Study of Groundwater Seepage into Lake Biwa

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STUDY OF GROUNDWATER SEEPAGE INTO LAKE BIWA

Masao KOBAYASHI

ABSTRACT

This study was undertaken to investigate the process of shallow groundwater flow into a lake and to determine the spatial and temporal variation of groundwater seepage into Lake Biwa of Shiga Prefecture in Japan and also to evaluate the groundwater component of the water balance in the lake. Seepage meter, piezometer, core drilling and water level techniques were employed for the field measurements. Before regular measurements were taken, some tests were conducted to evaluate the seepage meter technique.

Seepage meter technique was found to be most reliable by using a baggie collector initially prefilled with 200ml of water and a large inside diameter (10mm) plastic tube. The quality of water collected by seepage meter provided a good indication of composition of groundwater in the aquifer underlying the lake for high seepage sites but not at low seepage sites. It was observed that the concentrations of the major constituents of seepage water were 20-60% lower than that of the groundwater below the lake bottom at about

0.3m depth.

Data of groundwater potentials in the lake, the quality of groundwater and seepage flux showed that the shallow groundwater in the aquifer moves horizontally toward the lake and then veers rapidly upward on the shore line near the inflection point at the lakebed and seeps out within about 20m distance from the shore. Confined groundwater enters the lake through a thin low permeable layer. Seepage patterns obtained nearshore around the western shore of the lake were also consistent with the flow models predicted by modeling studies.

Seepage fluxes around the lake varied significantly ranging from 0.01 to 4.9 $\mu m \cdot s^{-1}$. The variability can be attributed to either the heterogeneity of the lake bottom sediments or lakebed configuration. Seasonal change in the total amounts of seepage extending perpendicularly from the shore was found and may have been caused by precipitation. Three seepage patterns were observed: (1) area where seepage flux decreases with increasing distance from the shore; (2) area where the distribution of seepage flux is uniform off-shore, probably as a result of the heterogeneity of a lake-bed configuration; (3) area where uniform seepage occurs near the shore and increases considerably offshore before it declines exponentially farther offshore. Detailed coring data within the lake showed that the extremely high offshore

seepage is associated with the confined aquifer exposed to the lake bottom offshore.

The groundwater discharge around the eastern shore was twofold larger than that around the western shore of the lake. However, the specific discharge in the areas around the Hira mountains and the northern end part of the lake was higher($2\sim3\mathrm{mm}\cdot\mathrm{d}^{-1}$) and that in the areas around the eastern shore($0.3\sim1.3\mathrm{mm}\cdot\mathrm{d}^{-1}$). The amount of groundwater seepage into Lake Biwa was estimated to be $270\mathrm{mm}\cdot\mathrm{y}^{-1}$ ($0.85\ \mathrm{km}^3\cdot\mathrm{y}^{-1}$). This value accounted for about 25% of the total inflow including surface water and groundwater into the lake.

These results indicate that the applicability of usefulness of the seepage meter technique and the theoretical models for understanding groundwater flow into a lake are strongly confirmed through the field measurements. Also, the configuration of the lakebed and the hydrogeological heterogeneity in the flow system have a significant effect on the seepage pattern within the lake.

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CHAPTER 1

INTRODUCTION

1-1. Previous studies

Groundwater is one of the most important components in the water balance and chemical budget of lakes. Over the past ten years, a number of studies on groundwater seepage into the lake were conducted both theoretically and observationally, particularly in Canada and U.S.A. The increased number of studies coincide with the introduction of seepage meter technique developed by Lee(1977).

Concerning theoretical studies, McBride and Pfannkuch (1975) examined steady state groundwater flow into lakes by modeling hypothetical half lakes. The study showed that a significant rate of seepage occurs near the shore and the flux generally decreases exponentially as a function of distance from the shore. In addition, the validity of the models were confirmed by Lee's field measurements of seepage rate.

Winter(1976, 1978) modeled the groundwater flow into and from hypothetical small lakes. This simulation study showed that groundwater flow near lakes is controlled by a variety of hydrogeological conditions within the groundwater systems. Specifically, he demonstrated that hydraulic heterogeneities within the aquifer can contribute seepage.

Winter and Pfannkuch(1984) used numerical simulations of whole lake models to evaluate the effects of anisotropy and geometry of the groundwater system on seepage through lakebed. The simulation analysis showed that a general decrease with distance from shore and the distance over which that decrease occurs increase as bulk anisotropy increase, and the occurrence of nearshore is accentuated by restricting lower permeability sediments to offshore areas.

Munter and Anderson(1981) examined the seepage rates from natural flow systems around lakes by numerical simulations of two and three dimensional groundwater flow models. The models showed the importance of the vertical hydraulic conductivity of a littoral lakebed sediments to estimate lake seepage rates.

More recently, Fukuo and Kaihotsu(1988) have conducted theoretical analysis of seepage flow of a confined groundwater into a gentle slope bottom of a lake. They have shown that most of the confined groundwater flows into the lake through the confining layer. However, such phenomenon has not been well investigated in a field.

Most of the field studies made so far are the estimation of groundwater discharge into lakes using hydrogeological informations and Darcy's law(Karnaskas and Anderson, 1978;

Kyoto Agricultural Land Administration Office, 1951), well water levels and tracer analysis (Jaquet, 1976), stable isotopes(Matsuo et al., 1979; Turner et al., 1984) or the water balance method(Yoshikoshi, 1978; Fujino, 1980).

In recent years, the direct seepage measurement techniques(Lee, 1972; Fellows and Brezonik, 1980) were employed to measure the quantity and the quality of the groundwater seepage into lakes. Although some measurement errors exist in this method(Shaw and Prepas, 1989; Belanger and Mikutel, 1985), the usefulness of the seepage meter technique has been documented by John and Lock(1977), Woessner and Sullivan(1984) and Shaw and Prepas(1990a).

Lee(1972) employed the direct method using seepage meter to study septic tank seepage into Lake Sallie in Minnesota. The study showed that the distribution of seepage flux and chemistry of seepage concurred with a theoretical flow net and the rate and direction of seepage flux were correlated with water level elevation.

Following studies are also made by Dowing and Peterka (1978), Lee(1977), Kobayashi(1985), Isiorho and Matisoff (1989) and Shaw and Prepas(1990b). A common conclusion of these studies is that seepage flux is generally highest near the shore and decrease with distance from the shore.

Although, groundwater seepage into lakes is rarely measured in Japan, it is generally known that groundwater seeps into through the lake bottom in Lake Biwa (Katsura et al., 1982; Tsurumaki and Kobayashi, 1989) and seeps out in Lake Ikeda (Satoh, 1986). Kawabata (1982a) also indicated that the amount of seepage could not be ignored in Lake Biwa.

On the other hand, these phenomena occur near the shore as they have been indicated in theoretical studies mentioned above. However, there has been insufficient field testings of these models to verify their validity. Cherkauer and Nader (1989a) showed that the uniform seepage pattern predicted by the mathematical simulations was not norm and that the simulations done to date may not be applicable to a large and heterogeneous system. Furthermore, relatively little attention has been paid to the process of groundwater flow into a lake, and few field researches were made, probably because of perceived difficulties in setting up devices for monitoring the groundwater potentials, sampling of groundwater or seepage flux at a different depth in a lake.

To obtain a better understanding of groundwater discharge into a lake, it is necessary to conduct the field observations for the process of groundwater flow into the lake and seepage patterns around the lake.

1-2. Objectives of the study

The main objectives of the study are as follows:

(1) To investigate the process of groundwater flow into

the lake and to evaluate the effectiveness of mathematical models nearshore as predicted in published studies by comparing the field observations. The usefulness of seepage meter technique for studying groundwater seepage into a lake is also to be evaluated.

(2) To determine the spatial and temporal variations of seepage flux within the lake by the seepage meter technique and also to evaluate the variation of seepage pattern in correlation with the bottom sediments, morphology of the lakebed, rainfall level and the distance from the shore. The results from the measurements were also to be used to estimate the annual amount of seepage into the lake and the evaluation of the percentage of this component to the water balance in the lake.

Lake Biwa which is the largest lake in Japan and the most valuable water resources in the Kinki district was selected for this study.

CHAPTER 2

DESCRIPTION OF STUDY AREA

2-1. Physical dimensions of Lake Biwa

Lake Biwa which is located on latitude 35°N and longitude 136°E is considered to be a tectonic lake (Yoshimura, 1937). Figure 1 shows the location of the study area. The lake has a surface area of $674km^2$ and shore line of 235km. It has a maximum length of 63km along the north-south direction; a maximum depth of 104m and a volume of $27.5 \times 10^9 m^3$.

The lake is asymmetrical in shape with a maximum and minimum width of about 23km and 1.35km, respectively. The lake is divided into two parts, namely the Northern and the Southern Lakes with a mean depth of 44m and 3.5m, respectively. As might be expected from the wide difference in depth, the two lakes differ considerably in water quality as well as physical properties (National Institute for Research Advancement, 1984).

2-2. Topography and hydrogeology of the drainage basin of Lake Biwa

Lake Biwa is surrounded on the east by the Suzuka and Ibuki mountains, on the west by the Hira-Hiei mountains, on the north by the Ibuki and Yasaka mountains and on the south

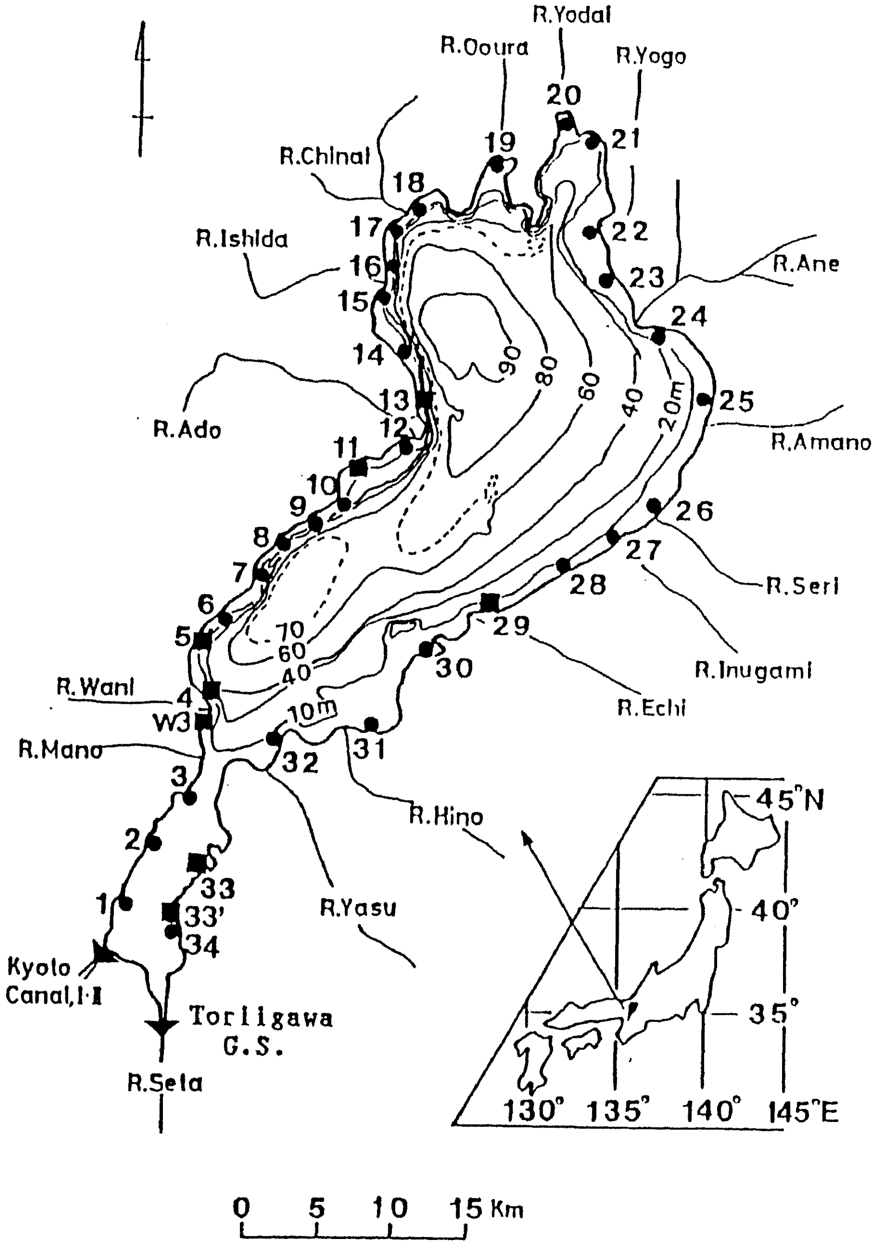


Figure 1. Map of Lake Biwa showing the locations of seepage measurements and the bathymetric map. Closed circles and solid squares show the single meter site and the specific site for seepage observations of the temporal and spatial variations along the transect offshore, respectively.

by the Kizu mountains (Fig. 2). Mountain peaks range from 300 to 1,000m high. The Hira-Hiei and the Yasaka mountains rise abruptly from the lake. Forest-covered mountains account for nearly 60% of the drainage basin of Lake Biwa ($3,168km^2$: excluding the water surface area) and the farm land (mostly paddy field) makes up 25% of the land area.

The bedrock of the study area consists of granite and rocks of Paleozoic and is underlain by Ko-Biwako Group which is about 1,000m thick and is composed of gravel, sand and clay with thin tuff intercalations of more than ten beds (Tatekawa, 1980).

Ko-Biwako Group is underlain by Terrace and Alluvial deposits which consist of gravel, sand, clay and silt from the bottom upward. The thickness of each deposit ranges from about 20 to 30m and 5 to 10m respectively near the shore. In the terrace deposit, permeable cobble and gravel lenses with a high infiltration capacity are interbeded and is underlain by thin clay lenses (1-5m thick) which serve as a discontinuous confining layer (Kinki Regional Construction Office, 1962).

It is likely that any water held in this fractured aquifer is reaching the lake at the eastern shore of the lake, especially in the region of the Echi river delta (Takatani and Nishida, 1964). Sand is the predominant material in the alluvial deposits, although silt and clay lenses which contain fine sand and organic materials are common.

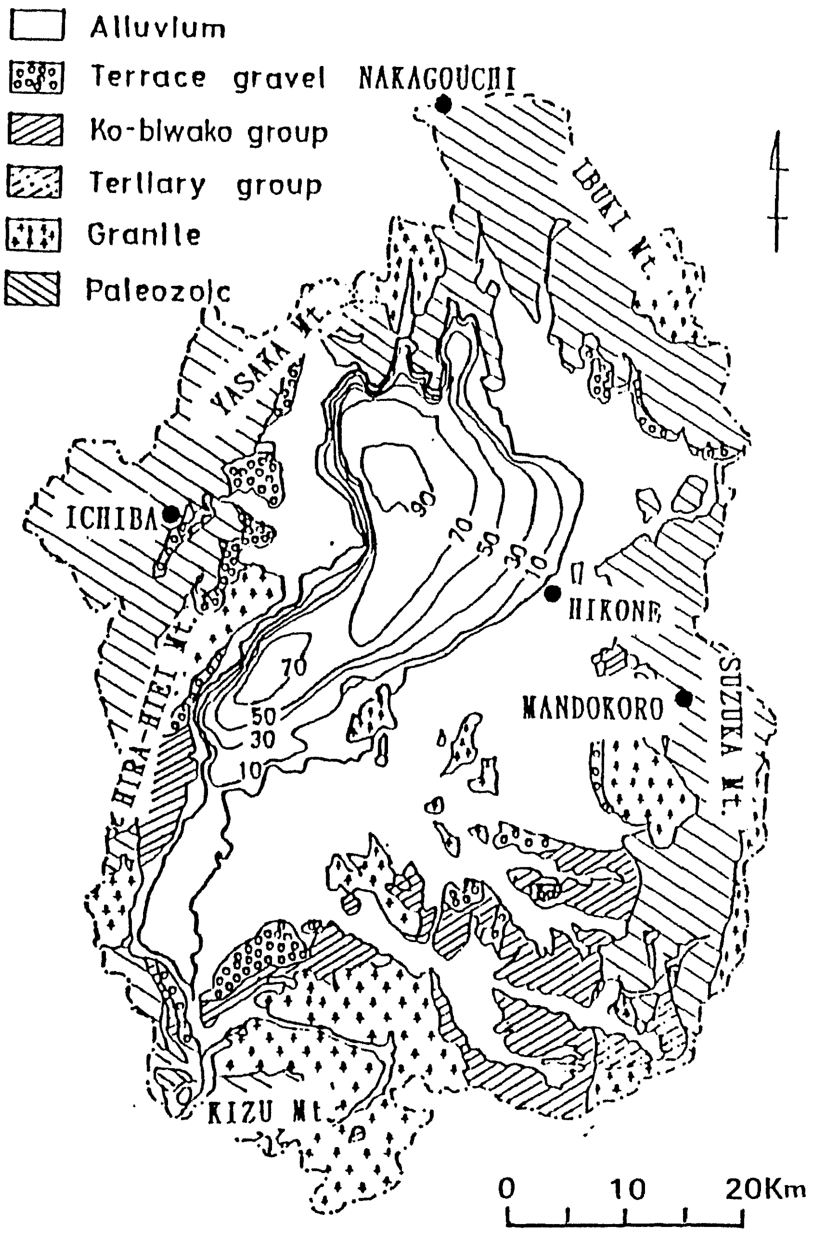


Figure 2. Surface geological map around Lake Biwa(after Foundation of Nature Conservation in Shiga Prefecture, 1979) and the rain gauging stations(black dot).

Springs are observed on the western shore of the lake and there are many flowing wells, particularly in the regions on the eastern (Echi river delta) and western shores (Ado river delta). The depth of the flowing wells are about 20m on the western shore and 60 ~ 110m on the eastern shore, respectively.

Hydraulic conductivities (K) of the surficial deposits are highly variable: K for clay and silt ranges from 10^{-8} to 10^{-6} $cm \cdot s^{-1}$ and for sand and gravel it ranges from 10^{-3} to 10^{-1} $cm \cdot s^{-1}$ (Kayane et al., 1984). The surficial deposits are assumed to be continuous from the shore to the lake and make up the aquifer which is being investigated.

2-3. Lakebed configuration and the bottom sediments

The lakebed generally declines to the west on the whole. The western side of the lake has steep slopes, however, the eastern side slopes much more gently (Fig. 2). Most of the bottom is covered by mud with a depth of more than 10m and it accounts for nearly 75% of the lake. Whereas the lake shore area is mostly covered by sand or sandy gravel, some parts of the lake shore are muddy, the Southern Lake, and rocky in the northern part of the lake. Fine-grained sediments also exist offshore of the lake, but the exact thickness of the sediments are unknown (Kotani, 1971).

CHAPTER 3

WATER BALANCE COMPONENTS OF LAKE BIWA

In Lake Biwa basin, there are only two outlets from the lake(Fig. 1). The outflow from the lake is controlled by weir at each gauging station constructed at these outlets. They are the Toriigawa gauging station situated at the upper most end of the Seta river, which is the only natural outlet from Lake Biwa and the Kyoto Canals(Ⅰ,Ⅱ) gauging station, situated at the southern end of the lake, which was constructed in 1890 for agricultural and municipal water supply purposes. The change in water level by pumping water from the lake for irrigation purpose is negligible (Sugawara, 1973). Groundwater discharge into the lake through the lake-bed has not yet been monitored during the period of the previous survey. Thus the water balance expressed in a water depth for Lake Biwa may be written as follows:

$$\Delta H = P + R + G - D - E \qquad \cdots\cdots \quad (1)$$

where

ΔH : the change of the lake water level or the change of the lake water storage from the beginnings to the end of a water year.

P : the amount of precipitation falling on the lake surface

R : the amount of surface inflow into the lake from the land such as rivers and irrigation canals

G : the amount of groundwater inflow into the lake

D : the amount of outflow from the lake

E : the amount of evaporation from the lake surface.

All variables are usually expressed in mm or cm and are measured at the same period. The components required in the evaluation of the water balance are discussed below.

3-1. Precipitation

Long term annual total precipitation from 1896 to 1980 at the Hikone Local Meteorological Observatory located on the north-eastern part of the study area averages 1671mm. Lake Biwa annually receives 1600 ~ 1900mm of precipitation as shown in Table 1 (Kotoda, 1978; Fujino, 1980 and Kawabata, 1982b). The annual total precipitation on the drainage basin of Lake Biwa averages about 1900mm.

Significant regional variation of precipitation exists in the watershed of Lake Biwa. High amounts of precipitation occurs in the northern part near the Ibuki and the Yasaka mountains; while near the plane in the southern part of the lake low amount of precipitation occurs. The annual average

Table 1. Water balance components of the drainage basin of Lake Biwa

References Items	Units	Kotoda (1978)	Fujino (1980)	Kawabata (1982)	KALAO[1] (1951)
Land surface					
Area	(km^2)	3,131	3,170	3,170	3,170
Precipitation	(mm·y^{-1})	1,941	1,950	1,893	-
	(km^3·y^{-1})	6.1	6.18	6.0	-
Evapotranspiration	(mm·y^{-1})	676	527	473	-
	(km^3·y^{-1})	2.1	1.67	1.5	-
Outflow*	(mm·y^{-1})	1,263	1,427	1,420	-
	(km^3·y^{-1})	4.0	4.51	4.5	-
Outflow(G**)	(mm·y^{-1})	-	322	143 ~ 215	-
	(km^3·y^{-1})	-	1.02	0.45 ~ 0.68	-
Lake surface					
Area	(km^2)	717	680	680	680
Precipitation	(mm·y^{-1})	1,637	1,690	1,912	-
	(km^3·y^{-1})	1.2	1.13	1.3	-
Evaporation	(mm·y^{-1})	811	766	882	-
	(km^3·y^{-1})	0.6	0.52	0.6	-
Inflow*	(mm·y^{-1})	5,578	6,632	6,618	-
	(km^3·y^{-1})	4.0	4.51	4.5	-
Inflow(G**)	(mm·y^{-1})	-	1,500	662 ~ 1,000	8,411
	(km^3·y^{-1})	-	1.02	0.45 ~ 0.68	5.72
Outflow	(mm·y^{-1})	6,416	7,559	7,647	-
	(km^3·y^{-1})	4.6	5.14	5.2	-

(Continued)

Table 1. Water balance components of the drainage basin of Lake Biwa.

Total of the land and lake surfaces					
Area	(km^2)	3,848	3,850	3,850	-
Precipitation	($mm \cdot y^{-1}$)	1,884	1,904	1,896	-
	($km^3 \cdot y^{-1}$)	7.3	7.33	7.3	-
Evaporation	($mm \cdot y^{-1}$)	701	568	545	-
	($km^3 \cdot y^{-1}$)	2.7	2.19	2.1	-
Inflow*	($mm \cdot y^{-1}$)	1,040	1,171	1,169	-
	($km^3 \cdot y^{-1}$)	4.0	4.51	4.5	-
Outflow*	($mm \cdot y^{-1}$)	1,195	1,335	1,351	-
	($km^3 \cdot y^{-1}$)	4.6	5.14	5.2	-
Change of water	($mm \cdot y^{-1}$)	0***	0***	0***	-
storage	($km^3 \cdot y^{-1}$)	0***	0***	0***	-

Outflow* and Inflow*: Each value includes surface water and groundwater. G** shows the amount of groundwater flow into the lake from the land. 0***: It is expected that the changes of water storage on the land and the lake have marked variations in a short time scale of water valance computation. However, the annual water balance is considered, these values could be neglected without an undue loss of accuracy, because these changes of water storage are generally small in comparison to the other quantities such as precipitation. KALAO1) indicates Kyoto Agricultural Land Administration Office.

precipitation during from 1941 to 1970 at the Nakagouch rain gauging station(Fig. 2), in the northern end of the basin is about 3000mm. The Mandokoro in the east has an annual average precipitation of about 2000mm. The annual average precipitation in the plane is about 1600mm(Nakajima and Ushiromachi, 1983). The high precipitation in the northern part is caused by snow fall during the winter season which is a characteristic of the Japan Sea-type-climate.

