situated close to forestry units and canal construction. Site S3, especially, showed the highest sedimentation rate between 1898 and 1963, because a canal was built in 1898 close to the sampling site. The sedimentation rates in the middle and northern zones, except for Site C3, increased between 1963 and 2004 because of further forestry, construction of drainage networks, and pasture development in the surrounding watersheds and wetlands. The sedimentation rate at Site C3 between 1898 and 1963 increased with sediment inflow from the Takkobu River, but decreased thereafter (Fig. 4),

Table 3. Comparison of sedimentation rates among the three zones for the four historical periods.

	Average sedimentation (mm year^{-1})					Kruskal-Wallis one-way ANOVA	
	Northern zone Median (range)	Middle zone Median (range)	Southern zone Median (range)	Kushiro River†	Takkobu River†	x^2	P
1694-1739	0.4 (0.2-0.7)	0.4 (0.2-0.7)	0.3 (0.2-0.7)	1.1	0.7	0.244	0.885
1739-1898	0.4 (0.1-0.7)	0.5 (0.4-0.9)	0.4 (0.3-0.4)*	1.1	0.4	5.464	0.065
1898-1963	1.5 (0.6-2.2)*	2.5 (1.7-3.9)*	4.1 (2.3-5.9)*	5.5	4.8	7.962	0.019
1963-2004	2.7 (2.0-3.9)	4.0 (1.5-4.4)	3.4 (3.0-3.9)	5.3	12.8	2.430	0.297

*significantly different from eacg other.

†not included in the statistical analysis.

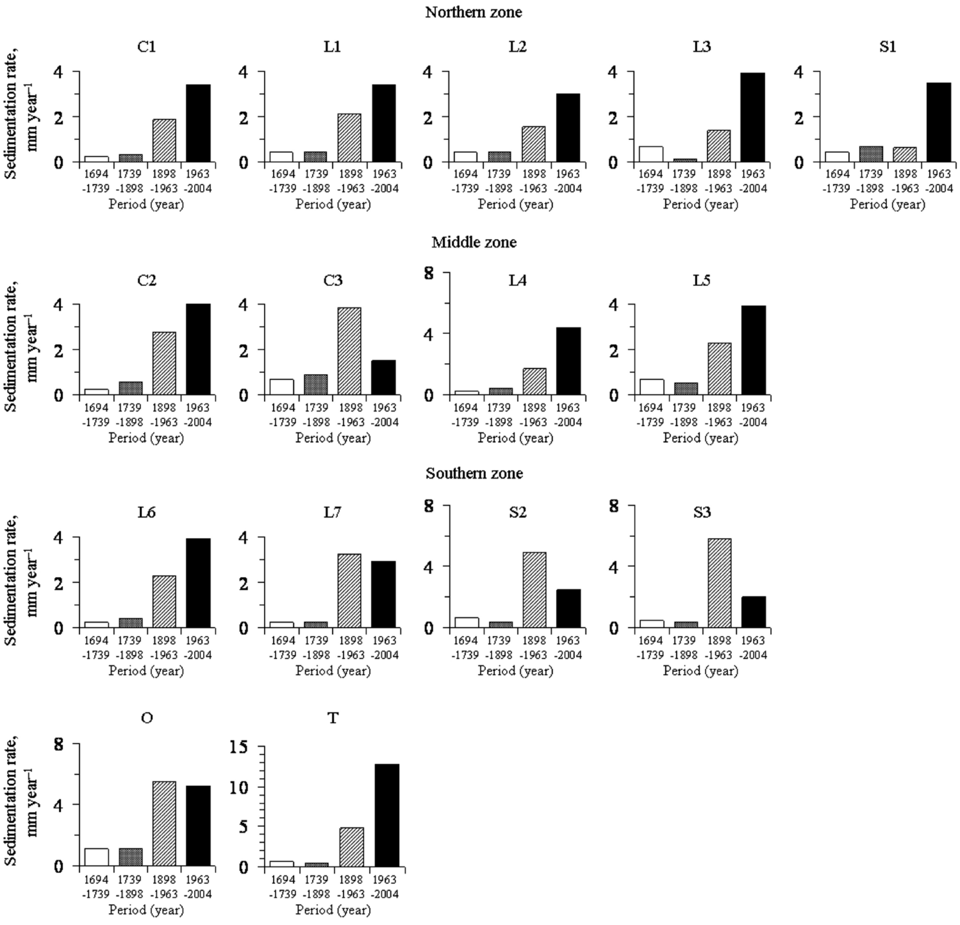

Fig. 4. Spatial variation of sedimentation rates in Lake Takkobu between 1694 and 2004.