Precipitation in the drainage basin of the lake mostly occurs during rainy season from June to July and Typhoon season of late summer and autumn. About 40% of the annual precipitation falls during these seasons(Ikeda et al.,1979). The lowest amount of precipitation occurs in August and January (except in the northern part) which is characteristic of the Seto Inland Sea-type-climate(Nakajima, 1980).

It is to be noted that the amount of water(volume of snow fall x snow density) which is stored on the land around the northern part of the basin as accumulated snow from January to March is important as a source of groundwater recharge.

3-2. Inflow and outflow of the lake

More than 120 streams of various sizes directly flow into the lake but the flow of each stream is not monitored, so far that the amount of inflow(R) into the lake is estimated from the records of outflow(D) and the changes of the lake water level at the Toriigawa gauging station and the Kyoto Canals(Ⅰ,Ⅱ). The annual amount of inflow into the lake from the land surface including both surface water and groundwater to be 1000 ~ 1200 mm$\cdot$y^{-1}, and the amount of outflow from the lake recorded cumulatively throughout the year at the two gauging stations is about 1200 ~ 1300mm$\cdot$y^{-1} which is calculated for the land surface area(Table 1).

3-3. Evaporation

The amount of annual evaporation(E) from Lake Biwa estimated by the heat balance method(Ito and Okamoto, 1974) was about 700mm ~ 800mm. Kotoda(1978) estimated the annual evaporation using the aerodynamic method on the lake and gave similar value(Table 1). These estimated values of evaporation are more than 40% of the annual precipitation on the lake surface. The seasonal change of evaporation from the lake shows a higher rate in autumn and winter seasons (September-March) than in spring and summer seasons(April-August) (Ikebuchi et al., 1988).

3-4. Groundwater flow into the lake

The amount of groundwater flow into the lake(G) is estimated to be 322mm$\cdot$y^{-1}, calculated for the land surface area, from the residual of water balance equation(1) (Fujino, 1980). By using equation(1) in combination with Darcy's law and the continuity equation, G was estimated to be 1486 mm$\cdot$y^{-1} (Kyoto Agricultural Land Administration Office, 1951).

On the other hand, Maruyama et al.(1986) calculated the amount of groundwater flow into the lake from the data of recharge amounts collected by direct measurements at the Yasu river fan on the eastern shore of Lake Biwa. The amount of groundwater flow into the lake along the shore line of 10km is estimated at 0.87 ~ 1.06m$^3\cdot$s^{-1} (0.013 ~ 0.017km$^3\cdot$y^{-1}) in the irrigation season and 0.22m$^3\cdot$s^{-1} (0.0035km$^3\cdot$y^{-1}) in the other season. Assuming the shore line of 157km(total shore line of 235km X 2/3), the annual groundwater discharge into the lake is estimated at 946mm$\cdot$ y^{-1}. Each amount of groundwater obtained at two different seasons was used for half a year in the calculation, respectively.

3-5. Change of the lake water level

The water level of Lake Biwa is a very important factor for the study of water balance of the lake as seen from equation(1). Change of the water level of Lake Biwa is not only caused by the variation of natural condition but also under the artificial control of weir. The level changes in accordance with precipitation except with snow melt season (Fig. 3, Ikeda et al. 1979). For the past ten years, the annual maximum water level recorded is 0.63m above the standard level of the lake(T. P. 84.371m = ±0) at the Tori-

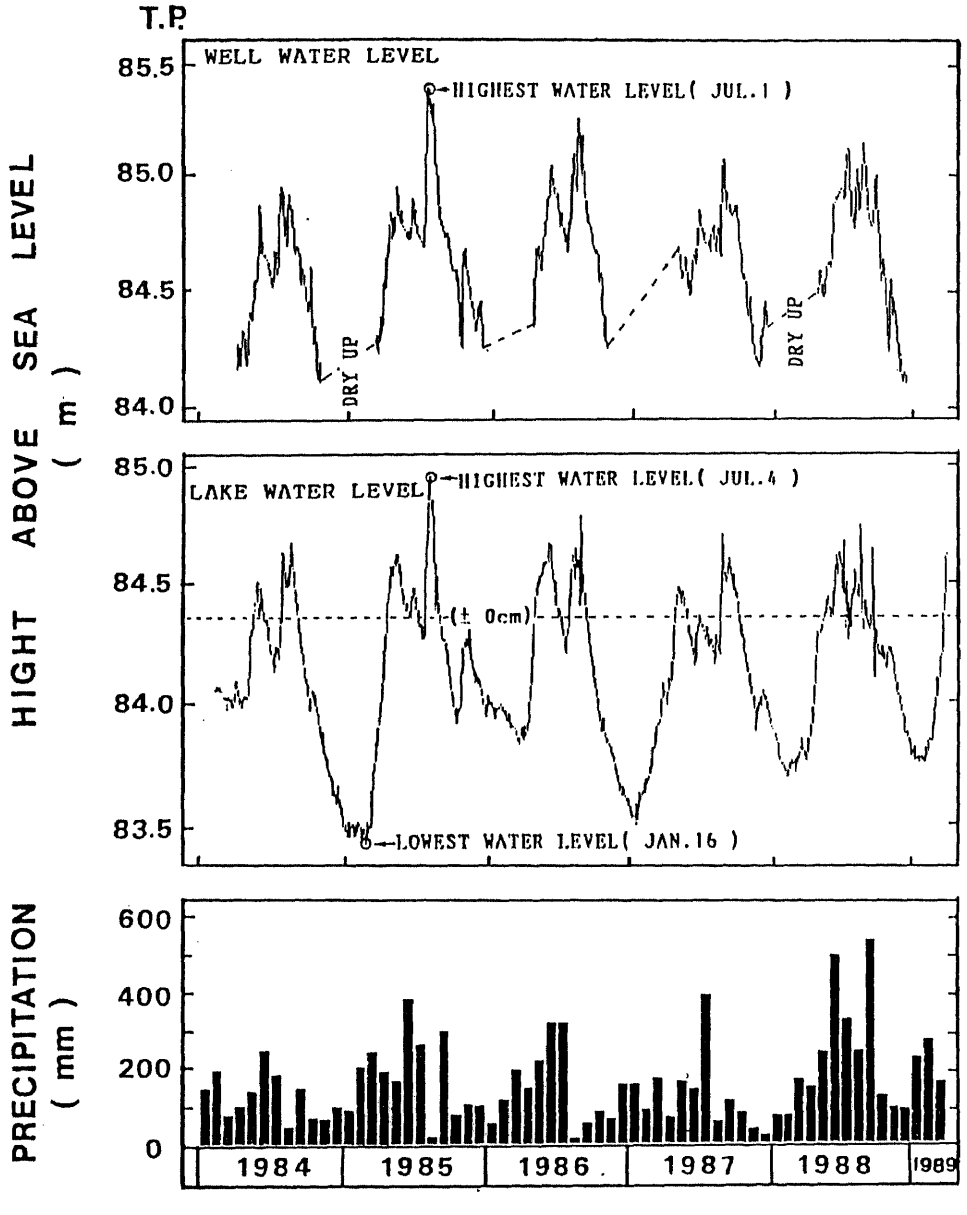


Figure 3. Monthly variations of well water level, lake water level and precipitation during study period. Each level of well water and lake water was recorded near the shore at Sta.4 and the Toriigawa gauging station shown in Figure 1, respectively.

igawa gauging station. This level recorded during a flood in July 1985. The minimum water level recorded is 0.98m below the standard level during a drought from August to December in 1984. However, the water level has usually been controlled within a range from +0.5m to -0.5m(Fig. 3).

CHAPTER 4

OBSERVATION METHODS

4-1. Seepage measurements

4-1-1. Seepage meter

In this study, two types of seepage meters similar to those described by Lee(1977) were constructed to measure groundwater seepage into the lake. One is the type of length of 15 ~ 20cm long made by cutting the end section of 55 gallon metal drum(Fig. 4(A)). The other is the box type of dimension 50X50X15cm made from thin (2mm thick) metal boards (Fig. 4(D)). The four metal boards of which many small holes were drilled through were attached to each side of the meter to prevent the apparatus from sinking into the sediment surface, especially when the sediments are soft and loose (Appendix I. 1).

Seepage meters were inserted with the open end down into the sediments until its top come very close to the top of the sediments. After the meters have been installed in the sediments, each hole was fitted with a one hole rubber bung covered with screened nylon mesh to allow ventilation of water within the meter and left in place until the measurements start. For water sample collection, a polyethylene

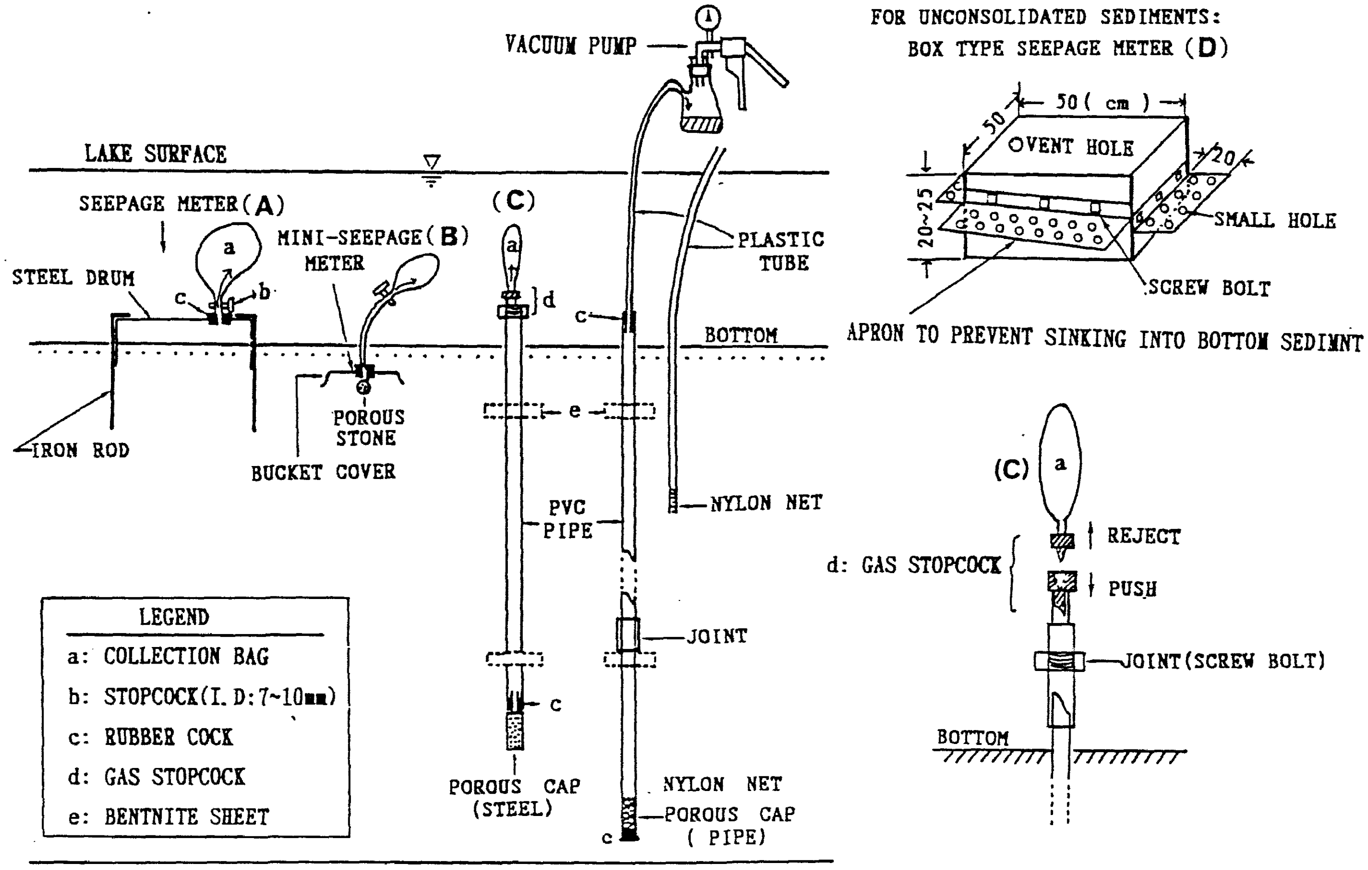


Figure 4. Installations of seepage meter((A), (B) and (D)) and piezometer ((C) and (E) for sampling of groundwater in the lake. Mini-seepage meter (B) was used only for sampling of groundwater seepage. Samples of groundwater were collected by suction by vaccum(E) or by natural flowing(C).

bags of volume ranging from one to 4 liters fitted with a plastic tube(or stopcock) with 0.9 ~ 1.0cm I.D.(baggie collector) were prepared and they attached to the top hole of the meter through the rubber bung(Appendix Ⅰ. 1).

For the first five months of the study, emptied bags were used to collect the samples in accordance with the method described by Kobayashi(1984). However, after five months the bags were initially prefilled with 200ml of water before they were attached to the seepage meter with exception of sampling of water for chemical analysis, because of the reason described below(5-1-1). When prepared collectors are attached to the top hole of the meter, the stopcock is opened and the bag is filled with water(Appendix Ⅱ. 1).

After a certain time, usually one hour, the stopcock is closed and the baggie collector removed. The volume of water in the baggie collector is then measured and the seepage flux($\mu m \cdot s^{-1}$) is calculated from the volume(cm^3) of sample collected divided by the sampling duration time(sec) and the area covered(0.25 ~ 0.255cm^2) by the meter. All meters were left in place once installed at each site through the study period. These installations of meters and measurements were done with snorkels in shallow water less than 1.5m depth and scuba tanks in deep water.

4-1-2. Test of the seepage meter technique

Before regular measurements were taken, some in-situ tests were conducted to evaluate the seepage meter technique because there are some technical or measurement errors associated with it.

First, a number of measurements were made to determine the effects of the funneling seepage from a small diameter tube through a large diameter tube into the baggie collector. Because seepage meter should offer no resistance to the flow of seepage through the tube and into the bag. However, resistance to flow through a tube is proportional to the flow rate and inversely proportional to the tubing diameter (Fellows and Brezonik, 1980) and seepage rates(or flow) obtained with small diameter tubes are smaller than those obtained with large tubes(Lee, 1972).

Each set of measurement was done repeatedly on different date over a 10 hour period at each site of high(Sta. 5), medium (Sta. 4) and low seepage sites(Sta. 33) shown in Figure 1. The inside diameters(I.D.) of the tube were used ranging from 4 to 15mm and 4 or 6 meters were installed at 5 -120cm intervals in the sandy sediments near the shore.

Second set of measurement was done over a 6 hour period with each data collection lasting for an hour in order to compare the data from using bags which were prefilled with 200ml or 500ml of water and that from using empty bags. Since an anomalous, short-term influx of water into the bag was usually observed after they are attached to seepage meters; the bags were partially expanded and a significant influx of water drawn into the bags was observed visually for one to 5 minutes durations.

The third one was conducted to estimate the precision of the seepage results, two sets of repetitive measurements were done using adjacent meters over a 11 hour period in February, 1984 at Sta. W3, and over a 8 hour period on 25 August 1984 at Sta. 5. For seepage measurements, all bags were prefilled with 200ml of water.

The last one is sampling of waters from seepage meters, piezometers and the lake for chemical analysis. This was done because seepage water is generally assumed to be equivalent to the groundwater water in the sediments lying just below the sediment-water interface and considered to be mixed with lake water. However, the relationship between the quality of seepage water and groundwater in the aquifer under the lake is not well established. It is desirable to evaluate quality of sampled water for the estimation of material loading into the lake(Appendixes Ⅱ and Ⅶ) or for investigation of the groundwater flow into the lake by using tracers. Each water sample was collected from seepage meters and a number of piezometers(4-2-3) which were installed at various depth ranging from 0.3 ~ 5.0m in the lake bottom sediments at two sites(Stas. 4 and 5). Samples of water were collected once a month from August to November, 1984 and again in December, 1985.

4-1-3. Sampling of seepage water for chemical analysis

Samples of seepage water for chemical analysis were collected two weeks after the installation of seepage meters, as the lake water entrapped within the meter after original emplacement at the meter had almost been flushed out in 10 days after installation. This is because that a quantity by 100 to 500 times of the volume of water within the meter above the sediment surface was flushed out over the period (10 days) and the electrical conductivity(E.C.) of the water trapped within the meter was clearly different from that of the lake water (Fig. 5). The E.C. and pH of the water samples were determined in-situ. The water samples for chemical analysis which were collected in polyethylene bottles were transported back to the laboratory and stored at -20°C until the start of the analysis. Alkalinity, reported as HCO_3^-, is determined by titrating the samples with acid(0.02N H_2SO_4) with bromocresol green-methyl as an indicator. Ca^{2+}, Mg^{2+}, Na^+ and K^+ were analyzed by the flame emission atomic absorption spectrophotometer (HITACHI Model 108). Cl^-, SO_4^{2-} and SiO_2 were determined by the mercuric nitrate method, turbidimetric method and ammonium molybdate yellow method or ionchromatography method(Cl^- and SO_4^{2-}), respectively(Hanya, 1960; Jap. Soci. Analy. Chemi. Hokkaido, 1981).

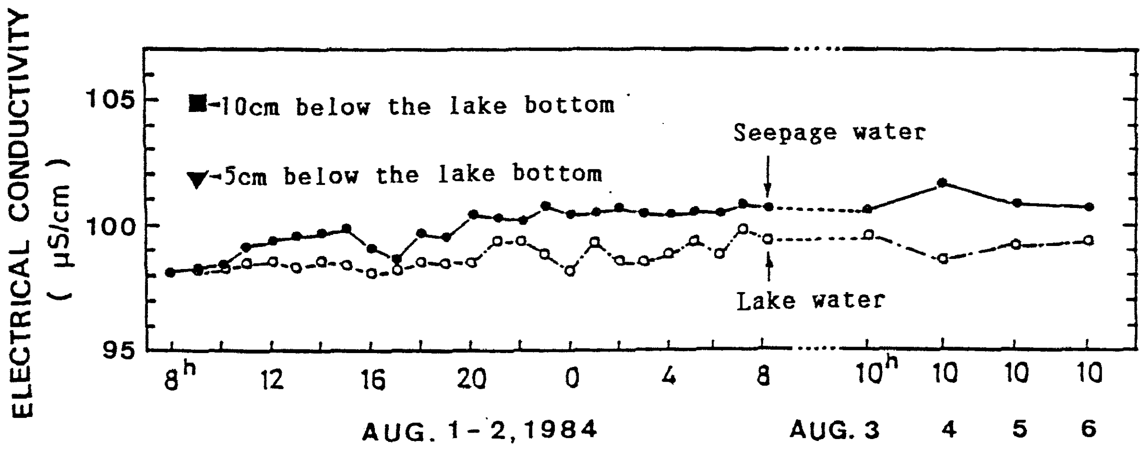


Figure 5. Temporal trend of the electrical conductivity of the water collected by seepage meter and of the lake water at Sta. W3(Fig. 1). Solid square and triangle show the value of electrical conductivity of the groundwater at each depth in the lake.

4-1-4. Seepage meter installation

According to the established geology of the area (Water Resources Development Corporation, 1973), 76 sampling stations along the lake shore were selected(Figs. 1 and 6). Eight sites among the 76 stations were selected for the determination of the spatial and temporal variations of seepage flux(or pattern). Hydrogeological conditions of these selected sites, i.e geological formations and nature of bottom sediments, are well known from previous studies (Kinki Regional Construction Office, 1962; Akai and Uno, 1967; Kotani, 1971). One or two seepage meters were usually installed at 1 ~ 1.5m depth at each of the 68 stations. Samples were collected one to 5 times during from summer through autumn from 1984 to 1985.

At eight transect sites, 4 to 15 seepage meters were installed along the transect perpendicular to the shore line. The transects were arranged within 220m from the shore line and in the water, within the depth of about 0.3 to 10m. Seepage measurements were made once or twice a month throughout 1984 and 1985 at Stas. 4, 5 and 33. At stations 11, 13, 29, W3 and 33′, samples were taken twice or three times during summer months in 1985 and 1987.

The installation of seepage meters was done simultaneously to examine the characteristics of the lake bottom sediments from core samples. The cores were taken with in-

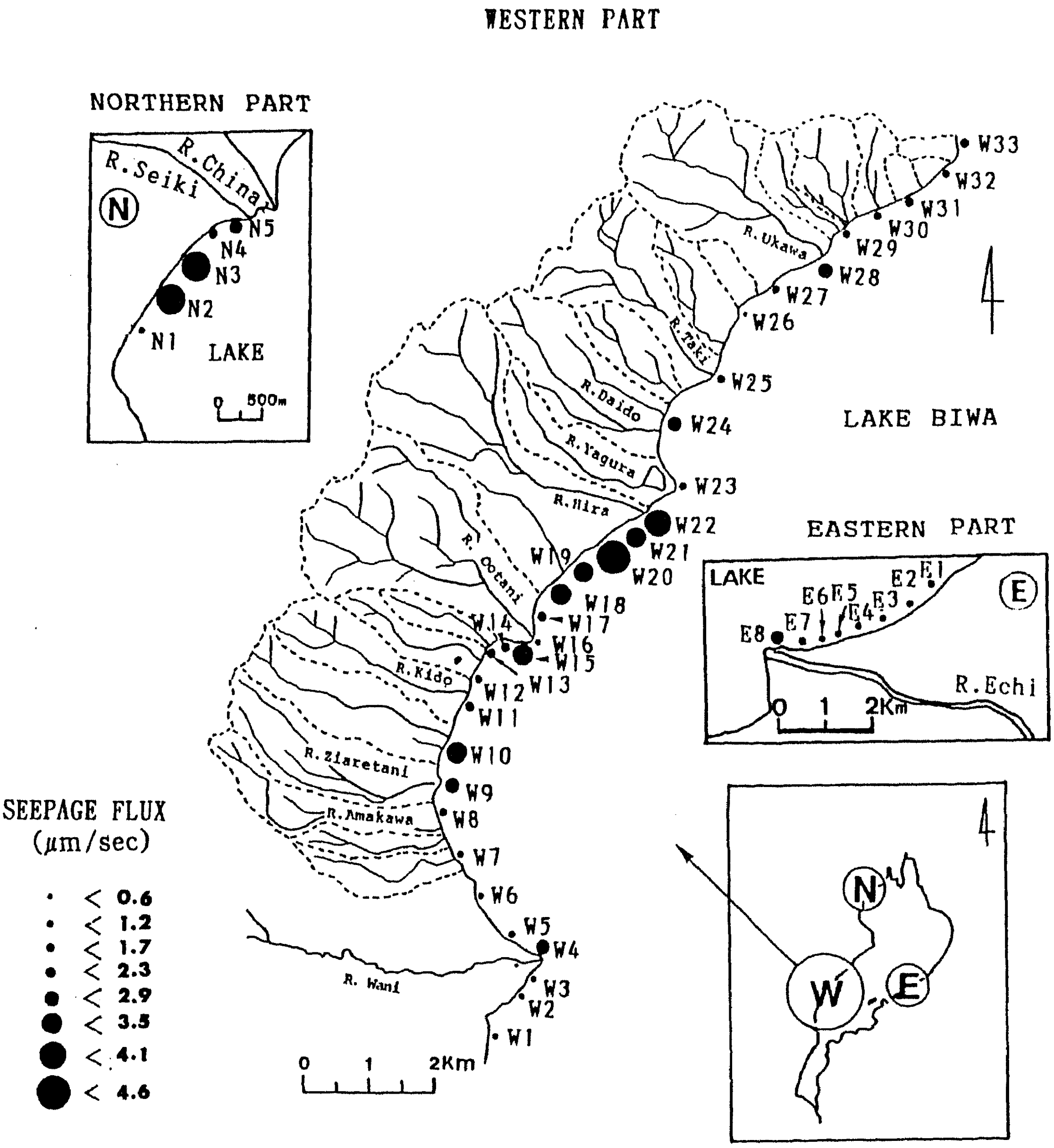


Figure 6. Locations of seepage measurements around the northern, western and eastern parts of the lake showing the results of seepage flux at each station.

side diameter of 3cm steel pipes or with hard plastic pipes (2mm wall thick) from an area adjacent to the meters (Appendix Ⅱ. 2). The core samples of length ranging from 10 to 50cm were allowed to dry and were tested for the grain-size distributions.

4-2. Observation of groundwater flow into the lake

The observations were conducted at the western shore of Lake Biwa (Imajyuku beach (Sta. W3), Appendix Ⅱ. 1) which is situated near the estuary of the Wani river (Fig.1). This site provided an excellent opportunity where $CaCl_2$ was sprinkled on a tennis court near the shore, which can be used as an excellent tracer, and because we were doing seepage measurements concurrently on other sites of the western shoreline.

For the observations, well water level measurements were firstly done to determine the shallow groundwater flow into the lake. Secondly, various field techniques such as core drilling, a nest of piezometers and mini-seepage meters (Fig. 4 (B)) were employed to determine the process of groundwater flow into the lake in conjunction with mapping the distributions of dissolved constituents mainly in groundwaters in the lake and seepage waters, and that of groundwater potentials near the shore. Thirdly, seepage fluxes along the transect offshore were measured using seepage meters.

4-2-1. Hydrogeology of the study area

The subsurface geological deposits of the study area consist of the alluvial and terrace deposits. Although sand is the predominant materials in the subsurface layer, silt and clay lenses are common(Figs. 2, 7).

The direction of the shallow groundwater flow is lakeward perpendicular to the shore line and the flow patterns were generally consistent throughout the year(Fig. 8). The hydraulic gradient toward the lake was about 0.005 in summer and the water table near the shore was usually higher than the lake water level. As a results the shallow groundwater flows into the lake.

4-2-2. Core drilling program

The cores were taken with steel pipes or hard plastic pipes (2mm wall thick) from an area adjacent to the individual meter along the transect line Y-Y(Fig. 8). The casing pipes were advanced using a handheld vibrating hammer or Jack hummer(offshore). The core samples of length ranging from 0.3 to 5m were allowed to dry and were tested to obtain grain-size distributions using sieves.

4-2-3. Piezometer and installation

Piezometers were constructed to measure hydraulic head in the aquifer and to collect groundwater from the bottom of the sediment layer and the shallow groundwater near the shore.

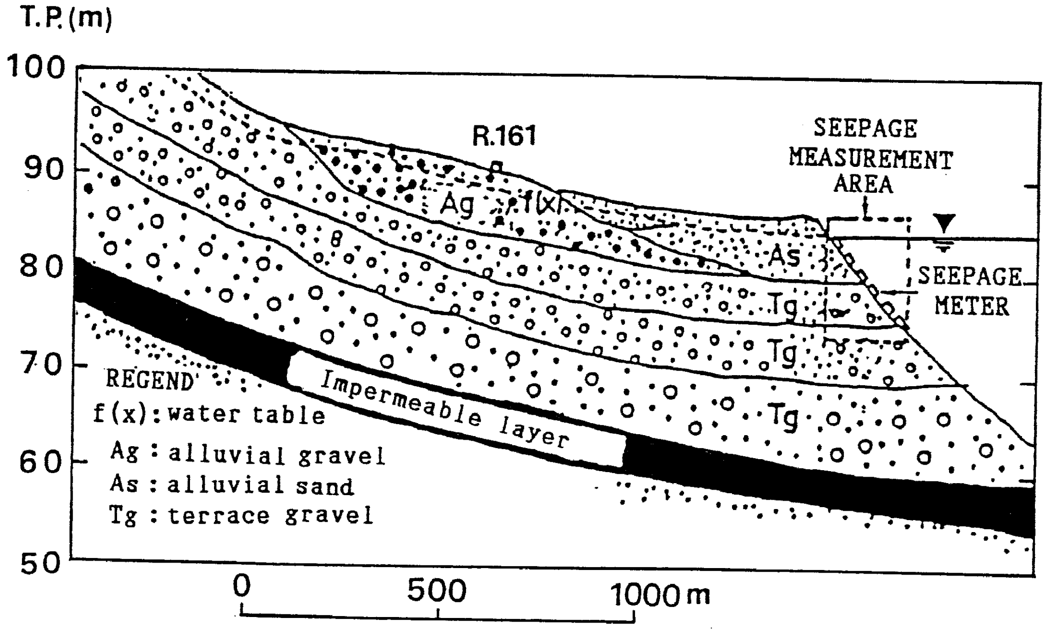


Figure 7. Generalized geological cross-section view along the line X-X shown in Figure 8(after Water Resources Development Corporation, 1973).

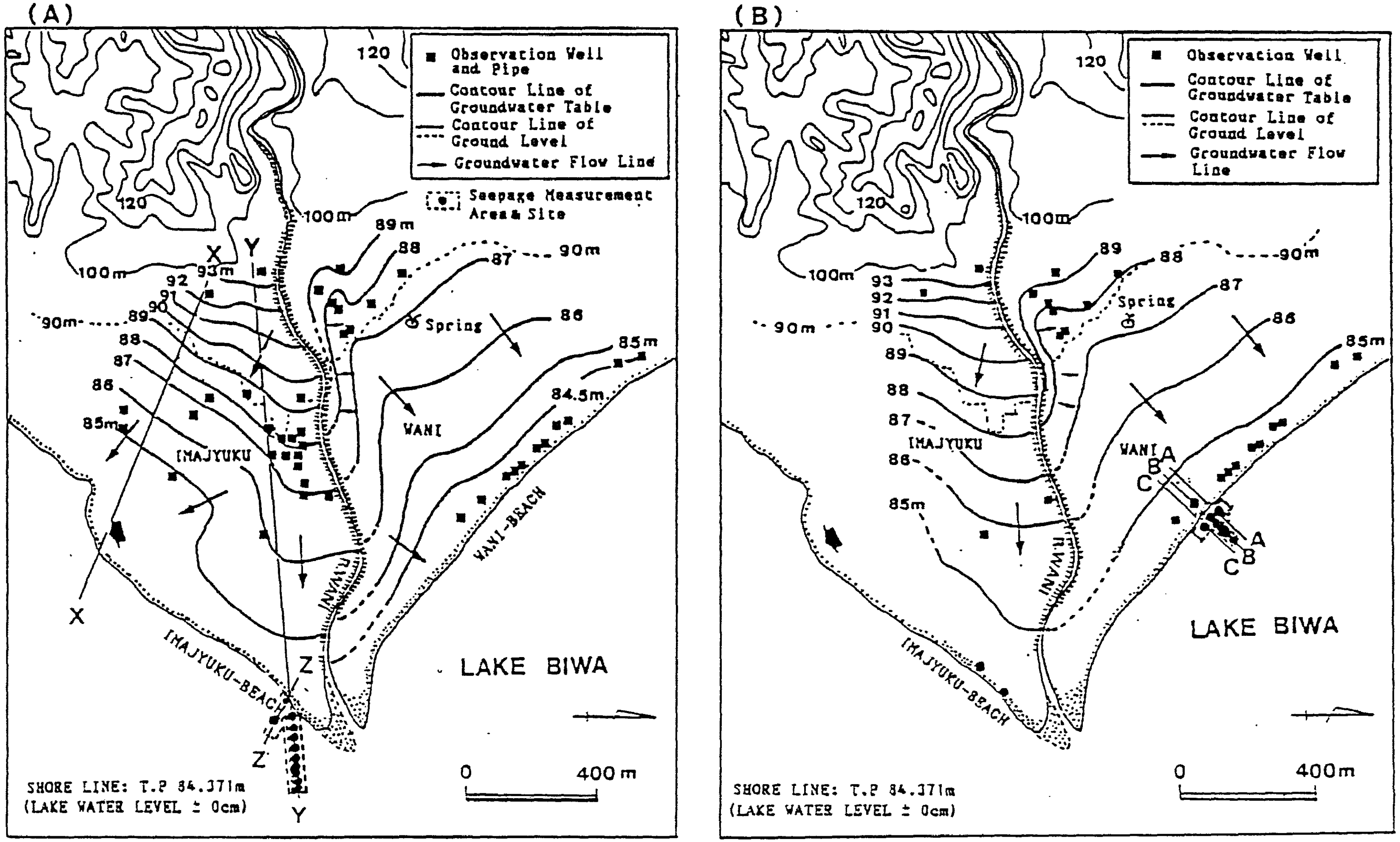


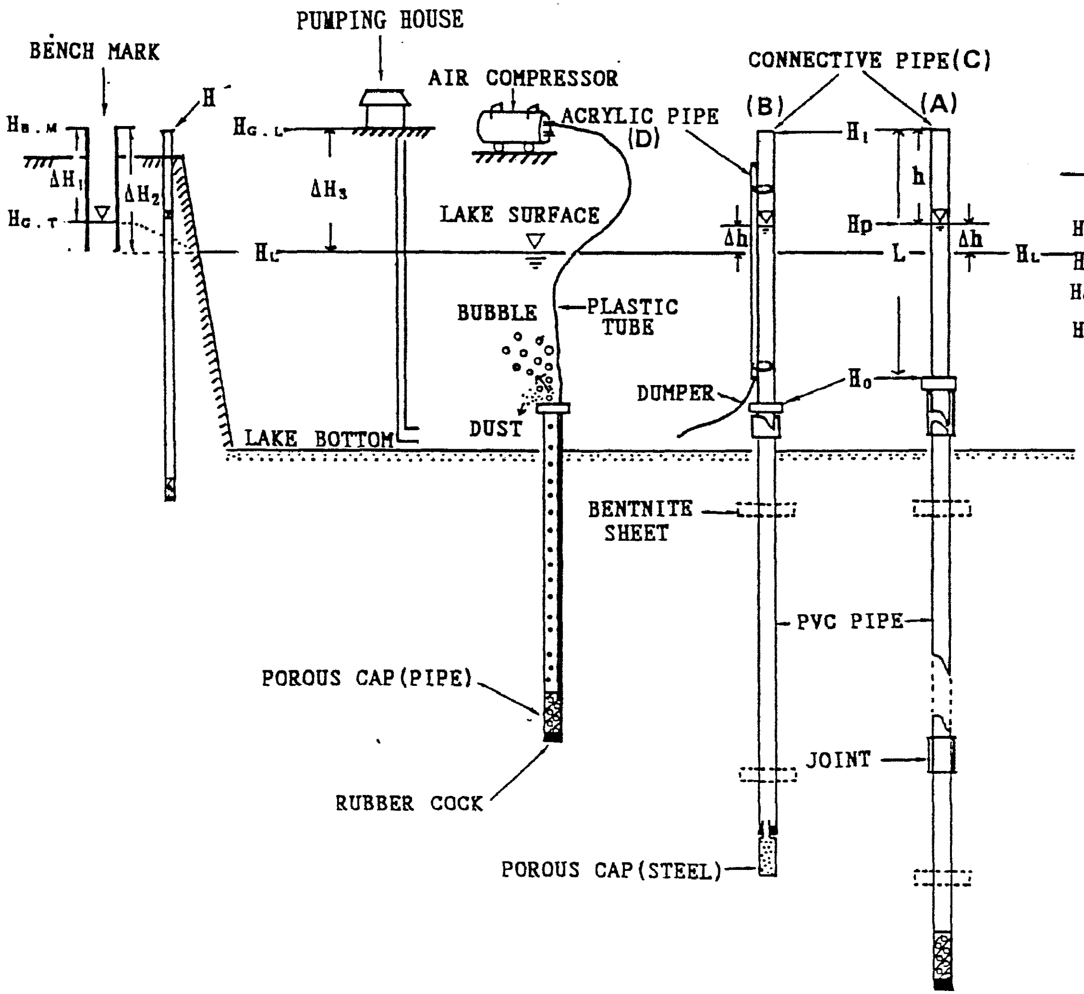
Figure 8. Contour maps of water table in the area of the Wani river delta and the seepage measurement sites along the transect offshore; (A) for 17 July 1991 and (B) for 30 October 1983(after Shiga Prefectural Government, 1983).

A schematic diagram of the two types of piezometer arrays used for the study is shown in Figure 9. One consists of PVC pipe of inside diameter ranging between 1.3 and 2cm with one end slotted. The slotted end was wrapped five times with nylon mesh to prevent excessive accumulation of silt and clay in the pipe(Fig. 9(D)). The other type which consists of 10cm length porous cap(steel) with rubber cock attached was pushed into the well point(Fig. 9(B)). Bentonite seals were attached to the two portions of each pipe. Using a handheld vibrating hammer or a Jack hammer, these instruments were installed in a similar manner as Lee and Cherry (1978)(Appendix Ⅳ. 1) The pipes were driven to the desired depth into the aquifer and left in place during the study period. Before measurements of hydraulic head and sampling of water, silty sand and organic matters in the pipes were removed by flushing the water using compressed air.

Nests of piezometers were installed near the shore along the transect line Y-Y, perpendicular to the shore, in the direction of decreasing hydraulic potential, and were installed around an observation well(Fig. 10 and Appendix Ⅲ. 2).

4-2-4. Hydraulic head measurement

At the beginning of the project, the differences in hydraulic heads relative to the lake water levels were measured using a manometer in the same manner as Lee and Cherry



LEGEND

$H_{B.M}$: ELEVATION SEA LEVEL(a.s.l) OF
H' : BENCH MARK
$H_{G.T}$: ELEVATION(a.s.l) OF GROUNDWATER TABLE
$H_{G.L}$: ELEVATION (a.s.l) OF PUMPING HOUSE
H_L : ELEVATION(a.s.l) OF LAKE SURFACE
H_I : ELEVATION(a.s.l) OF THE TOP OF THE PIPE
H_P : ELEVATION(a.s.l) OF PIEZOMETRIC HEAD
H_0 : ELEVATION OF THE TOP OF THE PIEZOMETER
L : LENGTH OF THE PIPE
h : LENGTH FROM THE TOP OF THE PIPE TO THE PIEZOMETRIC HEAD
Δh : HEAD DIFFERENCE BETWEEN PIEZOMETRIC HEAD AND LAKE SURFACE

$\Delta H_1 = H_{B.M} - H_{G.T}$

$\Delta H_2 = H_{B.M} - H_L$

$\Delta H_3 = H_{G.L} - H_L$

$H_P = H_I - h = (H_0+L) - h$ (m)

Figure 9. General feature and installations of piezometer for hydraulic head measurement.

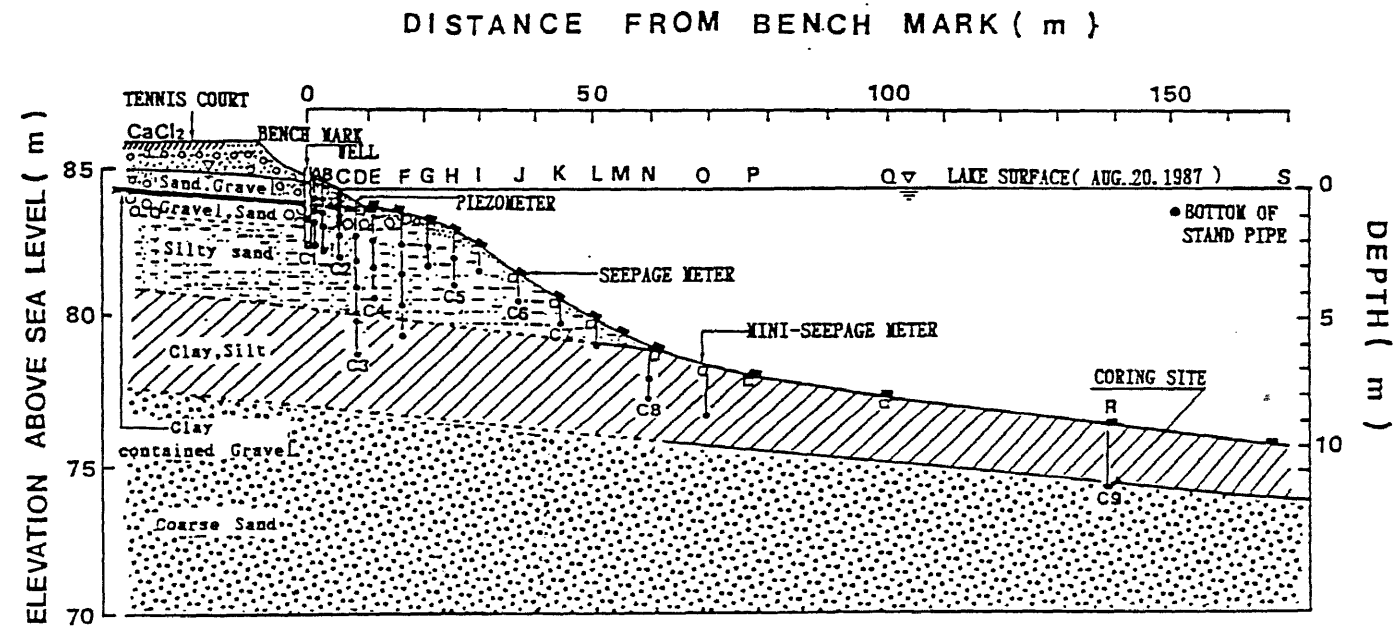


Figure 10. Locations of seepage meter, mini-seepage meter, piezometer and stand pipe for core sampling extending along the transect line Y-Y(Fig. 8A), and showing the geological and topographical cross section view.

(1987). However, it was very difficult to read the head difference, because the lake water level fluctuated continuously when there was a wave or a ripple. However, the following procedure was adopted to measure the hydraulic heads (Fig. 9):

(1) First, we leveled the top of each pipe in water [H_0] and a certain length of PVC pipe [L] connected to the top of each pipe, and the elevation above sea level of the hydraulic head [Hp] of each piezometer was measured by meter stick in mm unit.

(2) Second, the lake water level was measured using a narrow diameter electrical tape consisting of inside diameter of 1mm cable at the pumping house near the shore.

Therefore the head difference [Δh] could also be obtained (Appendix Ⅳ. 2). When the lake surface is calm, the degree of accuracy for this method is ± 1mm.

4-2-5. Mini-seepage meter and installation

Mini-seepage meters were constructed from bucket cover to avoid contamination of groundwater sample (seepage water) by the lake water (Fig. 4(B) and Appendix Ⅴ. 1). The device was successful in collecting groundwater discharging through the lake bottom. The meters were then installed at a depth of 20-30cm within the bottom sediments since the water at that depth is thought to represent the water quality of groundwater in the lakebed as described below(5-1-2). Three transects(C-C, D-D and F-F) were selected within an area of 60m by 20m parallel to the shore line and 35 mini-seepage meters were evenly spaced along each of the three transects (Fig. 11).

On the other, twenty four seepage meters and 14 mini-seepage meters were installed along the transect Y-Y. Each seepage meter was arranged the first 2-170m from the shore and in water at depth ranging about 0.2 to 10m(Fig. 10). All meters were left in place once installed throughout the study period. Near the shore(within about 15m distance from shore), seepage measurements were done once in a month from July 1987 to October 1988. However, data from all the seepage meters along the transect line Y-Y were collected only three times in October, 1987 and August, 1988. Data could not be obtained at sites where collection bag was ripped off or a small amount of water was collected, or meters were disturbed.

4-2-6. Sampling of groundwater in the lake for chemical analysis

Samples of seepage water for chemical analysis were collected one week after installation of the mini-seepage meters. Samples of groundwater were also collected after the piezometers were installed and 24 hours after the flushing process was completed. Before collecting water from the

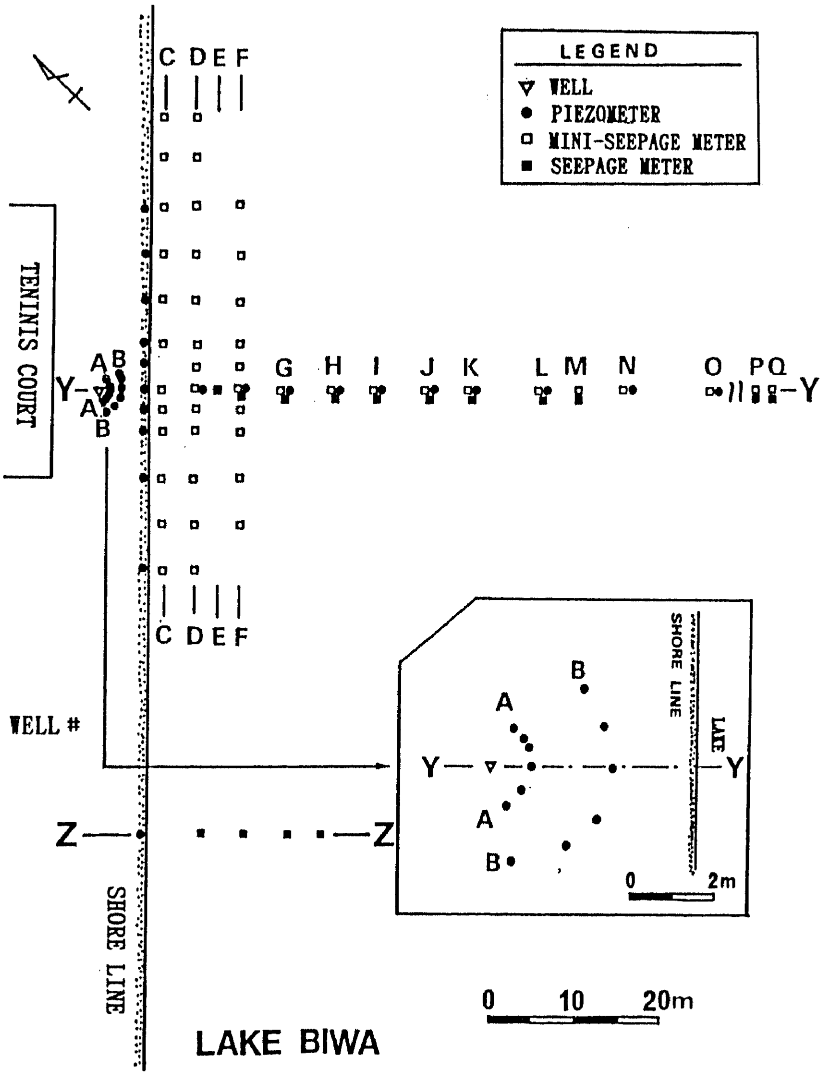


Figure 11. Installations of seepage meter, piezometer and a observation well at Imajyuku beach(Fig. 8) in plane view.

pipes, 250ml of water in the pipe was removed to collect the water sample from the desired depth of the aquifer.

The water sample was collected by applying gentle suction(Appendix V. 2) or directly using collectors with a gas stopcock (Fig. 4(C)). At the same time, samples of lake water were collected. Samples of groundwater were collected once a month from July to October, 1987 and from July, August 1988 and again in August, 1989.

All samples of water collected were analyzed in the same manner as described in the section (4-1-3).

CHAPTER 5

RESULTS AND DISCUSSION

5-1. Evaluation of the seepage meter technique

5-1-1. Effects of the collection device on seepage flux

As seen in Figure 12, the seepage amount was nearly constant inespective of the diameter of the tube (or stopcocks) at the site with low seepage flux (Sta. 33). However, it increased linearly with increasing inside diameter (I.D.) of the tube until the diameter of 8 to 10mm at Sta. 4 (medium seepage flux) and Sta. 5 (high seepage flux). It then remains constant inespective the diameter. The amounts of seepage obtained with a small diameter tube (4mm I.D.) at the medium and high seepage sites were about 30% and 50% lower than those with large diameter tubes, respectively.

This indicates that seepage fluxes calculated from the results obtained with small diameter tubes are extremely underestimated, particularly at the high seepage site. The lower seepage flux obtained from small diameter tube is probably due to resistance to flow through the tube into the bag.