probably because the water course of the Takkobu River was altered when drainage engineering works were implemented in the 1950s–1960s. A decrease in the sedimentation rate between 1963 and 2004 in the southern zone may be explained by steepening and shallowing of the lake-bottom morphology with sedimentation and the resultant reduction of sediment retention capacity. Thus, sediment was transported into the middle and northern zone, promoting sediment deposition after 1963.

The sedimentation rate after 1898 at Site T, located close to the Takkobu River mouth, increased by 7–32 times compared with that under natural conditions before 1898. This can be attributed to forestry, construction of drainage networks, and agricultural development in the Takkobu River watershed (Ahn et al., 2006). The elevated natural sedimentation rate at Site O in 1694–1739 and 1739-1898, the highest sedimentation rate among all sites for these two periods, may have been caused by sediment influx from the Kushiro River into the lake during high flow discharges. The high sedimentation rate after 1898 at Site O can be attributed to a further increase of sediment from the Kushiro River into the lake. Development of the Kushiro River watershed began from 1880 to the 1890s with group settlement and river channel excavation (小疇 et al., 2003). In the 1940s, floodplain wetlands in the Kushiro River watershed were developed into cattle farms, and since the 1960s, land consolidation and the introduction of agricultural machinery were promoted (Nakamura et al., 2004). As watershed development proceeds, the lake shallows with increasing sedimentation rates.

Relationships between land-use change and sedimentation rates in the lake Land use changes accelerated sedimentation in Lake Takkobu. An elevated sediment input to a lake depends on several factors, such as plowing, deforestation, changes in land use, land drains, building, and road construction. Cattle farming in the Kushiro district started in the 1940s, and a full-scale promotion of the dairy industry was initiated in the 1960s (Ministry of the Environment, 2003), leading to an increased sediment inflow to Lake Takkobu after the 1960s. Accelerated accumulation observed in lake sediments has been associated with conversion of natural land to farmland (Van der Post et al., 1997; Walling et al., 2003). Van der Post et al. (1997) discussed the influence of grazing pressure on sedimentation at Blelham Tarn in the English Lake district. They plotted the annual sediment accumulation against the number of sheep for two parishes adjacent to a lake and found an extremely close relationship (Fig. 5). In order to examine the effects of watershed land use on sedimentation rates in Lake Takkobu, I compared sedimentation research results and the livestock density of the Lake Takkobu watershed with the relationship found by Van der Post et al. (1997). Livestock in the Lake Takkobu watershed in 1898-1963 refers to horses and in 1963-2004, to cattle (北海道環境科学研究センタ-, 2005). In comparison with the trend shown by Van der Post et al. (1997), the Lake Takkobu watershed data showed a slightly higher sedimentation rate. This may be partly because Lake Takkobu has been subjected to a sediment-rich influx from the Kushiro River. In addition, sediment may have directly entered the stream networks, because remote farms as well as drainage engineering works, deforestation, and agricultural development are situated close to the streams and lake. This analysis suggested that Lake Takkobu has been strongly influenced by land use change, particularly near to it, and by the cumulative impacts of the Kushiro River watershed.

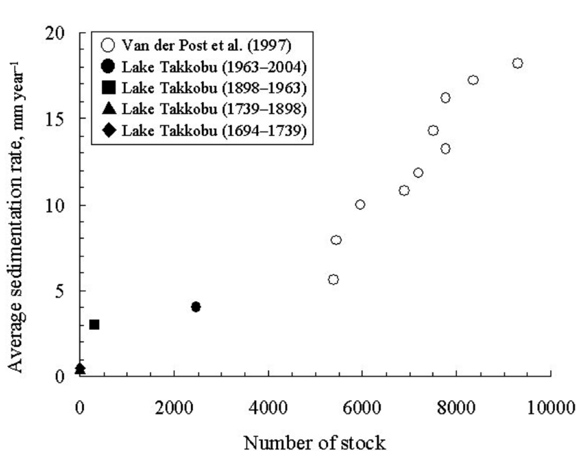

Fig. 5. Average sedimentation rate and the total number of stock in the lake watersheds.

Summary Sedimentation rates estimated for the past ca 300 years in Lake Takkobu indicate that watershed development has strongly influenced the shallowing process in the lake by increasing sediment production. The period of land use alteration started in the 1880s. The natural sedimentation rate before 1898 was slow at 0.1−1.1 mm year^{-1}. However, the sedimentation rates after land use development were about 6-12 times higher than that under natural conditions, accelerating lake shallowing over the last ca 100 years. Sedimentation rates between 1898 and 1963 differed in different parts of the lake because of spatial variation in the sediment flux from the contributing rivers and their watersheds. The sedimentation rate in the southern zone between 1898 and 1963 was greater than in other zones, reflecting continuous exploitation of forest resources and canal construction. The sedimentation rate after 1963 did not vary among the three zones; decreasing sedimentation was found at most of the southern sites, whereas an increasing trend was observed at the middle and northern sites. At the southern zone, this result can be explained by shallowing of lake-bottom morphology with sedimentation and the resultant reduction of sediment retention capacity. The sedimentation rate close to river mouths increased by 5−32 times compared with the natural, earlier level. The accumulation of fine sediment and associated nutrients result in environmental degradation of the lake ecosystem, as evidenced by water pollution and the extinction of aquatic plant species.

In order to prevent degradation of the aquatic environment, reduction of fine sediment loading from rivers and slowing sedimentation rates in lakes are necessary. In the long run, watershed management is the best way to reduce sedimentation (Bruk, 1985). Many studies have extolled the virtues of watershed-based approaches to sediment reduction (Pattinson et al., 1994). In particular, the cumulative impacts on the aquatic ecosystem in the watershed context must be considered in the Kushiro River watershed. For this reason, environmental management policies and laws to regulate land use change are required. Riparian buffers should be preserved or reestablished to reduce inflows of sediment along the edge of Lake Takkobu. Sluices between the Kushiro River and Lake Takkobu may function effectively to prevent sediment inflow to the lake during short-term flooding.

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산림과 농업 개발로 인한 쿠시로습원 타호부호수의 최근 토사동태

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농지 개발로 인한 다량의 세립토사 유입은 타호부호수의 생태계를 악화시키고 있다. 호수 퇴적물의 물리적 특성, ^{137}Cs과 화산재를 이용한 연대측정을 위해 호수 퇴적물 시료 15개를 채취하였다. 타호부호수에서 과거 300년간 토사퇴적속도를 조사한 결과, 유역에서 인위적 개발이 없는 1898년 이전 자연상태에서는 토사퇴적량이 0.1–1.1 mm year^{-1}였고, 인위적 개발이 시작된 1898년 이후에는 0.6–12.8 mm year^{-1}로 급격하게 증가하였다. 즉, 산림벌채, 하천공사와 농지개발 이후 토사퇴적량은 자연상태보다 6–12배 증가하여 호수의 수심이 얕아지는 현상을 가속시켰다. 1898년부터 1963년 사이의 호수 토사퇴적속도는 개별 소유역으로부터 토사유입 영향에 따라 공간적인 변화가 나타났다. 특히 1898년부터 1963년 사이의 호수 남쪽부분의 토사퇴적량은 산림벌채에 의한 숯 생산과 생산된 숯을 수송하기 위한 운하공사로 인해 호수 중앙과 북쪽부분보다 많았다. 하지만 1963년 이후 남쪽부분의 토사퇴적량이 감소하고 중앙과 북쪽부분에서 토사퇴적량이 증가하여 호수 안에서 토사퇴적의 공간적 변화는 없었다. 왜냐하면 호수 남쪽부분에서 많은 양의 토사퇴적은 호수 수심을 얕게 하여 토사를 침전시키는 능력을 감소시켰기 때문으로 생각되었다. 특히 하천 출구에 위치한 지점의 토사퇴적량은 자연상태에 비해 5–32배 높았다. 그리고 쿠시로강(평상시 타호부호수는 쿠시로강으로 배수)은 홍수시 탁수가 역류하여 호수로 유입하기 때문에 토사 유입 증가에 공헌하고 있는 것으로 나타났다.