Lee (1972) observed 30% lower flows with 0.32cm I.D. tube than with either 0.64 or 1.4cm I.D. tubes. Fellows and

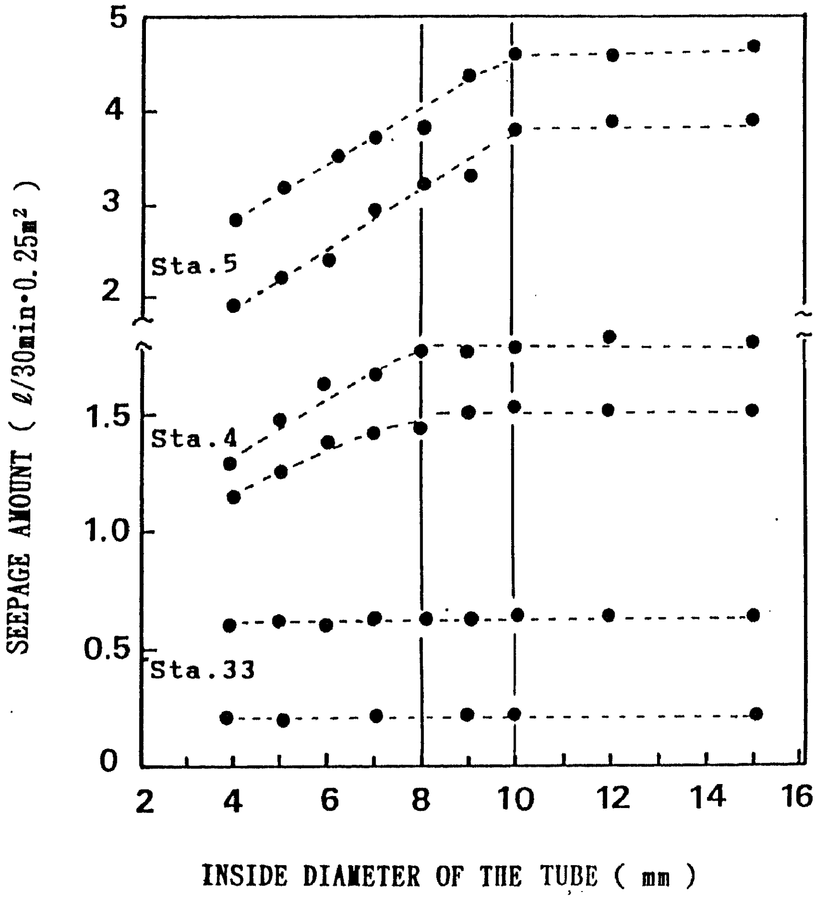


Figure 12. Effect of the inside diameter of the plastic tube on seepage amount at each meter site for Stas. 4, 5 and 33(Fig. 1).

Brezonik(1980) also showed that inaccuracy in seepage measurement is minimized by using 9mm I. D. plastic tube. Thus, it can be concluded that the inaccuracy of seepage measurements is minimized by using a large diameter tube of 10mm I.D.

On the other hand, the seepage flux obtained with initially empty bag was usually about 10~50% higher than that obtained with a bag prefilled with 200ml of water (Table 2). This seems to be caused by capillary action as a result of anomalous short-term influx of water as described above in the section(4-1-2). That is, it was usually observed that the volume of water collected by initially empty bag increased significantly within a short duration(5 ~ 10 minutes) after the start of measurement, particularly at the high seepage site (Sta. 5). However, it generally increased linearly with increasing time interval as seen in Figure 13.

As a results, the seepage flux calculated from data collected over a short duration is higher than that calculated over a half an hour or a longer time interval. For example, the seepage flux calculated over a 100 minutes was 54% of that calculated over a 10 minutes.

Shaw and Prepas(1989) suggested that the short-term influx of water into the bag may be due to the mechanical properties of the plastic bag and it may alleviate by partially filling bag with 1000ml of water before they are attached to

Table 2. Comparison of seepage flux collected by bags with initially empty and with prefilled with 200ml of water

Duration time (h)	Seepage flux ($\mu m \cdot s^{-1}$) Added volume of water (ml) 0	200	500
11 - 12	1.87	1.63	1.54
12 - 13	1.93	1.53	1.40
13 - 14	2.13	1.70	1.55
14 - 15	1.91	1.49	1.33
15 - 16	2.16	1.73	1.48
16 - 17	2.10	1.67	1.45
Average	2.02	1.63	1.46
S. D.	0.13	0.10	0.08
C. V.	0.06	0.06	0.06

Each of S. D. and C. V. shows standard deviation and coefficient of variation.

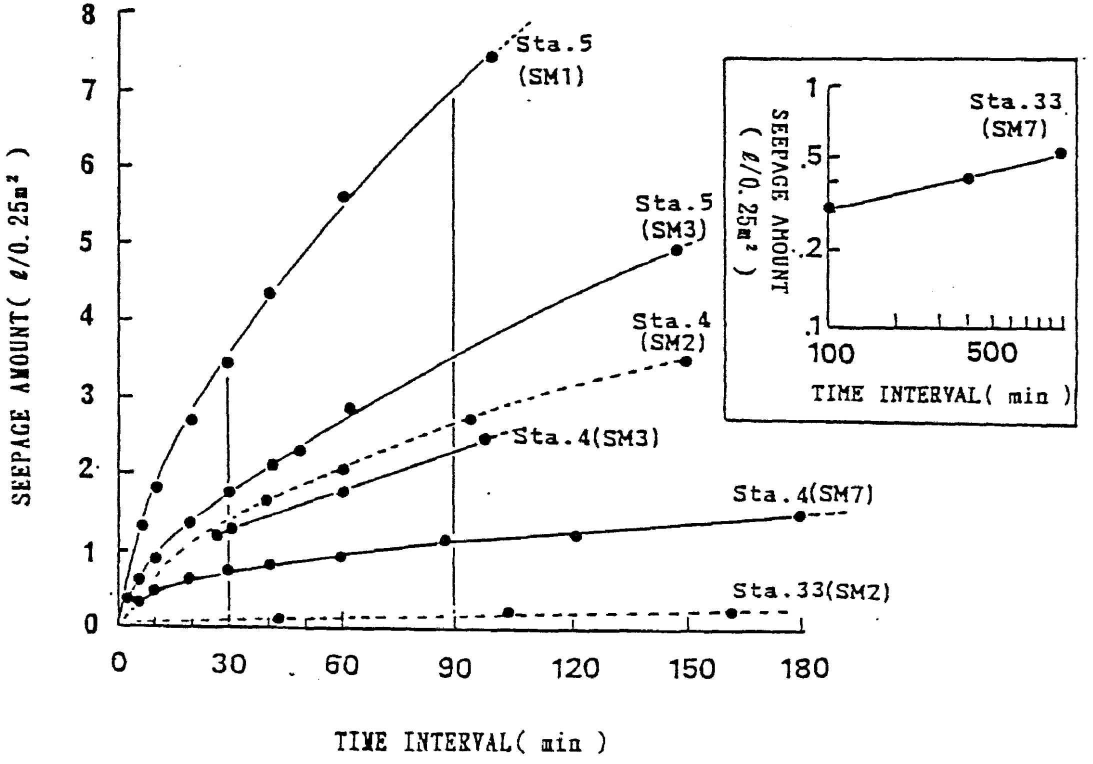


Figure 13. Relation between the amount of water collected by seepage meter and a time interval. Data obtained at three specific sites(Stas. 4, 5 and 33) in 1984.

seepage meter. However, it may be difficult to alleviate the mechanical properties of the plastic bag and there were insignificant differences in seepage flux between the bags prefilled with 200ml of water and that with 500ml (Table 2). Thus we employed the bag prefilled with 200ml of water before they are attached to the seepage meters during the field observations.

For the reproducibility of the seepage results, a small change in seepage flux can be seen in a day time. However, relatively good reproducibility was obtained as shown in Table 3. Fukuo (1992) reported that a higher seepage amount is often obtained at the time of rough surface blown by wind. In this study, however, all measurements were carried out as much as possible under calm surface condition. Thus the variability of seepage flux in the day time may be small with the coefficient of variation of seepage flux lower than 0.1 ~ 0.2.

5-1-2. Water quality of samples collected by seepage meter

As shown in Figure 14, the vertical profiles of E. C. and the concentrations of major constituents of the groundwaters in the lake were generally linear with depth in the layer from 2.5m to 20-30 cm below the bottom. Then, E. C. (or concentration) decreased in the sediments just lying below the sediment-water interface. Such exponential convex-up profiles in the layer close to the surface of the bottom

Table 3. Precision measurements and the variation of seepage flux in a day time.

Duration time (h)	Seepage flux ($\mu m \cdot s^{-1}$) Seepage meter number SM1	SM2	SM3	SM4
10 - 11	5.47	5.56	3.10	2.74
11 - 12	4.98	5.10	3.32	2.95
12 - 13	5.97	6.10	3.21	2.92
13 - 14	5.90	5.67	3.76	3.43
14 - 15	5.56	5.53	3.65	2.99
15 - 16	4.67	4.25	3.82	3.04
16 - 17	4.24	4.40	3.87	3.15
17 - 18	4.19	4.14	3.81	2.88
18 - 19	-	-	3.70	3.04
19 - 20	-	-	3.68	3.10
20 - 21	-	-	3.80	2.99
Average	5.12	5.09	3.61	3.02
S. D.	0.71	0.74	0.16	0.27
C. V.	0.14	0.12	0.06	0.07

Each of S. D. and C. V. shows standard deviation and coefficient of variation.

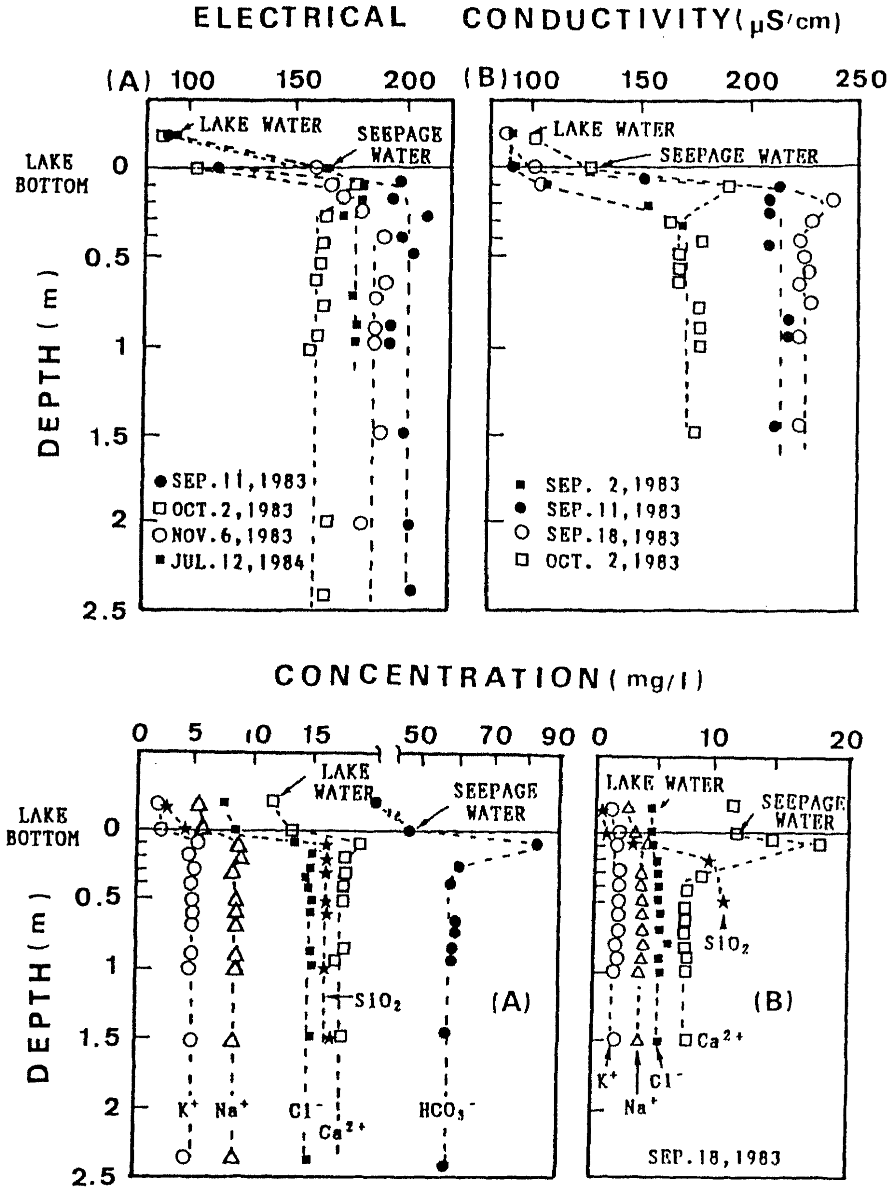


Figure 14. Electrical conductivity and concentrations of some major constituents in the water collected by seepage meter and a lake water and its vertical profiles of the groundwater in the lake at Sta. 4(Fig. 1). (A) and (B) situated at 10m and 36m distance from shore,

may be due to the mixing of the lake water or biochemical reactions in that layer. The E. C. of seepage water was clearly higher than that of lake water. However, it was 20-60% (average 26%) lower than that of the groundwater in the layer 0.3-2.5m below the lake bottom. Although the concentrations of K^+, Na^+ and Cl^- of seepage water were comparatively similar to those of the groundwater offshore (Fig. 14B), these results indicate that water collected by seepage meter at a relatively low seepage site is assumed to be equivalent to the groundwater just lying below sediment-water interface but not to groundwater flowing through the aquifer at the bottom of the lake.

On the other hand, the vertical profiles of E. C. of groundwater at the site of high seepage (Sta. 5) were linear with depth in the layer from the depth of 5m to the surface of the bottom (Fig. 15). The E. C. (or concentrations) of water samples showed following relationships: lake water ≧ seepage water ≧ groundwater. However, there are insignificant differences in E. C. (or concentration) of each type of waters. The results indicate that the quality of seepage water is not affected by sediment-water reactions but by vertical diffusional mixing of the lake water. Thus, water collected by seepage meter is assumed to be equivalent to that of groundwater flowing through the aquifer at the bottom of the lake at the site with high seepage.

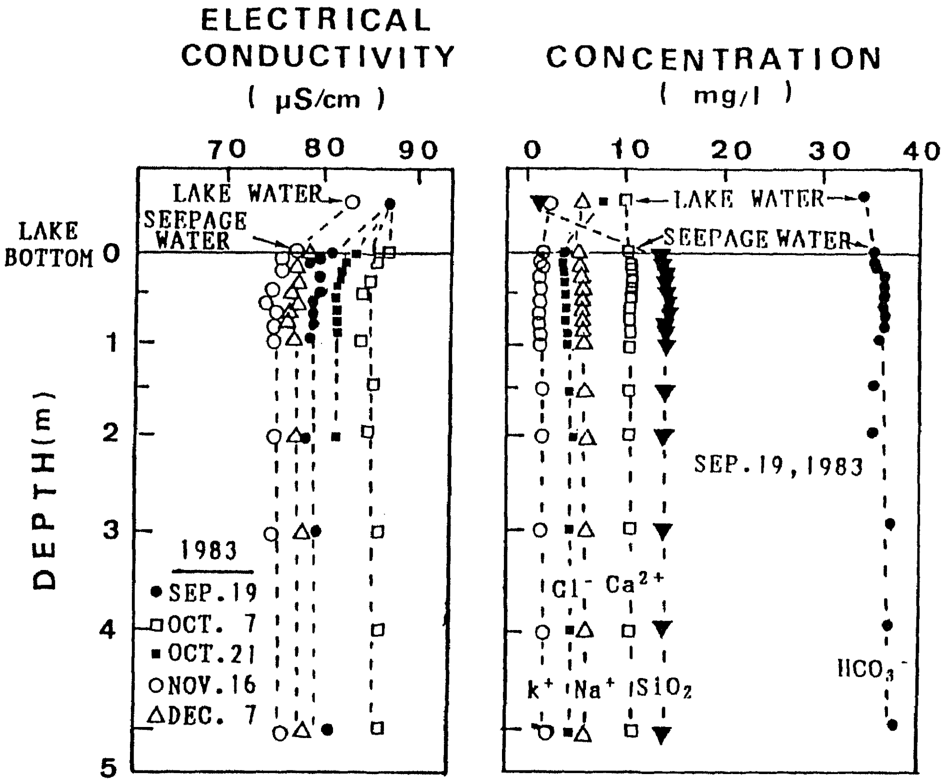


Figure 15. Electrical conductivity and concentrations of some major constituents in the water collected by seepage meter and lake water and its vertical profiles of the groundwater in the lake at Sta. 5 (Fig. 1).

5-2. Groundwater flow into the lake

5-2-1. Stratigraphical condition

Figure 9, as shown in the section(4-2-3), is drawn by the core data(Fig. 16) from 8 points along the transect line Y-Y and by established hydrogeoligical data. Coarse sand is the major constituent of the deepest part of the bed at the lakebed. The coarse sand is overlain by clay and silt layer which is about 2m thick and that renders the aquifer confin-silty sand, except for the upper thin clay layer(about 15cm thick). However, some gravels were found in the upper part of this layer. Near the shore line, gravel, pebble and cobble were found. The bottom sediments offshore consist of mud(10-20cm thick) and is underlain by clay and silt layer.

5-2-2. Groundwater flow process determined by groundwater potentials in the aquifer in the lake

Equipotential lines drawn by the distribution of hydraulic heads in the aquifer and the inferred flow lines are shown in Figure 17. As the hydraulic head of the shallow groundwater on the shore is usually higher than that in the aquifer in the lake, the shallow groundwater evidently seeps into the lake through the lake bottom. The distribution of equipotential lines in the upper zone nearshore and that in the lower zone above the impermeable layer are generally vertical. However, the equipotential lines in the middle

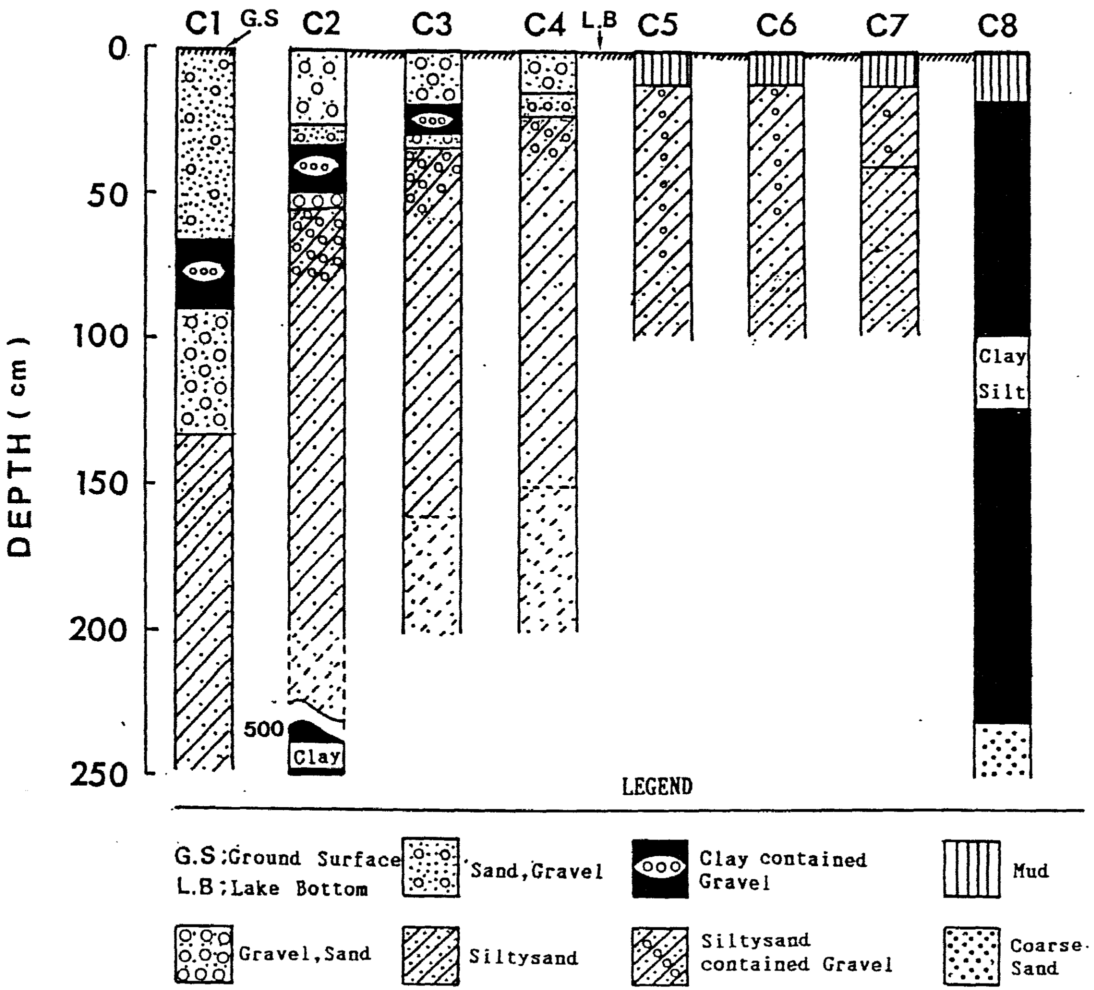


Figure 16. Geological colums of the lake bottom sediments. Coring sites are shown in Figure 9.

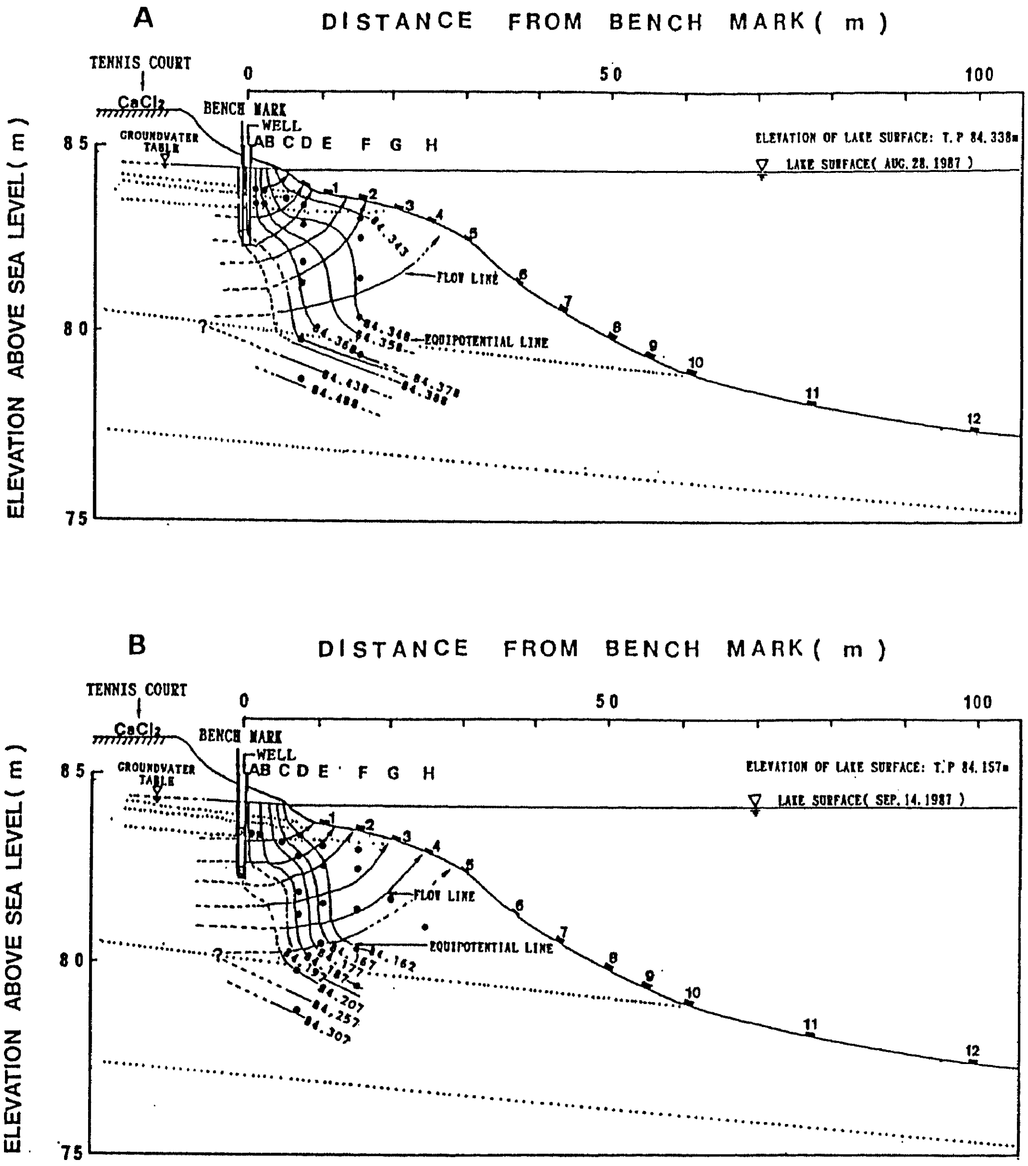


Figure 17. Equipotential lines of hydraulic head along the transect line Y-Y(Fig. 8A); A for 28 August and B for 14 September 1987, respectively. Arrows show inferred flow lines.

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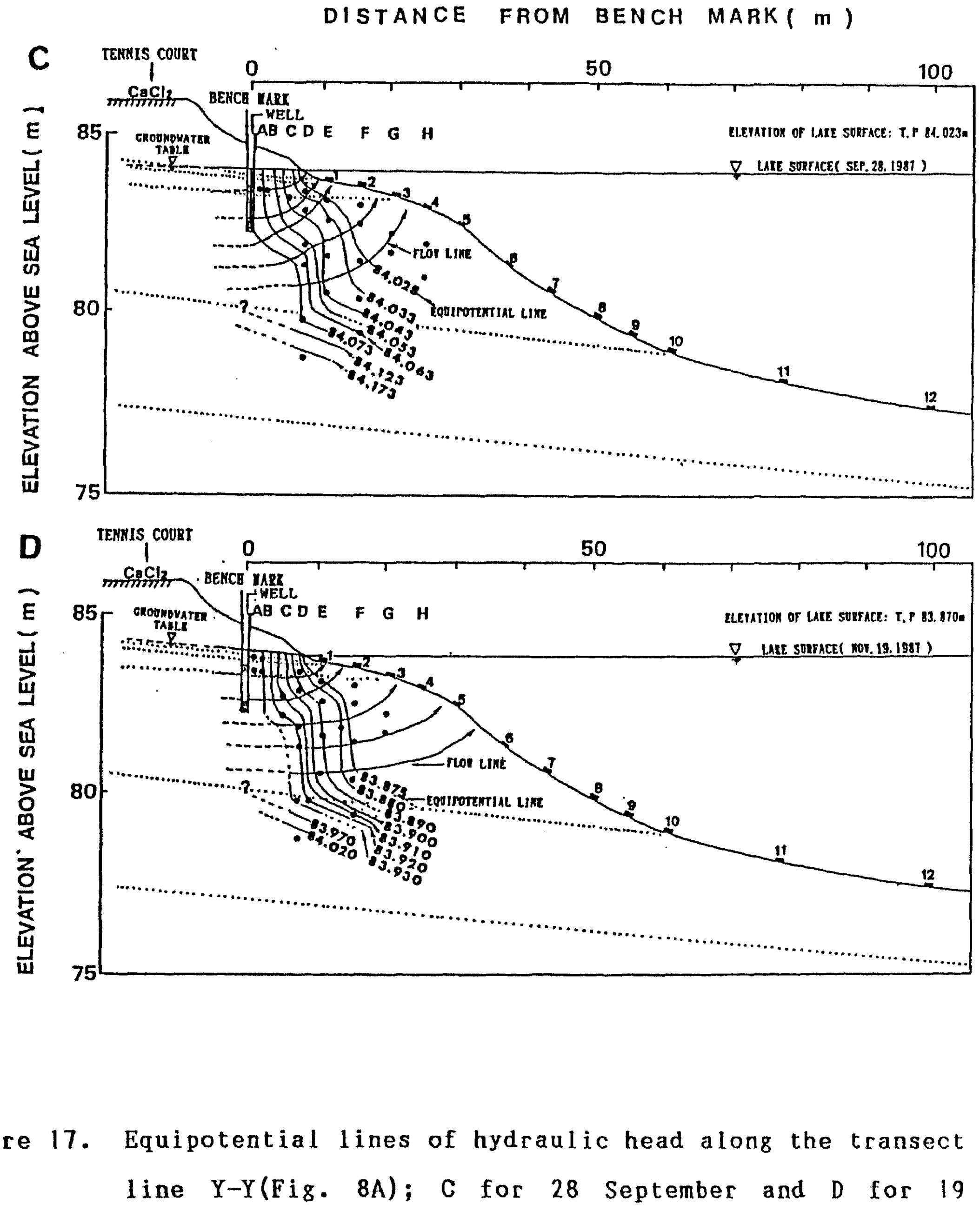

Figure 17. Equipotential lines of hydraulic head along the transect line Y-Y(Fig. 8A); C for 28 September and D for 19 November 1987, respectively. Arrows show inferred flow lines.

zone of the unconfined aquifer in the lake concaved upward and the flow lines are concentrated near the shore within about 20m from the shore line.

The results of these measurements are nearly identical and were quite similar to those obtained at different dates (Fig. 17(C), (D)).

5-2-3. Groundwater flow process determined by tracer by pollutants

The distributions of the quality of seepage water are presented in Figures 18 and 19. The maps of isolines for Cl^- concentrations illustrated in Figure 19 as enclosed by a quadrilateral are the shallow groundwater data sampled from piezometers at the depth of 0.6m nearshore.

Seepage water near the shore were mostly Ca-Cl or Ca-HCO_3-Cl types and had higher concentrations within the zone about 15m distance from the shore line. The contaminated zone, which had higher Cl^- concentrations, extended also approximately to about 60m in length along the shore line (Fig. 19B). However, Cl^- concentrations decreased to background level($10 mg \cdot l^{-1}$) farther offshore from about 20m distance during the study period. The distribution pattern of Cl^- concentrations of the shallow groundwater near the shore for July(Fig. 19A) is different from that in August (Fig. 19 B). There are water masses, having high Cl^- concentrations at each position(close to the well and the shoreline) of

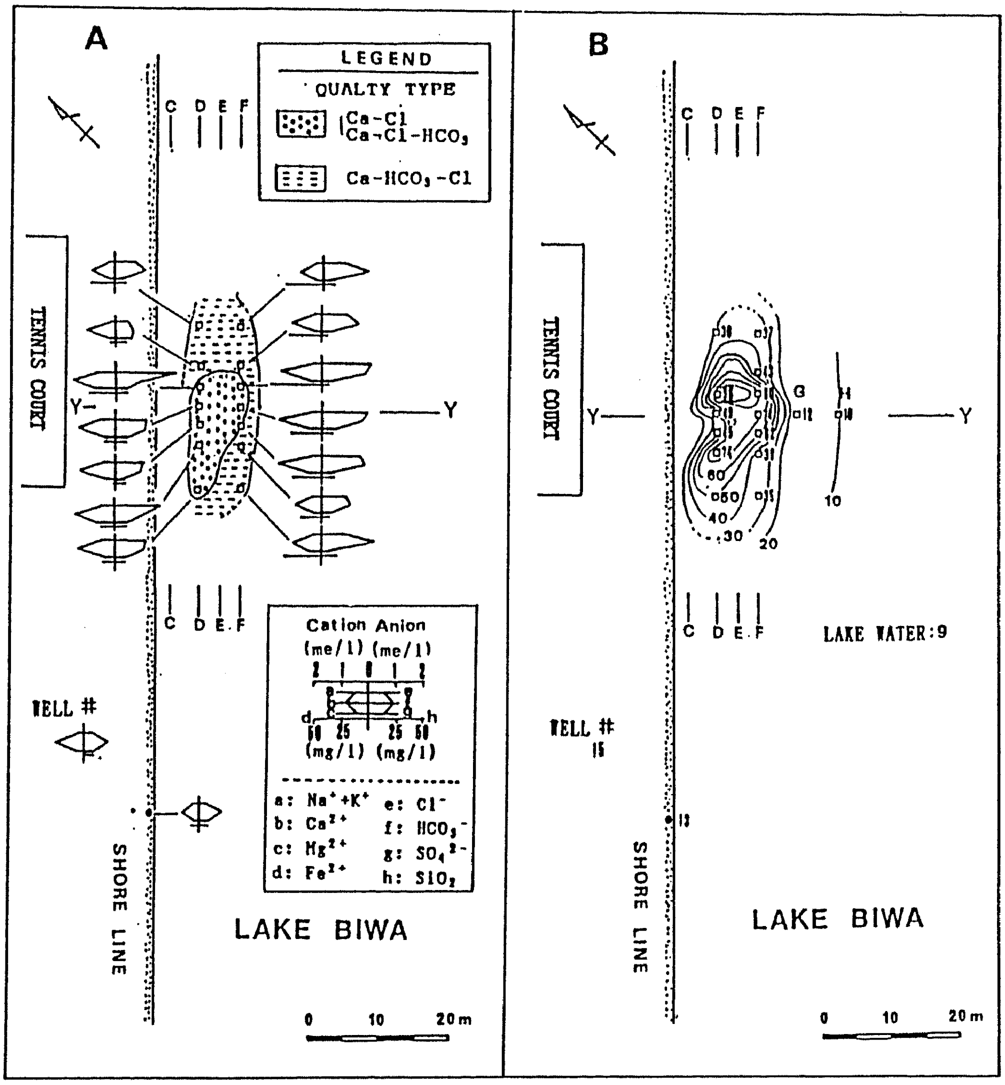

Figure 18. Distributions of the quality of seepage waters collected by mini-seepage meter for 30 October 1987: A is plotted as Stiff diagram; B and C show the isolines for Cl^- concentration($mg \cdot l^{-1}$).

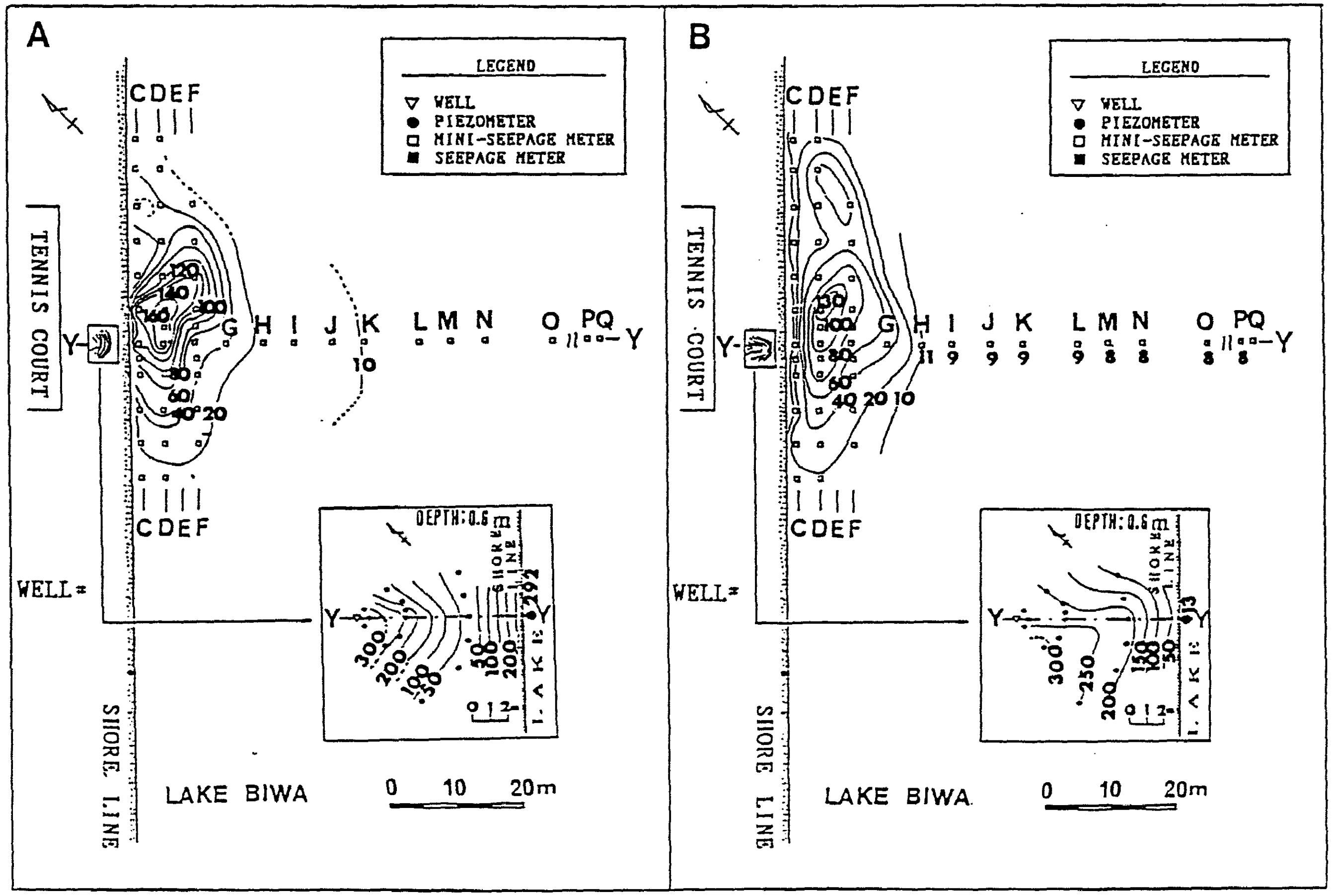

Figure 19. Isolines for Cl^- concentration($mg \cdot l^{-1}$) of seepage water; A for 15 July and B for 5 August 1989. Maps enclosed by a regular tetragon in each figure show iso-lines for Cl^- concentration of the groundwater at a depth of 0.6m near the observation well. Each map is drawn at a magnified scale.

July and the enclave of contour lines extend to the direction parallel to the shoreline. However, the water mass close to the shoreline disappears and the enclave of contour lines are projected to the west-east direction.

This could be explained that the shallow groundwater seeps out in the lake during from July to August, although the direction of groundwater flow changes.

Each pattern of the distributions of Cl^- concentrations in the shallow groundwater is consistent with that of seepage water collected by mini-seepage meter. Seepage water close to the shoreline in July have much higher levels of Cl^- than that in August and the degree of expansion of isolines for Cl^- concentrations in July are smaller than that of August.

These results show clearly that the shallow groundwater, with high $CaCl_2$ concentrations, moves toward the lake and seeps out in a narrow zone nearshore. As to the low concentrations of seepage water close to shore, it may be due to a mixing or a diffusion of lake water downward into the bottom sediments. Because near shore areas have been usually affected by a wave motion or seiche and the lake water infiltrate through the sediments nearshore, then the groundwater may be mixed with lake water.

Figure 20 shows the distributions of quality of the groundwater in the lake, which are plotted against depth

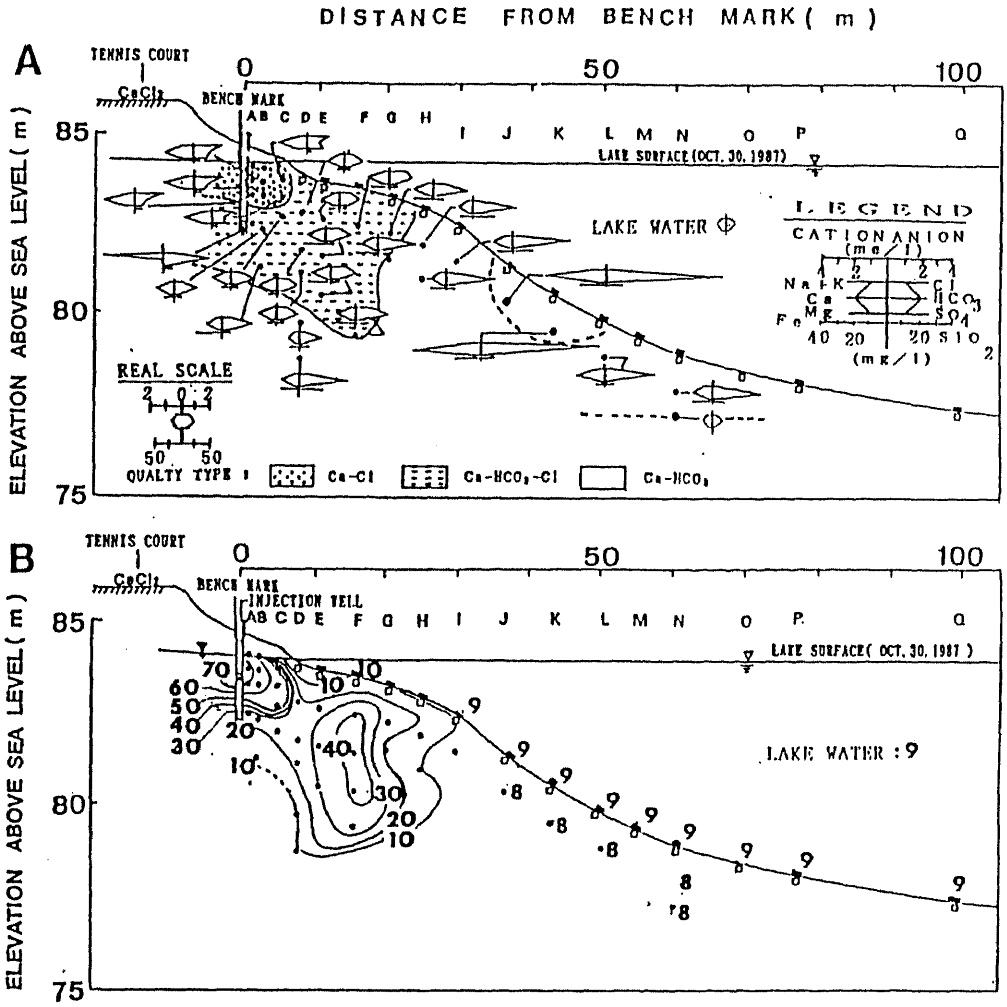

Figure 20. Distributions of the quality of the groundwater in the lake along the transect line Y-Y for 30 October 1987; A is plotted as Stiff diagram and B shows the isolines for Cl^- concentration($mg \cdot l^{-1}$).

below the lake bottom and beneath the water table. Waters with Ca-Cl or Ca-HCO_3-Cl types occur up to about 3m below the lake bottom and to about 15m distance from the shoreline. However, in the layer down to over the depth of 3m below the lake bottom and off to 15m distance from the shoreline, water quality type is mostly Ca-HCO_3, with low Cl^- concentrations, although there are locations having high Ca^{2+} and HCO_3^- concentrations (Fig. 20A).

The vertical profiles of Cl^- concentrations are also very similar to those of the water quality types (Fig. 20B). Thus the groundwater near the shore, up to 3-4m below the lake bottom are apparently the contaminated shallow groundwater. While, isolines for Cl^- concentrations over 20mg•l^{-1} veer vertically upward on the shore line near the inflection point of the lakebed. The distribution patterns of isoline for Cl^- concentrations were quite similar to those obtained at different dates (Fig. 21 A~D). The results of this study also agree well with field measurements done by Frape and Patterson(1981) on the chemical compositions of the groundwater.

These results indicate that the groundwater from the shallow aquifer moves horizontally toward the lake near the shore and then the flow veers upward having an arcuate shape nearshore, and seeps out within about 20m distance from the shore. The groundwater from the deeper aquifer also enters

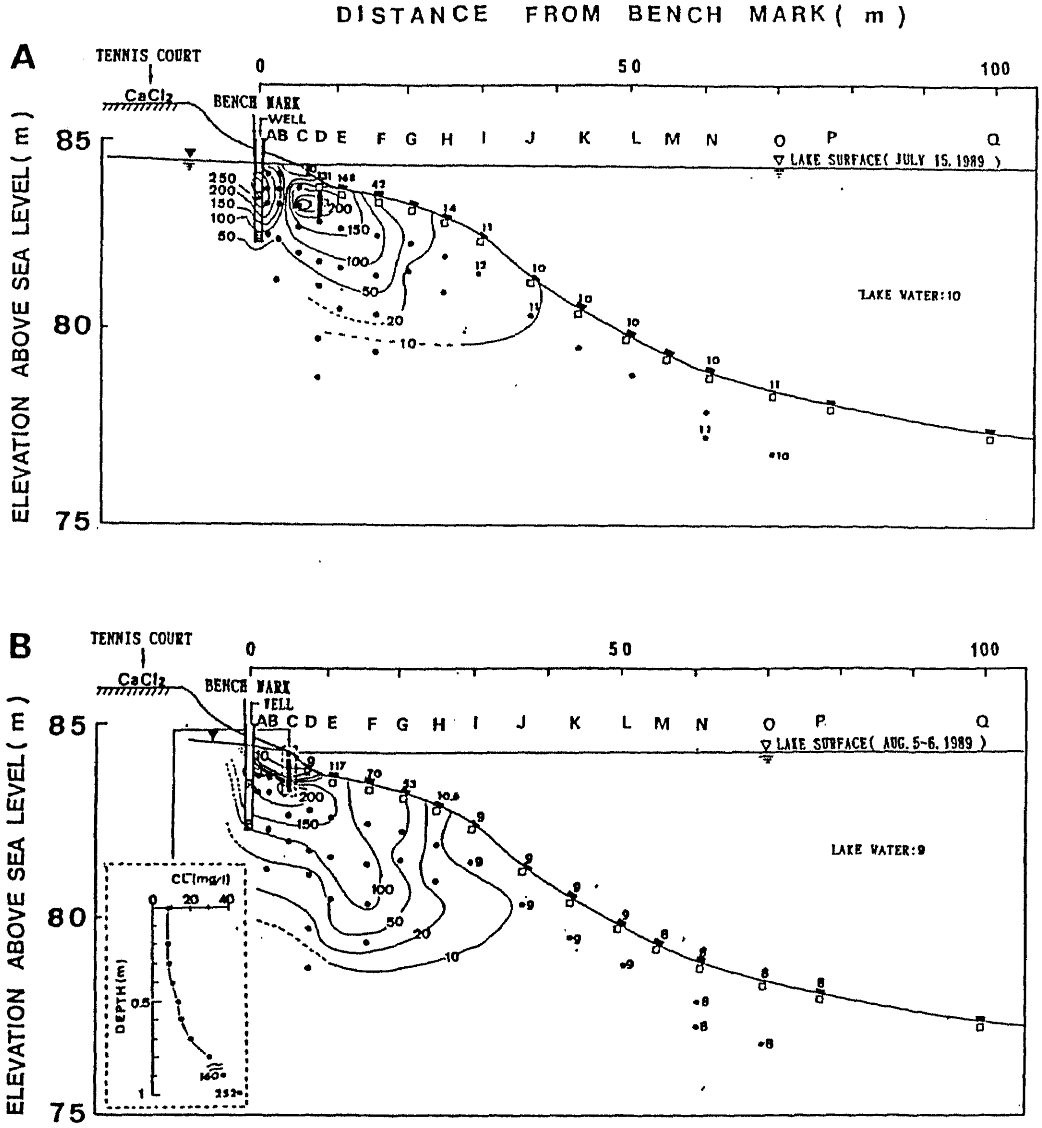

Figure 21. Isolines for Cl^- concentration($mg \cdot l^{-1}$) of the groundwater in the lake along the transect line Y-Y; A for July 15 1989 and B for August 5 1989, respectively.

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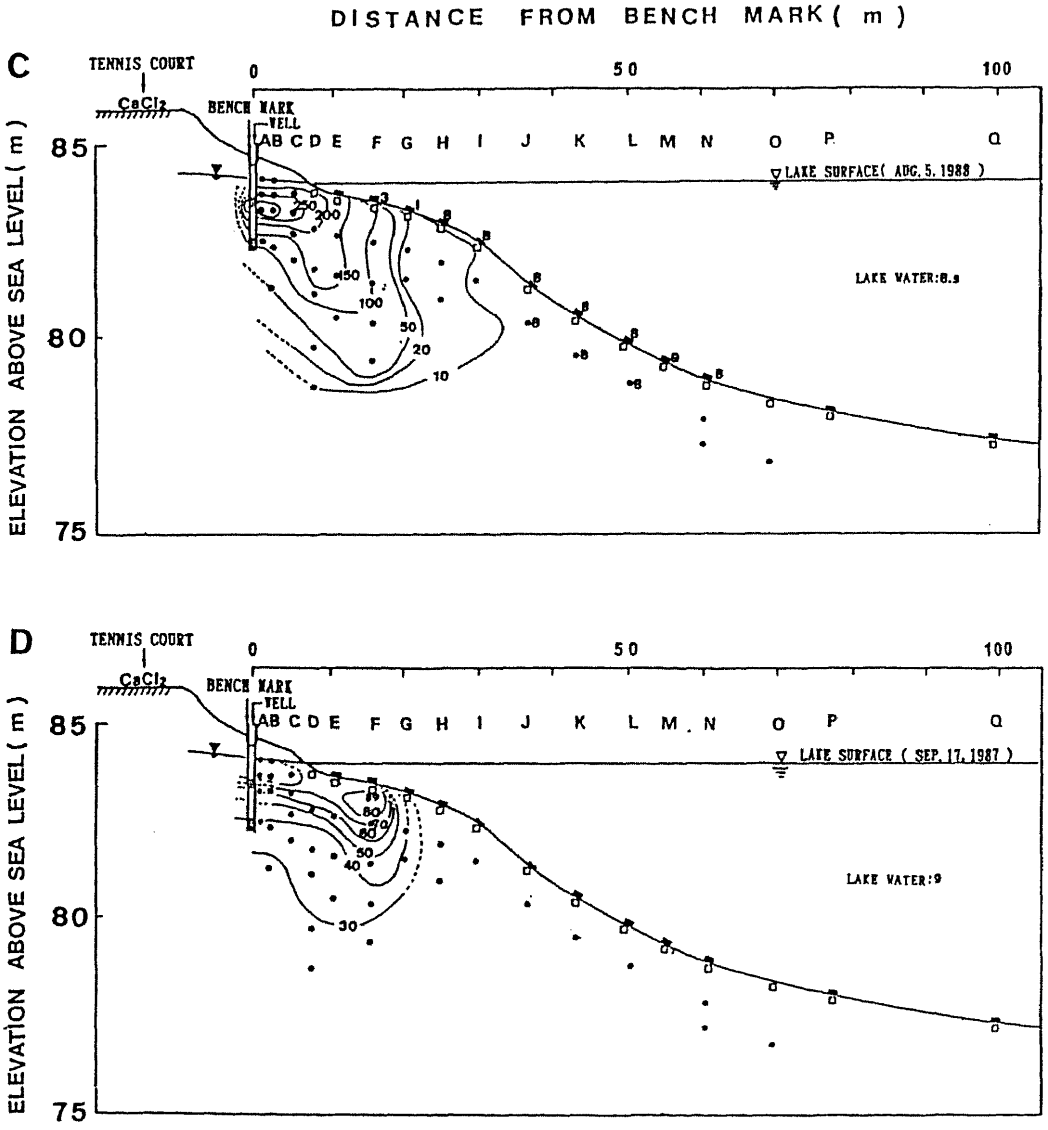


Figure 21. Isolines for Cl^- concentration($mg \cdot l^{-1}$) of the groundwater in the lake along the transect line Y-Y; C for August 5 1988 and D for 17 September1987, respectively.

the lake farther off from the shore. The distributions of Cl^- concentrations in the groundwater in the study area reveals clearly groundwater flow near the shore and a pattern of seepage.

5-2-4. Groundwater flow process estimated by seepage patterns

Seepage flux along the transect line Y-Y was higher near the shore and decreased rapidly with increasing distance within about 20~50m from the shore(Fig. 22). However, seepage fluxes remain constant on the bottom of the low permeable layer offshore to more than 60m(Fig. 9). Also, the seepage patterns did not show seasonal change on the whole.

These results suggest that the seepage flow lines are concentrated near the shore and the confined groundwater seeps out through the clayey silt layer offshore.

In summary, the distributions of groundwater potential were in agreement with those of the water quality and seepage flux measured with the seepage meter technique. Furthermore, the confined deeper groundwater discharges into the lake through a thin low permeable layer offshore. It is expected that the shallow groundwater in this area discharges into the lake showing the pattern as shown in Figure 23.

In Lake Biwa, similar seepage patterns have been observed as described in the section(5-3-3). At the western shore of the lake, the geological configuration, topography of the

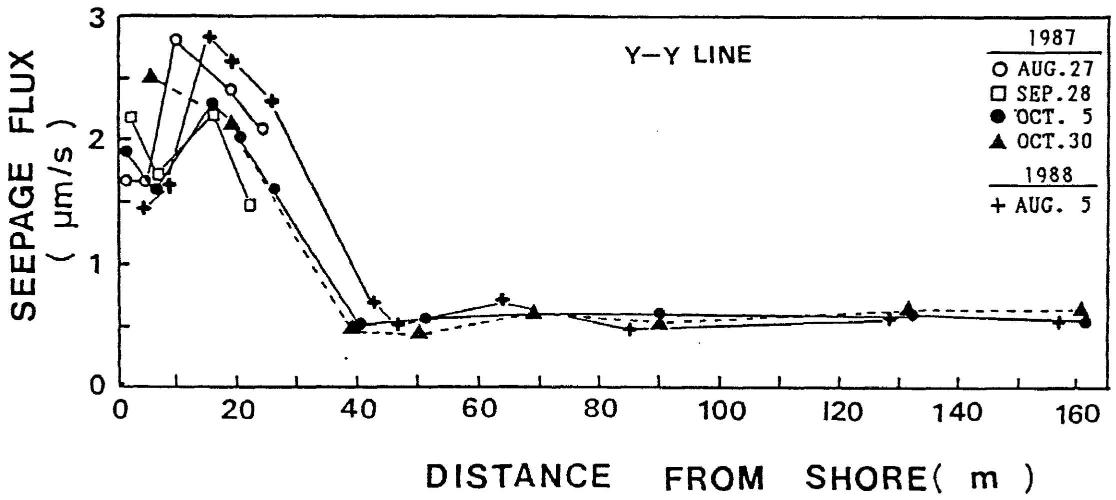


Figure 22. Seepage patterns along the transect line Y-Y at Sta. W3 (Figs. 1 and 8(A)).

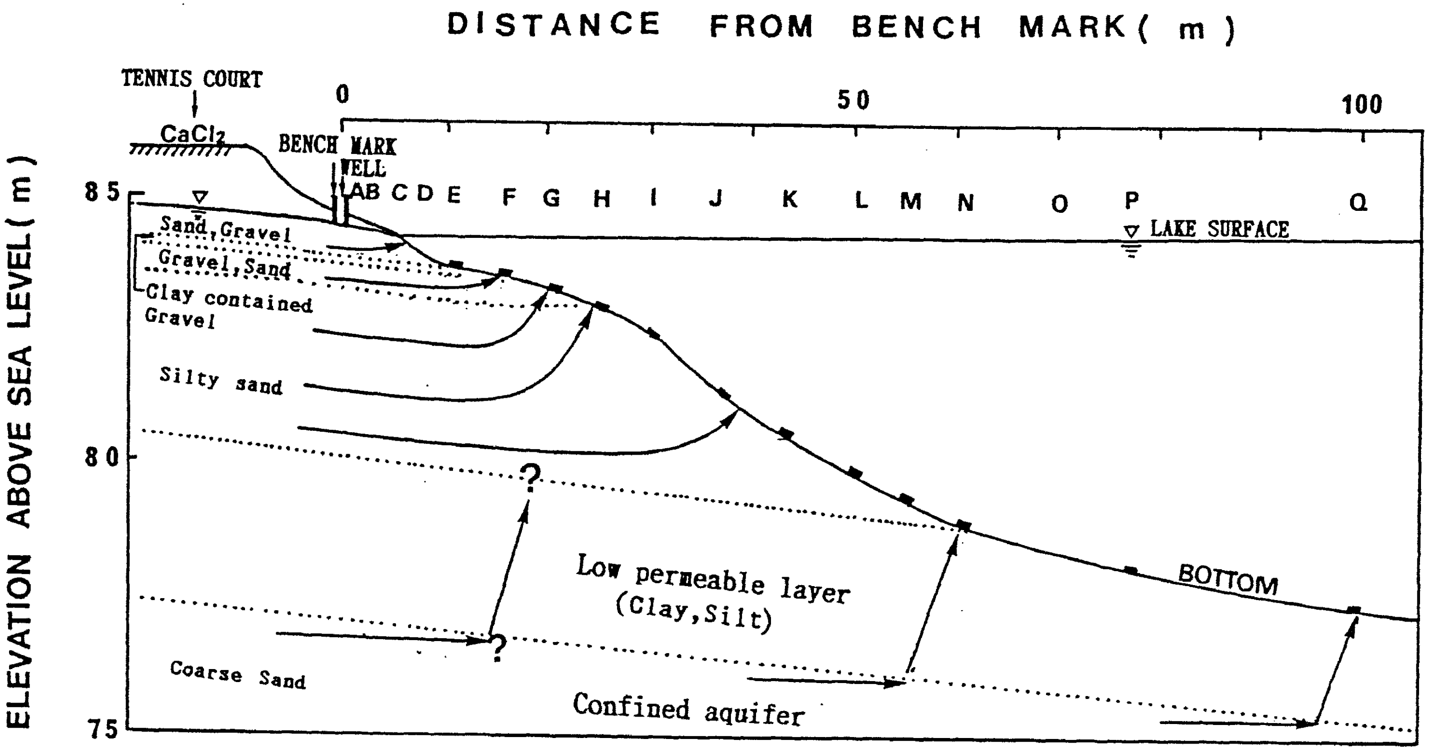


Figure 23. Schematic groundwater flow in the aquifer in the lake at the western shore of Lake Biwa (Wani river delta region). Arrows show inferred flow lines.

lakebed and the bottom sediments are generally similar. It is expected that the shallow groundwater in this region seeps into the lake within a narrow zone near the shore. In general, nearshore seepage zone is the area of more intense and effective pollutant transport when groundwater is contaminated. A number of nearshore samplings of seepage water or groundwater in the lake is necessary to evaluate a pollutant loading to the lake by groundwater seepage.

5-3. Results of seepage measurements

5-3-1. Spatial variation of seepage flux around the lake

The results of seepage flux obtained from a single undisturbed meter around the shoreline of the lake during from 1984 to 1985 are presented in Figure 24. It is obtained that seepage flux varied significantly from site to site, particularly around the western shore of the lake. Along the western and northern shores of the lake, seepage flux varied from as low as $0.04 \mu m \cdot s^{-1}$ to $4.85 \mu m \cdot s^{-1}$ (Tables 4-6). The spatial variation of seepage flux was relatively low around the eastern shore of the lake and the Southern Lake. The average seepage flux varied from $0.07 \mu m \cdot s^{-1}$ to $3.15 \mu m \cdot s^{-1}$ at the eastern shore and from $0.01 \mu m \cdot s^{-1}$ to $0.80 \mu m \cdot s^{-1}$ at the Southern Lake (Tables 4-6).

These significant spatial variation may be due to both the differences of hydraulic conductivity in the bottom

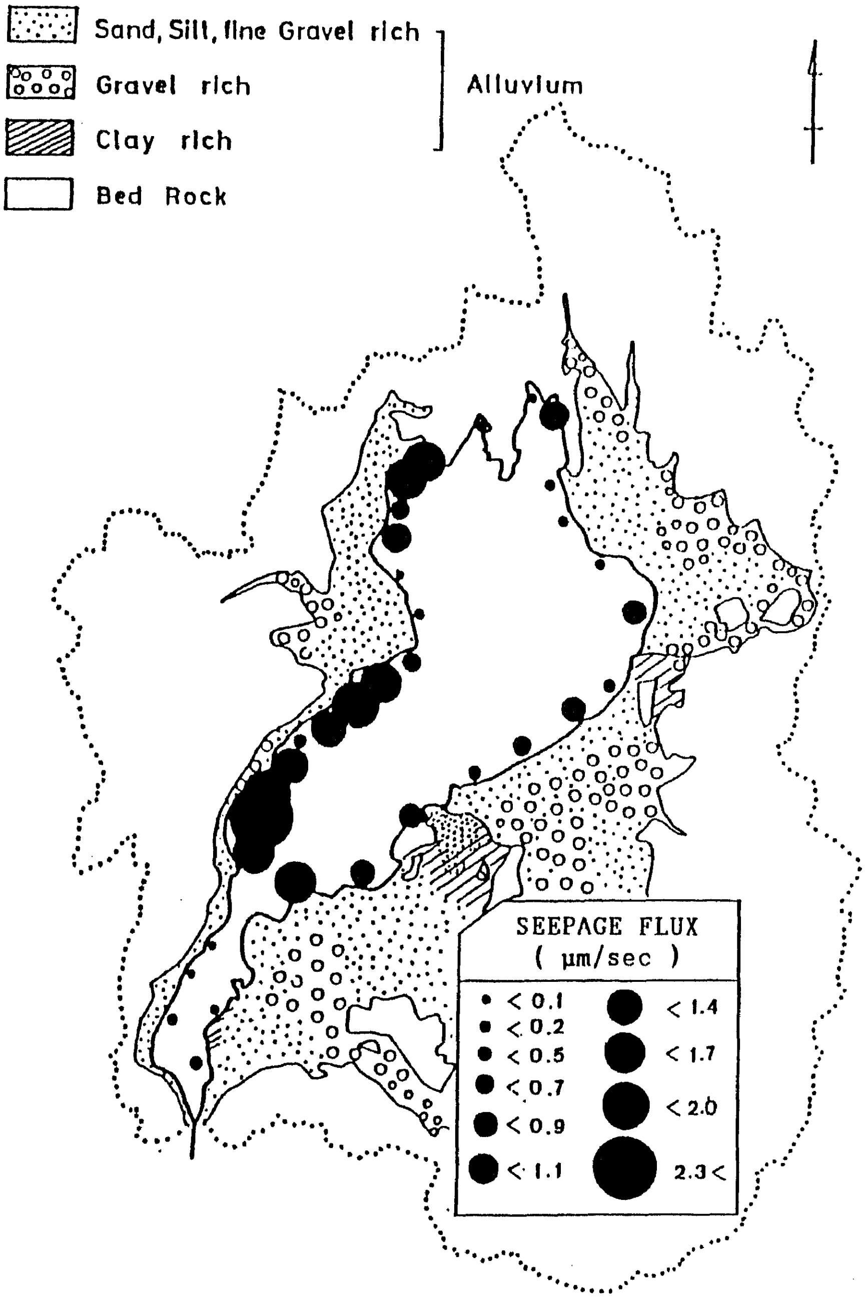


Figure 24. Spatial distribution of an average seepage flux around the lake in 1984.

Table 4. Sediment type, slope of lakebed and seepage flux at a single meter site around the lake.

Region	Station number	Sediment type	Slope of lakebed	Seepage flux($\mu m \cdot s^{-1}$) Average	Seepage flux($\mu m \cdot s^{-1}$) Maximum	Seepage flux($\mu m \cdot s^{-1}$) Minimum	NM*
Southern Lake	1	S & G	1/20	0.05	0.13	0.02	4
	2	sS	1/21	0.01	0.08	<0.01	4
	3	fS & G	1/30	0.02	0.05	0.01	4
Northern Lake Western shore	4(SM1)	G	1/ 8	1.24	2.49	0.24	22
	(SM2)	G	1/ 8	0.67	2.12	0.10	32
	(SM3)	G	1/ 8	0.60	1.87	0.07	20
	(SM4)	fS	1/30	0.45	0.78	0.12	5
	(SM5)	fS	1/30	0.50	1.37	0.09	21
	(SM6)	fS	1/30	0.55	0.87	0.18	9
	5	G & S	1/ 7	3.12	5.29	0.66	9
	6	G & S	1/10	1.33	1.55	0.92	4
	7	G & S	1/ 9	1.30	1.29	0.96	3
	8	G & S	1/ 9	0.44	0.85	0.19	4
	9	mS	1/14	0.53	0.78	0.19	4
	10	cS	1/ 9	0.82	1.26	0.41	4
	11	fS	1/33	0.53	0.89	0.12	4
	12	mS & fS	1/33	0.17	0.27	0.06	4
	13	mS & fS	1/38	0.10	0.32	0.08	4
	14	cS & mS	1/36	0.04	0.04	0.03	4
	15	S & G	1/11	0.53	0.67	0.14	4
	16	S & G	1/20	0.76	1.03	0.20	4

Each of S, G, P, sS, fS, mS, cS and C indicates sand, gravel pebble, silty sand, fine sand, medium sand coarse sand and clay, respectively. NM* is number of measurements.

(Continued)

Table 4. Sediment type, slope of lakebed and seepage flux at a single meter site around the lake.

Region		Station number	Sediment type	Slope of lakebed	Seepage flux($\mu m \cdot s^{-1}$)			NM*
					Average	Maximum	Minimum	
Northern Lake	Northern part	17	S & G	1/ 5	0.93	1.30	0.35	4
		18	mS	1/ 6	0.74	0.92	0.23	4
		19	mS	1/11	0.18	0.24	0.06	3
		20	S & G	1/25	0.13	0.33	0.07	4
		21	P & G	1/ 8	1.35	2.30	0.40	4
	Eastern shore	22	sS	1/63	0.15	0.33	0.07	4
		23	mS	1/23	0.20	0.27	0.15	4
		24	mS	1/23	0.25	0.40	0.15	4
		25	mS	1/34	0.69	0.80	0.48	4
		26	sS	1/63	0.42	0.59	0.32	4
		27	G & S	1/ 6	0.92	1.70	0.64	4
		28	mS	1/ 9	0.50	0.57	0.41	4
		29	cS	1/53	0.43	0.63	0.25	4
		30	fS	1/19	0.66	0.99	0.46	3
		31	mS	1/37	1.04	1.56	0.52	4
		32	cS	1/13	1.25	1.71	0.76	4
Southern Lake		33(SM1)	C	1/56	0.18	0.55	0.14	16
		(SM2)	S	1/130	1.27	3.88	0.51	14
		(SM3)	S	1/130	0.70	1.15	0.31	16
		33′	S	1/11	0.80	0.95	0.63	6
		34	fS	1/36	0.35	0.61	0.19	4
		Average		·········	0.64	1.09	0.28	
		Standard deviation		·········	0.56	1.03	0.25	
		Coefficient of variation		·········	0.870	0.943	0.885	

Table 5. Sediment type, slope of lakebed and seepage flux at a single meter site around the western shore of the lake.

Station number	Sediment type	Slope of lakebed	Seepage flux ($\mu m \cdot s^{-1}$)	Date of observation
W1	fS	1/38	1.17	24/8/85
W2	fS	1/25	0.81	24/8/85
W3(Imajyuku)	G & S	1/10	1.06	29/7/85
W4(Sta.4)	G & S	1/ 8	2.49	24/8/85
W5	fS	1/17	1.16	27/7/85
W6	fS	1/17	0.88	29/7/85
W7	fS	1/25	1.01	29/7/85
W8	S	1/11	1.43	29/7/85
W9	G & S	1/ 6	2.84	29/7/85
W10	G	1/ 8	2.99	29/7/85
W11	G & S	1/ 9	2.08	29/7/85
W12	G & S	1/ 7	1.39	29/7/85
W13	G & s	1/11	1.72	3/8/85
W14(Sta.5)	G & S	1/ 7	1.87	29/7/85
W15	G & S	1/ 7	3.15	30/7/85
W16	S	1/ 7	0.64	30/7/85
W17	G & S	1/ 8	2.21	30/7/85
W18	G & S	1/13	3.50	30/7/85
W19	G & S	1/14	3.10	30/7/85
W20	G & S	1/11	4.85	30/7/85
W21	G & S	1/ 8	3.92	14/8/85
W22	S & G	1/ 8	3.62	14/8/85
W23	S & G	1/ 8	1.55	14/8/85
W24(Sta.7)	P & S	1/ 8	2.68	14/8/85
W25	S & G	1/19	1.58	14/8/85
W26	fS	1/33	0.41	14/8/85
W27	cS & G	1/13	1.70	23/8/85
W28	G & S	1/ 8	2.84	24/8/85
W29(Sta.9)	mS	1/22	1.11	23/8/85
W30	G & S	1/11	1.78	23/8/85
W31	G & S	1/11	1.92	23/8/85
W32	S & G	1/ 8	1.33	23/8/85
W33	S & G	1/ 8	1.99	23/8/85

Each of S, G, P, cS, mS and fS indicates sand, gravel pebble, coarse sand, medium sand and fine sand, respectively.

Table 6. Sediment type, slope of lakebed and seepage flux at a single meter site around the eastern shore and the northern part of the lake.

Station number	Sediment type	Slope of lakebed	Seepage flux ($\mu m \cdot s^{-1}$)	Date of observation
E1	fS	1/93	1.49	15/9/85
E2	fS	1/107	1.27	15/9/85
E3	fS	1/129	1.38	15/9/85
E4	fS	1/129	1.44	15/9/85
E5	fS	1/136	1.33	15/9/85
E6	fS	1/164	0.87	14/9/85
E7	fS	1/132	1.47	14/9/85
E8	P & S	1/ 36	3.15	14/9/85
N1	fS	1/ 17	0.45	14/8/85
N2	sS	1/ 7	4.03	14/8/85
N3	sS	1/ 7	3.74	14/8/85
N4	sS	1/ 5	2.42	14/8/85
N5	P & S	1/ 7	2.91	14/8/85

Each of fS, P, S and sS indicates fine sand, pebble, sand and silty sand, respectively.

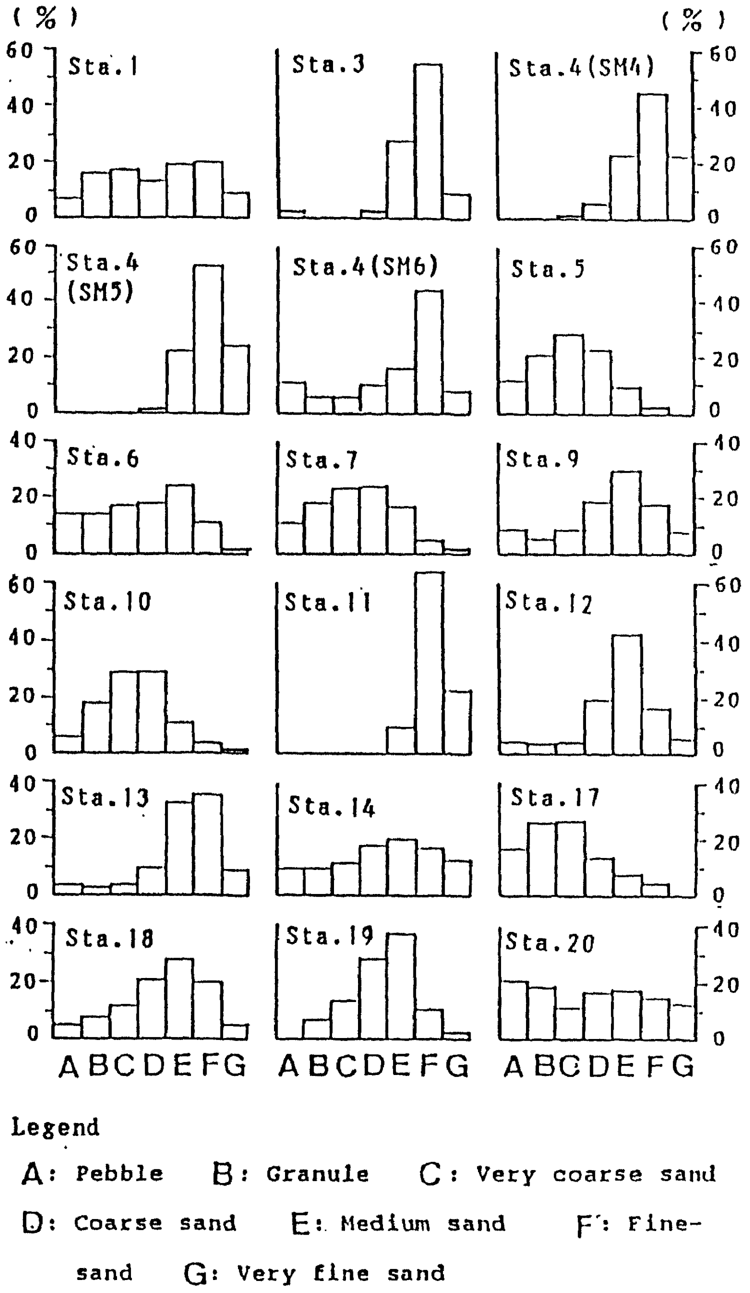


Figure 25. Some representative histograms of the bottom sediments at each observation site, western shore of the lake.

Table 7. Comparison of seepage flux vs. the bottom sediment types obtained at all measurement sites.

Sediment type	Range of seepage flux($\mu m \cdot s^{-1}$)					
	0.0 - 0.5	0.5 - 1.0	1.0 - 2.0	2.0 - 3.0	3.0 - 4.0	4.0 - 5.0
Pebble	-	-	3	2	1	-
Gravel	1	3	7	6	5	1
Coarse sand	3	5	7	1	2	1
Medium sand	5	5	2	-	-	-
Fine sand	4	10	8	-	-	-
Silt & Clay	3	-	-	-	-	-

Table 8. The relation between seepage flux vs. the slope of lakebed and the gradient of water table near the shoreline.

	Regression coefficient	Slope	Intercept	Number of measurements	Remarks
S*	0.685	3.88	0.16	27	
	0.959	11.7	2.36	4	Hira-river alluvial fan
G*	0.603	0.075	0.278	33	

S* and G* indicate the results of the seepage flux v.s the slope of lakebed and that v.s the gradient of water table, respectively.

sediments and lakebed configuration or the hydraulic gradient of groundwater near the shore at each site, because low seepage flux was observed at the bottom sediments which is composed of materials with low hydraulic conductivity. However, pebble, gravel and sand which has high hydraulic conductivity were dominant materials at the sites with high seepage fluxes(Fig. 25 and Table 7). Furthermore, a reasonable correlation exists between the seepage flux and the slope of lakebed or the hydraulic gradient near the shore, the best correlation was obtained with the slope of lakebed (Table 8).

5-3-2. Temporal variation of seepage flux

The temporal variation of seepage flux obtained at various sites at Stas. 4, 5, W3 and 33 is shown in Figure 26.

A seasonal march of seepage flux can be seen at Stas. 4 and 5, although seepage flux sometimes fluctuate to a high value. Seepage flux is generally high in late autumn and winter seasons while low values were observed at the beginning of summer season, except in July, 1985. At Stas, W3 and 33, a large peak is occasionally observed, however, seepage flux is generally constant with time. The coefficients of variation (C. V.) of seepage flux during the study period ranged from 0.13 to 0.53. The averages of C. V. at each site at Stas. 4, 5, 33 and W3 were 0.28 (SM2), 0.34(SM1), 0.33 (SM7) and 0.20(SM1), respectively(Table 9). The average of C.

Table 9. Statistical results of seepage flux at four specific sites during from 1984 to 1987.

Station number	Period of measurements	Seepage flux($\mu m \cdot s^{-1}$)				NM*	Remarks
		Average	Maximum	Minimum	C.V.**		
Sta.4							
6m offshore (SM2)	1984(1~12)	1.90	3.32	0.89	0.33	23	high permeable layer
	1985(1~12)	2.06	3.08	1.14	0.24	25	
	1986(1~12)	1.95	3.27	1.23	0.26	13	
	1987(1~ 7)	2.19	2.81	1.65	0.18	6	
	Average				0.28		
36m offshore (SM9)	1984(1~12)	1.13	1.76	0.73	0.24	18	low permeable layer
	1985(1~12)	1.37	2.06	0.76	0.25	22	
	Average				0.25		
Sta.5							
5m offshore (SM1)	1984(1~12)	4.35	6.37	1.85	0.32	25	high permeable layer
	1985(1~12)	3.07	5.89	1.99	0.31	22	
	1986(1~12)	3.37	5.56	1.68	0.38	18	
	Average				0.34		
Sta.33							
95m offshore (SM7)	1984(7~12)	0.16	0.32	0.03	0.47	13	low permeable layer
	1985(1~12)	0.17	0.55	0.16	0.18	9	
	Average				0.33		
145m offshore (SM10)	1984(7~12)	0.78	1.29	0.24	0.37	13	high permeable layer
	1985(1~12)	0.59	2.83	0.69	0.53	11	
	Average				0.45		
Sta.W3							
5m offshore (SM1)	1985(3~12)	1.60	2.70	1.04	0.27	23	low permeable layer
	1986(4~11)	1.23	1.46	0.93	0.13	10	
	Average				0.20		
10m offshore (SM3)	1985(3~12)	1.14	1.69	0.71	0.25	23	high permeable layer
	1986(4~11)	1.19	2.01	0.62	0.30	12	
	Average				0.28		

NM* and C. V.** indicate the number of measurements and coefficient of variation, respectively.

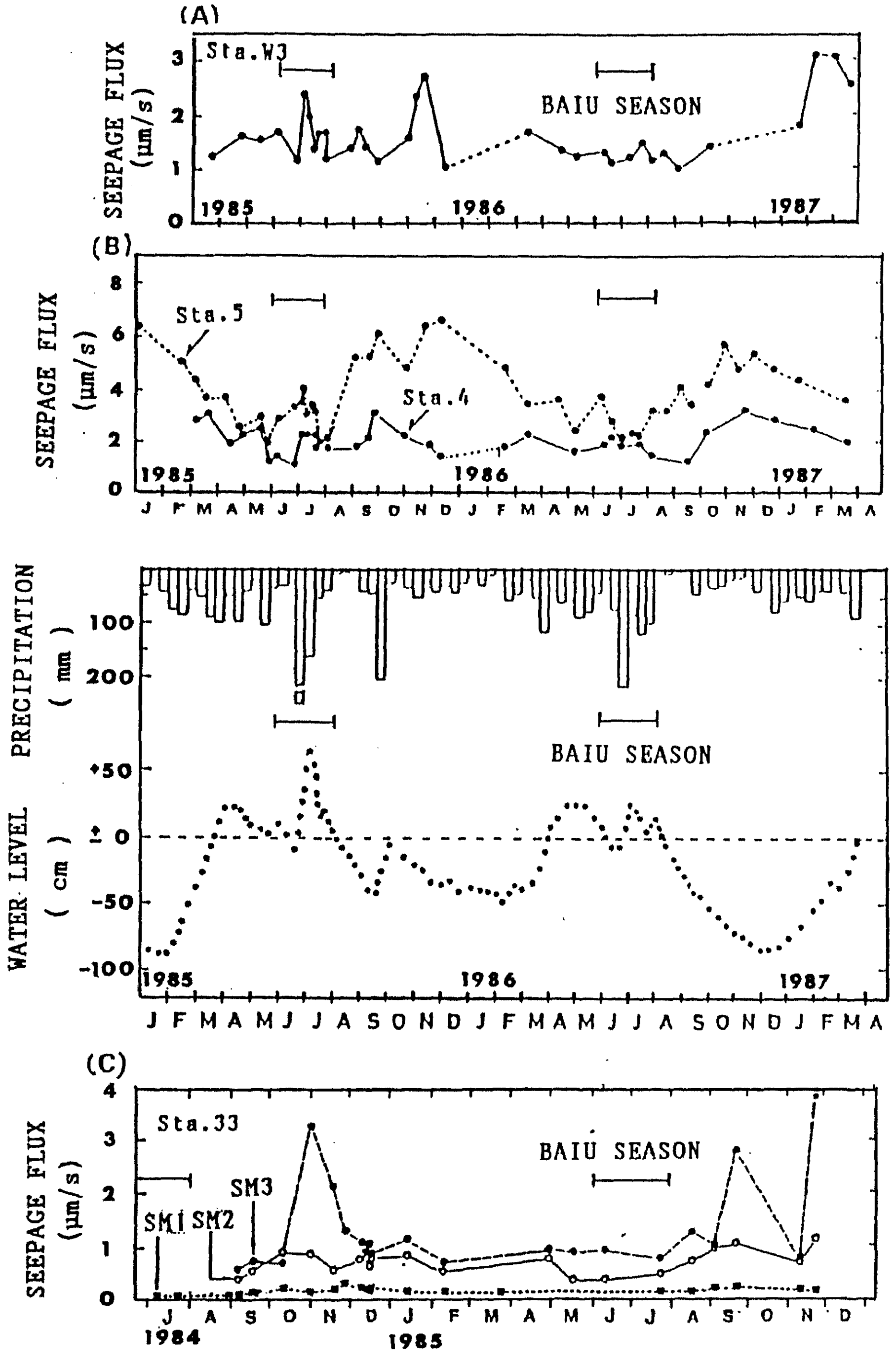


Figure 26. Temporal variations of the precipitation, lake water level and the seepage flux at a single meter for four specific sites(Stas. 4, 5, 33 and W3) during 1984 to 1987.

V. of all the sites was small(about 0.30) compared to that (0.9) of the spatial variation(Table 4).

Generally, the groundwater seepage into the lake responds to the variations of rainfall, lake water level and water level near shore. However, the seepage flux at two stations(Stas. 4 and 5) can be seen an inverse relationship between rainfall and the lake water level, except with short-term heavy rainfall period in July 1985 (Fig. 26).

In Lake Biwa, the hydraulic gradient nearshore at each site would not have been affected by rainfall, because the lake water level generally fluctuate synchronously with rainfall and with well water level(Fig. 27). Thus the temporal change of seepage flux at a single meter site may be due to the change of variation of the distance from the shore(or water depth). That is, at these sites, the seepage flux decreases with increasing distance from the shore as described in the section(5-3-3). The seepage flux at the undisturbed meter decreases(or increases) when the lake water level is high(or low) and the distance from the shore of the meter increases (or decreases) with increasing(or decreasing) lake water level(Appendix Ⅶ).

High value of seepage flux obtained from late June to mid July 1985(the end of the Baiu season) may be caused by the heavy rainfall. This occurred only in one occasion when there was unusually heavy rainfall of about 500mm in one

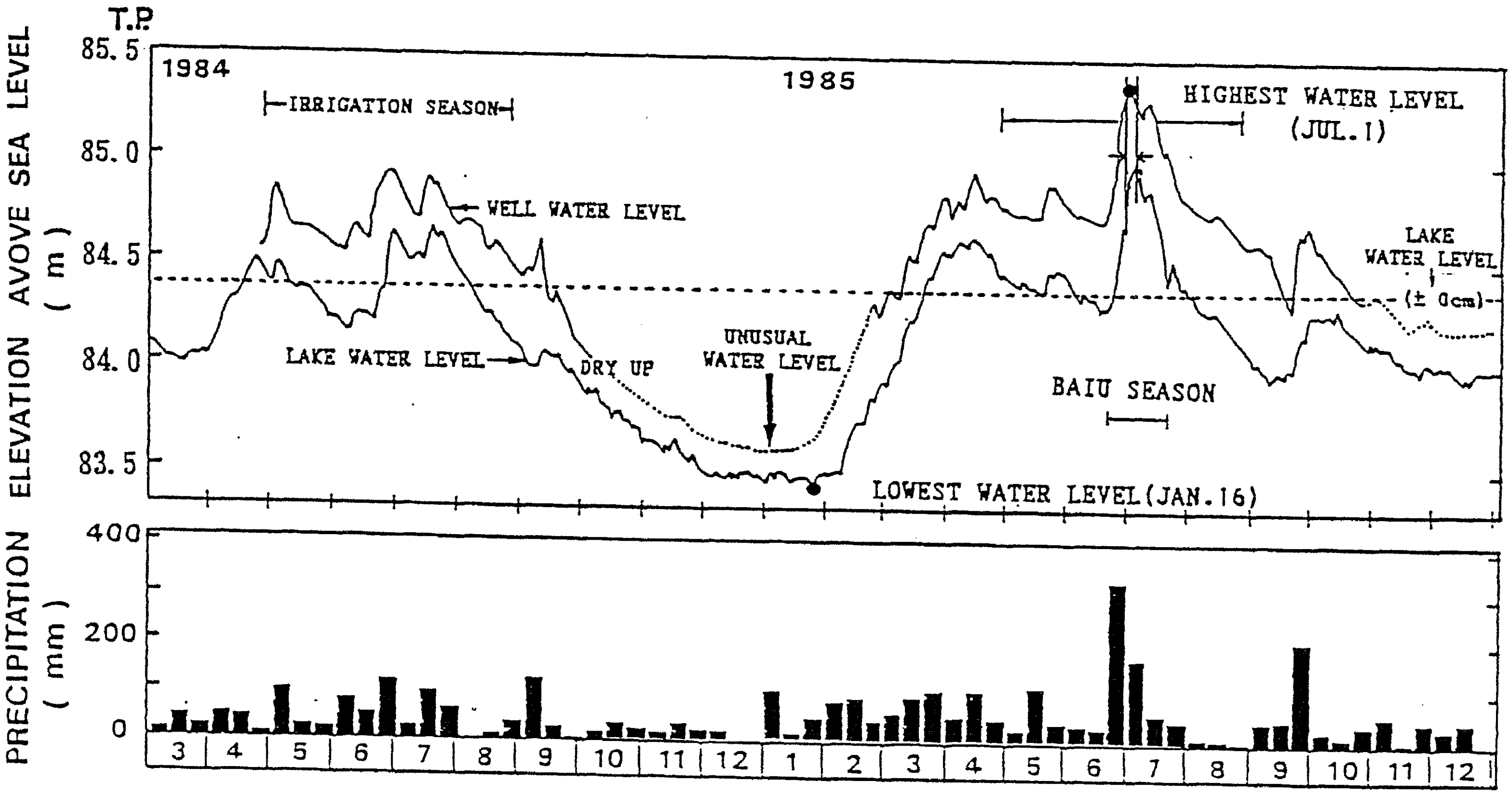


Figure 27. Resulting water level change in the well about 50m distance from the shore at Wani beach(Fig. 8A) and corresponding changes in the lake water level and the precipitation. Unusual lake water level was recorded on 16 January and 1 July 1985.

month period in total.

In general, the heavy rainfall caused a more rapid response of the groundwater level than the lake water level (Fig. 3). The heavy rainfall caused the development of a groundwater mound near the shore at each site, resulting in increased seepage flux. Such phenomena have also been observed by several workers.

Fellows and Brezonik (1980) showed that after a short-term rainfall events the nearshore seepage flows increased rapidly and decreased to near pre-rain flow. Cherkauer and Zager(1989) also indicated that the growing mound causes a local groundwater seepage into the lake in an expanding zone along the down gradient shore.

For the other two sites(Stas. W3 and 33) where evident temporal changes in seepage flux were not observed, rainfall may not influence the fluctuation of seepage except in unusuall heavy rainfall event. This is probably due to the effect either the position of seepage meter or the characteristics of the bottom sediments at each meter site. Because the meters at these sites were installed farther offshore and in relatively low permeable layer consisting of silty sand or silt.

As will be described in the section(5-3-5), however, the total seepage flux fluctuated in relation to the lake water level and precipitation for most of the study period(Fig.

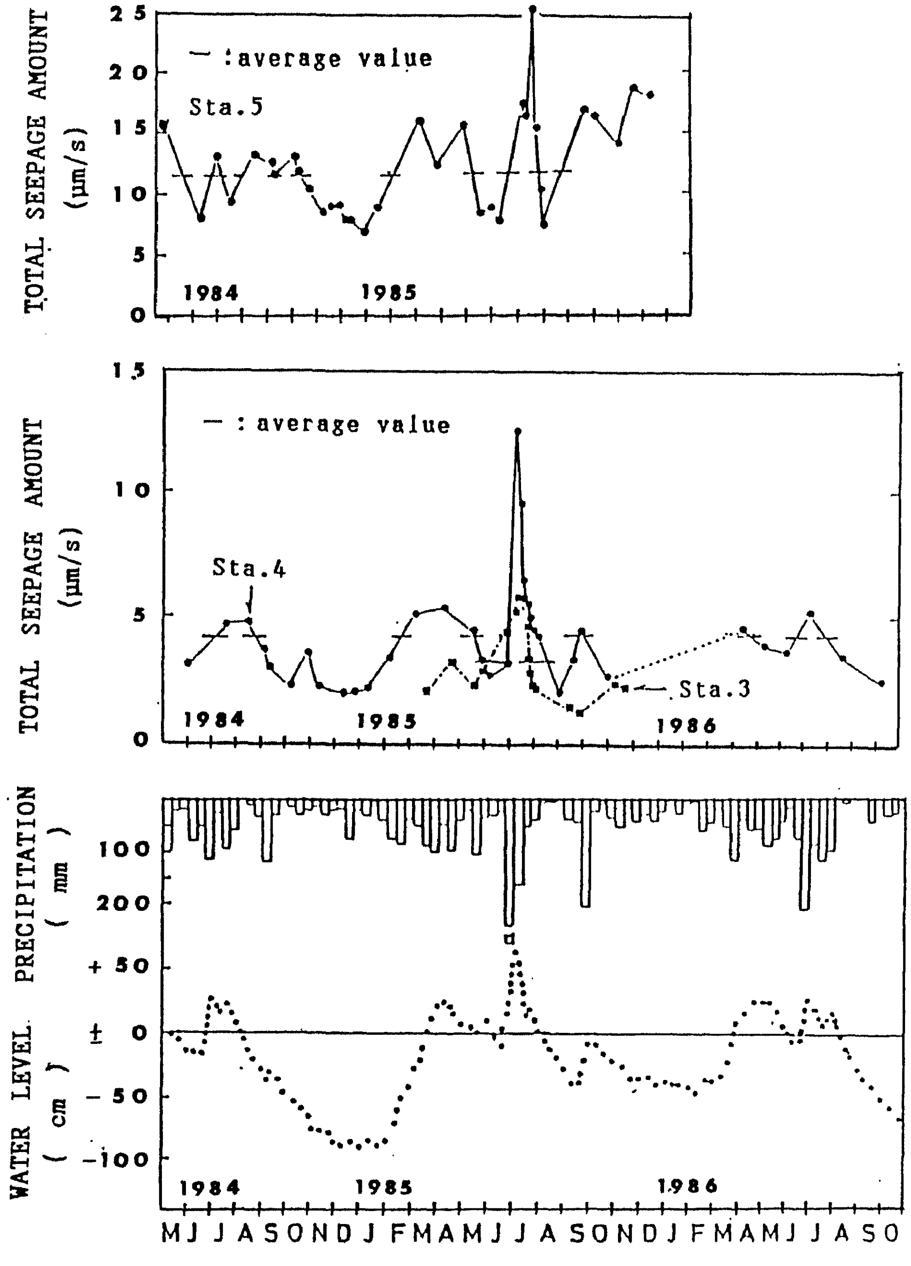


Figure 28. Temporal changes of the precipitation, lake water level and the total seepage flux calculated for a 1m wide strip extending perpendicularly from the shore into the the lake.

28). The average total seepage flux was obtained usually in summer or at the time when the lake water level is ± zero.

In Lake Biwa, seasonal change of the lake water level is correlated with precipitation except for March to April (Ikeda et al. 1979). Thus, a change in precipitation may have caused the observed increase or decrease in groundwater seepage into the lake.

5-3-3. Seepage patterns along the transect

At six of the eight transects, although the position of highest flux zone differs from site to site, seepage flux decreased abruptly with increasing distance from the shore (Type A, Figs. 29(A~D) and 30, Appendix Ⅶ). However, for Sta. W3, constant low seepage flux consistently occurred beyond about 40m offshore (Fig. 22). As described before in the section (5-2-1), the site is underlain by thin clayey silt offshore and the confined groundwater seeps into the lake through the low permeable layer. Seepage pattern obtained offshore at this site is a result of hydraulic connection between the underlying aquifer and the lake bottom sediments. For Sta. 5(Fig. 30), a zone of relatively high seepage flux exists at about 30-35m from the shore. As observed from the geological cross section(Fig. 30), the bottom sediments consist of gravel and sand with high hydraulic conductivity and this aquifer is weakly confined (Kayane et al., 1984). Therefore, seepage which did not

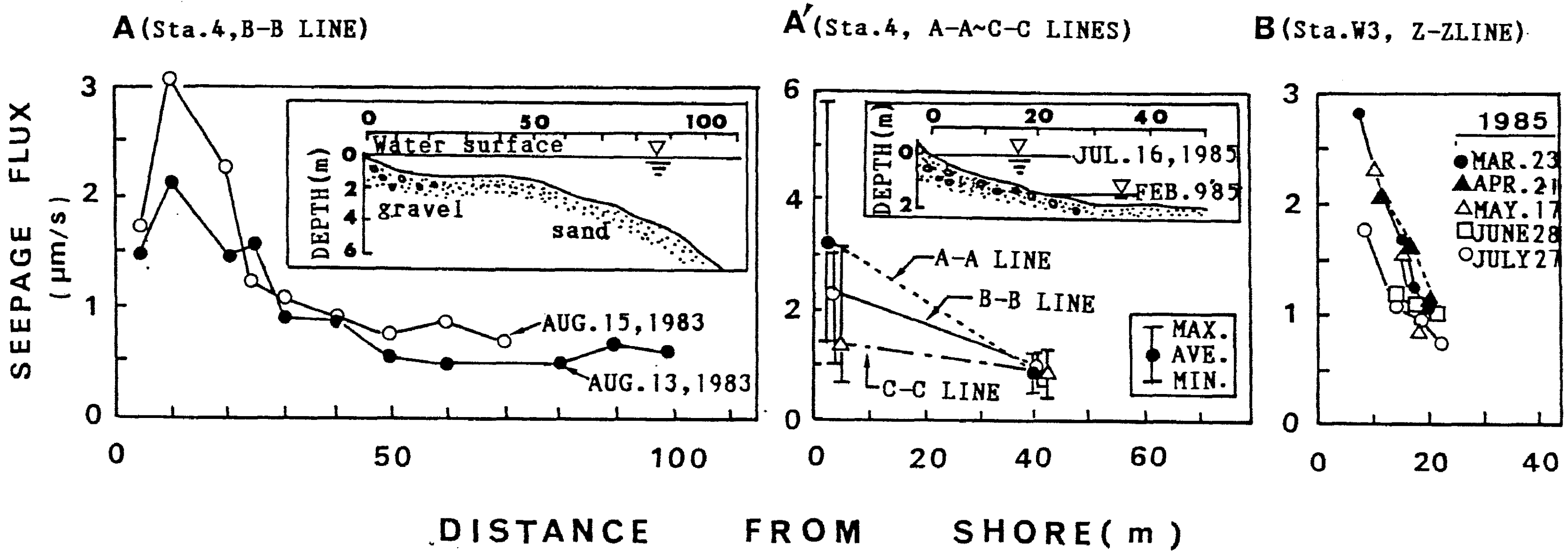


Figure 29. Seepage patterns along the transect offshore showing the bottom profile at each site. A, A′ and B show the results obtained at Sta. 4 (Figs. 1 and 8 (B)) and Sta. W3; Bars in A′ show a range for all measurements (solid lines) at each meter during 1984 to 1987.

(Continued)

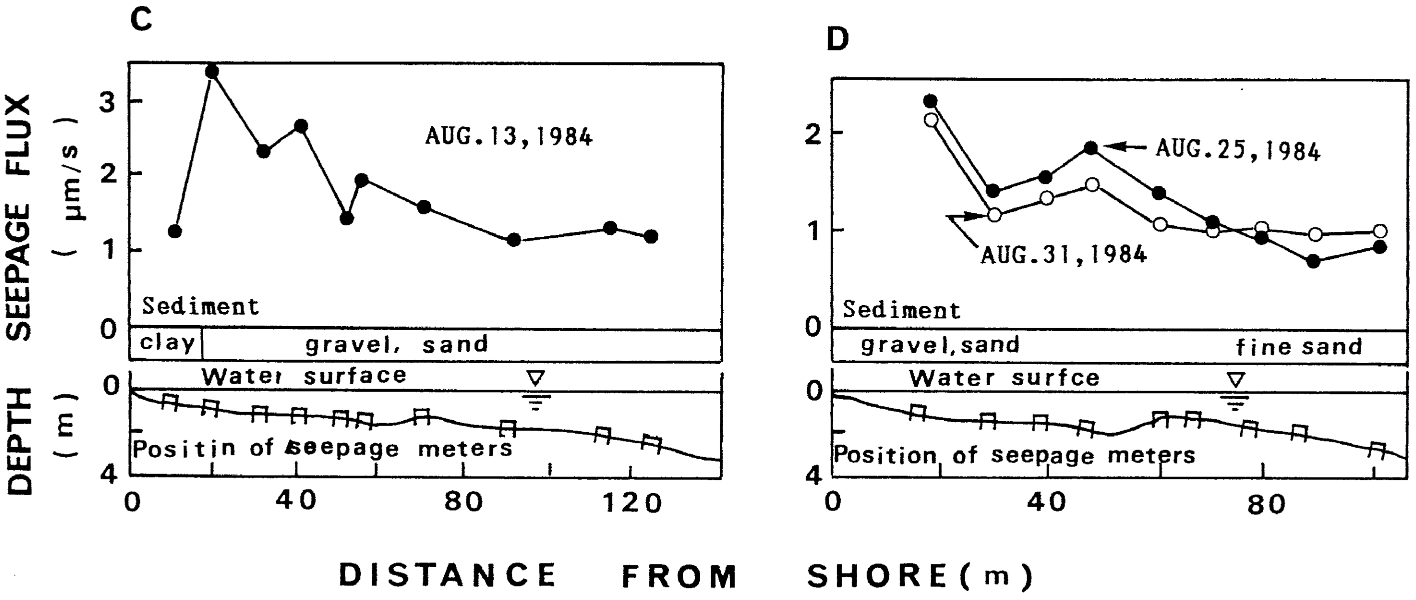


Figure 29. Seepage patterns along the transect offshore showing the bottom profiles at each site. C and D show the results obtained at Stas. 13 and 11(Fig. 1), respectively.

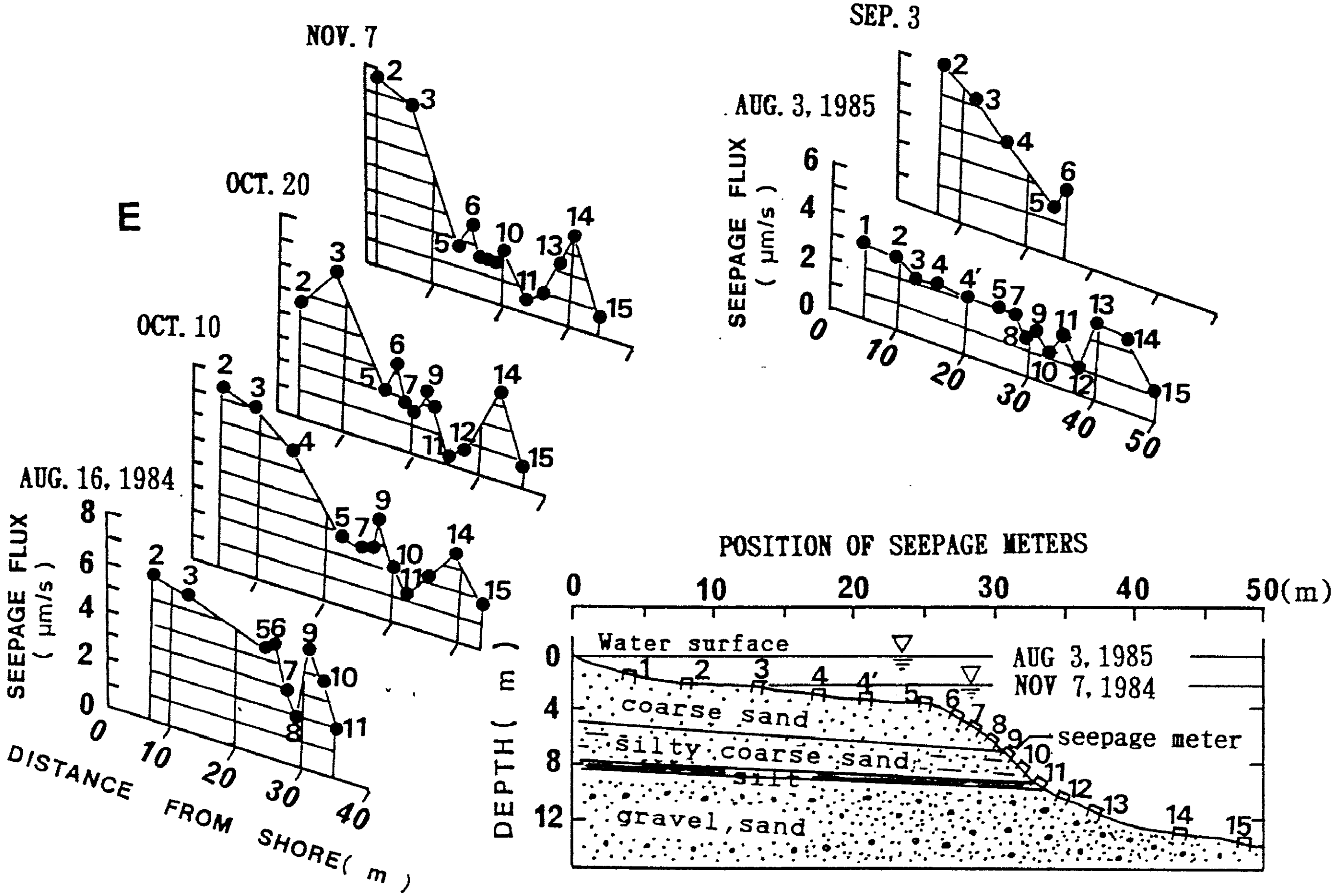


Figure 30. Summary of seepage patterns at Sta. 5(Fig. 1) showing the geological cross section along the same transect. Geological cross section based on the data from cores obtained at each meter site and that from Kayane et al. (1984).

decrease uniformly offshore must be attributed to the heterogeneity in the flow system.

On the other hand, at the remaining two transects (eastern shore of the lake), seepage showed different patterns from the other sites. One difference is that seepage flux showed constant distribution within about 200m distance from the shore(Type B, Fig. 31). The result indicates that the seepage flow lines at this site are more horizontal than vertical in the other site around the lake. The Type B pattern may be the result of the effect of the contour of the lakebed. The bottom sediments at this site consist of gravel and sand. However, the lakebed has much gentle slope(1/100) compared to that(1/10~ 1/40) at the site where Type A pattern is observed(western shore).

Pfannkuch and Winter (1984) predicted that the slope of the lakebed would have an effect on the configuration of the groundwater flow field beneath a lake. A gentler slope tends to cause depression of flow lines offshore and steeper slope causes compression closer to shore. These results indicate the importance of configuration(slope) of lakebed on seepage pattern.

Another finding is that seepage exhibits a relatively constant distribution in the area nearshore and reaches a peak at about 150m from the shore and then decreases exponentially away from the shore (Type C, Fig. 32). For Type C

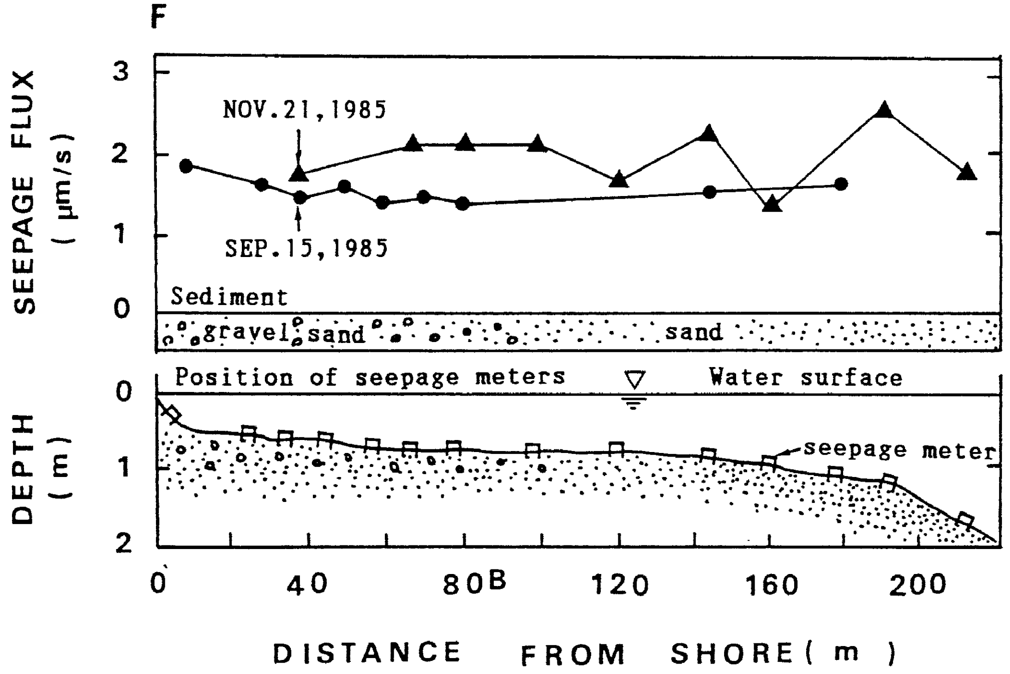


Figure 31. Seepage patterns along the ~~transect~~ offshore at Sta. 29 (Fig. 1) showing the bottom profile.

pattern, the seepage profile was consistent with the hydrogeological heterogeneity in the lakebed. That is, relatively constant low seepage fluxes occurred in areas near the shore where non-uniform clayey silt lens exists beneath the lake bottom. The highest offshore seepage occurred at the meter placed at the contact between the lake and the confined aquifer. This confined aquifer which is extending infinitely toward the shore is exposed to the lake bottom beyond about 150m from the shore as shown in Figure 32. Fukuo and Kaihotsu(1988) indicated that most of the groundwater flows into the lake through between the lake and the confined aquifer where a confined aquifer is exposed to a lake bottom with a gentle slope.

In summary, seepage patterns along the transect at various sites around the lake classified into three different patterns(Types A, B and C) and the patterns at all transects were consistent throughout most of the study period. Similar patterns of Type A and Type C have been observed by other researchers(Fellows and Brezonik, 1980; Cherkauer and Nader, 1989a; Shaw and Prepas, 1990b). However, Type B pattern has not been observed. Where Type A pattern was observed, the lakebed has relatively steep slope and the bottom sediments consisted of high permeable materials(sand and gravel) as a whole. Type B and C patterns were observed in lakebed with a gentle slope and with heterogeneities both in the bottom

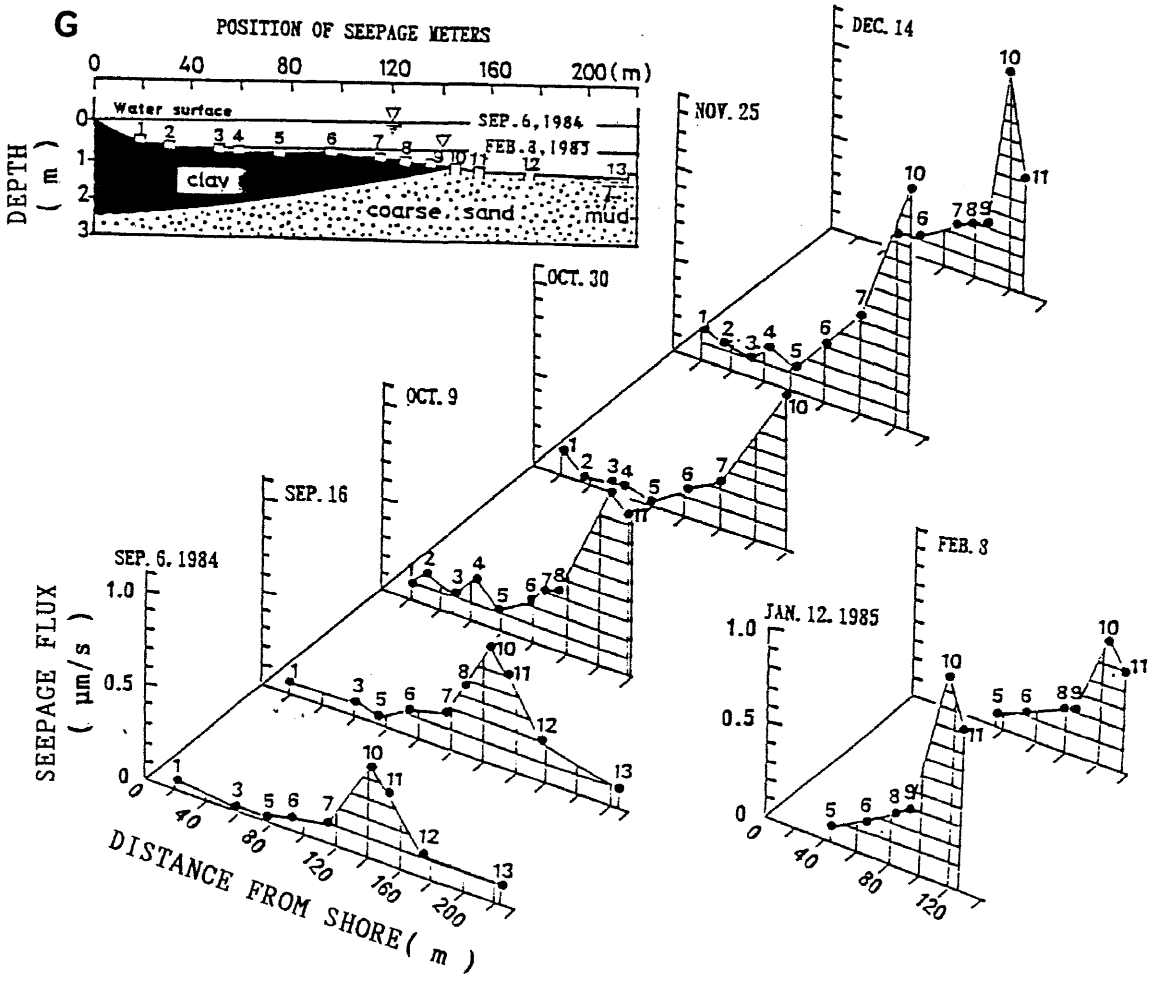


Figure 32. Summary of seepage patterns at Sta. 33(Fig. 1) showing the geological cross section along the same transect. Geological cross section based on the data from cores obtained at each meter site.

sediments and in the groundwater flow system.

Cherkauer and Nader (1989) pointed out that these anomalous seepage patterns (Types B and C) are much more common with larger water bodies. The seepage patterns obtained (Types A and C) also concurred with that predicted by mathematical simulations by other researchers.

These results showed that the slope of the lakebed and the heterogeneities both in the bottom sediments and flow system have a significant effect on seepage pattern. It seems logical that both the hydrogeological heterogeneity beneath the lake bottom and the variation in the sediment thickness are the cause of the observed seepage patterns.

5-3-4. Calculation of the amount of seepage into the lake

To estimate the amount of seepage into the lake, it is necessary to calculate the total seepage flux at each site. The total flux of seepage into the lake was calculated using a computer program developed by McBride and Pfannkuch (1975).

To apply this method, we determined the relationship between seepage flux and distance from the shore or water depth. For the sites where seepage flux decreased exponentially away from shore, we made a number of seepage flux measurements, and determined the regression lines as a function of distance from the shore or water depth.

Some representative results obtained are given in Table

Table 10. Results of regression coefficient, slope and intercept calculated for the equation: log seepage flux vs. water depth and distance from the shore.

Station number	Date	Regression coefficient	Slope	Intercept	Number of measurements
Sta.W3	14/9/1987	-0.998[-0.999]*	-0.292[-0.022]	0.803[0.793]	8
	5/10/1987	-0.951[-0.880]	-0.317[-0.032]	1.156[1.194]	14
	5/8/1988	-0.989[-0.971]	-0.191[-0.011]	0.991[1.200]	14
Sta.W3′	23/3/1985	-0.937[-0.981]	-2.176[-0.078]	1.474[1.185]	10
	28/5/1985	-0.995[-0.948]	-2.075[-0.121]	1.776[0.738]	6
	1/8/1985	-0.906[-0.909]	-1.438[-0.079]	1.438[0.079]	6
Sta.4	15/8/1984	-0.714[-0.832]	-0.801[-0.027]	1.148[0.802]	9
	27/12/1984	-0.941[-0.959]	-1.557[-0.030]	1.209[0.872]	8
	28/6/1985	-0.975[-0.917]	-0.891[-0.063]	1.001[0.600]	10
Sta.5	27/4/1985	-0.974[-0.990]	-0.309[-0.043]	1.397[1.767]	5
	27/5/1985	-0.996[-0.997]	-0.490[-0.066]	1.478[1.698]	8
	2/8/1985	-0.967[-0.965]	-0.105[-0.041]	1.219[1.412]	7
Sta.11	24/8/1984	-0.831[-0.920]	-0.789[-0.014]	1.404[1.329]	9
Sta.13	23/8/1984	-0.900[-0.750]	-0.832[-0.010]	1.609[1.145]	5

[ ]* indicates the results of log seepage flux v.s distance from shore.

10, in which a reasonable correlation exists between the log. of seepage flux, and that of distance from the shore or the log. of water depth throughout the year. The best correlation with distance from the shore was obtained for 4 of 6 sites and with water depth for two sites. Even so, there were insignificant differences in regression coefficients between log. of seepage flux to distance from the shore and that of water depth.

In general, a reasonable correlation exists between seepage flux and distance from the shore at which the measurements were made(Lee, 1977; John and Lock, 1977; and Fellows and Brezonik, 1980). However, Brock et al. (1982) and Lewis (1987) reported that seepage flux is correlated with water depth. It seems reasonable to use the equation of log. of seepage flux and that of water depth for calculations of the total seepage flux. Thus, we have employed the equation of log. seepage flux and water depth as follows. Then the bottom of the lake is subdivided into strips of 1m wide and extending perpendicularly from the shore into the lake.

$$S = \exp^{(-aD + b)} \qquad \cdots\cdots\cdot (2)$$

where,

S: seepage flux($\mu m \cdot s^{-1}$)

D: water depth(m)

a: slope of the regression line

b: intercept

Thus, the total flux of seepage(Q) is obtained by summing up the seepage flux at each strip by the equation below:

$$Q = \int^{Dn} \exp^{(-aD + b)} = \exp^{(b)} / a \cdot [1 - \exp^{(-aDn)}] \quad \cdot \cdot \ (3)$$

and

$$Dn = (-1 / a) \cdot \ln(1 - \alpha) \qquad \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \ (4)$$

where,

Q: the total seepage flux($\mu m \cdot s^{-1}$)

D_n: specific water depth(m)

α: fraction of the total seepage flux

The slope of regression line affects the calculation of the total seepage flux extending perpendicularly from the shore. As given in Tables 11 and 12, the slopes of the flux-depth curve varied significantly over the year. However, it is shown that the variation in slope has only a small effect on the seepage calculation for over a wide range of medium value slope(Brock et al., 1982). Thus we have employed the average slopes to calculate the total seepage flux and to

Table 11. Annual variation of slope, intercept and regression coefficient calculated for the equation of log. of seepage flux vs. water depth at Wani beach (Sta. 4).

Date	Slope	Intercept	Regression coefficient	Number of measurements
10/10/1984	-0.997	0.623	-0.998	4
08/11/1984	-1.679	1.291	-0.989	4
27/12/1984	-0.969	1.240	-0.969	10
11/01/1985	-1.721	1.350	-0.972	6
09/02/1985	-1.533	1.642	-0.984	5
22/03/1985	-0.986	2.130	-0.974	8
14/04/1985	-0.816	1.471	-0.991	12
27/05/1985	-0.811	0.944	-0.986	6
28/06/1985	-0.891	1.001	-0.975	10
07/07/1985	-0.232	0.554	-0.844	6
11/07/1985	-0.559	1.390	-0.821	6
16/07/1985	-0.442	1.119	-0.811	6
20/07/1985	-0.409	0.910	-0.902	6
27/07/1985	-0.433	0.857	-0.752	4
30/07/1985	-0.384	0.578	-0.664	9
04/08/1985	-0.757	1.172	-0.966	5
20/09/1985	-0.923	1.122	-0.938	5
28/09/1985	-1.334	1.038	-0.925	5
Average	-0.882	1.135		
S.D.	-0.448	0.392		
C.V.	0.508	0.345		

S.D.: Standard deviation, C.V.: Coefficient of variation.

Table 12. Annual variation of slope, intercept and regression coefficient calculated for the equation of log. seepage flux vs. water depth at Matsunoura beach (Sta. 5).

Date	Slope	Intercept	Regression coefficient	Number of measurements
15/08/1984	-0.125	1.652	-0.762	13
10/10/1984	-0.178	1.632	-0.939	7
20/10/1984	-0.363	2.036	-0.979	9
07/11/1984	-0.258	1.705	-0.890	8
07/12/1984	-1.147	2.192	-0.998	3
06/03/1985	-0.371	1.774	-0.864	8
14/04/1985	-0.436	1.828	-0.783	6
27/04/1985	-0.309	1.397	-0.974	5
27/05/1985	-0.490	1.478	-0.996	7
11/07/1985	-0.357	1.184	-0.948	6
20/07/1985	-0.283	1.484	-0.903	8
23/07/1985	-0.249	1.274	-0.716	8
02/08/1985	-0.105	1.219	-0.967	7
03/09/1985	-0.410	2.033	-0.976	8
Average	-0.363	1.647		
S.D.	-0.253	0.328		
C.V.	0.695	0.196		

S.D.: Standard deviation, C.V.: Coefficient of variation define the width of the zone of active seepage flux at each specific site(Table 13). The active seepage flux zone is defined by equation(4).

At each integration interval(1m depth), the flux at that depth and the area between that depth and the previous depth were measured. The area sectioned around the periphery of the lake for each site is measured using planimeter and the map of Lake Biwa(1/10000). All the seepage amounts($m^3 \cdot s^{-1}$) were then summed up to obtain the total seepage for the area sectioned for that site.

For the sites where such transect data were not obtained, regression equations were determined for each input of the seepage flux and the depth of measurements using the representative average slopes which were obtained at the specific sites(Table 13). The slope for each site was selected in proportion to the nearshore sediments and the slope of lakebed (Tables 4-6).

The boundary conditions are: (1) it was assumed that the flux at the shore line is zero, and (2) the width of the zone of active seepage flux(99% of total seepage flux) is within a depth of 3-10m(Table 13).

On the other hand, for sites(Stas. 29 and 33) where such discernible patterns were not obtained, the average flux along each transect was calculated by multiplyings the area under the curve of measured seepage flux by distance from

Table 13. Average slope and the width of the zone of highest seepage flux for calculations of the annual amount of seepage into the lake at each site.

Station Number	Average slope(N)*,	Width of the zone of rapid seepage flux**	Stations for application of average slope
W4	-0.250(6)	10	W1,W3,W4,W9~11,W17(6)~21
Sta.4(W5)	-0.882(18)	6	1,3,W1,W2,W5~8,W26(8),15 N5,19.20
Sta.5(W14)	-0.363(14)	10	W12~W16,W22~24(7),W25, W27~29(9),W30~33, 10,N1~5(17),18,21,30,32
Sta.11	-0.863(4)	5	16,25~28,31,E1~8
Sta.13	-0.532(3)	10	12,14,22~24
Sta.34	-1.810(1)	3	33′

(N)*: Number of measurements, ** Width of the zone of rapid seepage flux was caliculated for the equation of depth(m)=$(-1/\text{slope})\cdot\log(1-\alpha)$; α is set 0.99. Although the depth was determined each of 18,5,13,5,9 and 5m, we here assumed as above.

the shore line and dividing the results by the length of the transect. Thus, the average seepage flux weighted for the distance from the shore and individual fluxes were then summed up to obtain the total seepage amount for that site using the area sectioned.

The annual total amount of seepage was calculated using the total seepage amounts of all the sites over one year period. Data collected in summer season in 1984 and 1985 were mainly used for calculations. It seems reasonable to assume that these measurements can be used as average for the whole year, because the average total amount of seepage was obtained in summer season(5-3-2).

5-3-5. Groundwater component of the water balance

An annual amount of seepage into the lake at each site was calculated from the integrated total amounts of seepage for 12 month periods of measurements and summed up for sectioned areas. The groundwater discharge for each sectioned area and the specific discharge(groundwater discharge($km^3 \cdot y^{-1}$) / area of drainage basin(km^2)) calculated in terms of water depth($mm \cdot d^{-1}$) are shown in Figure 33 and Table 14.

The groundwater discharge around the eastern shore is about twofold larger than that around the western shore of the lake. The specific discharge(SD) varied from region to region in the same manner as seepage flux. The SD in the areas NO.2 and NO.5 was higher(about 2~3$mm \cdot d^{-1}$) than that in

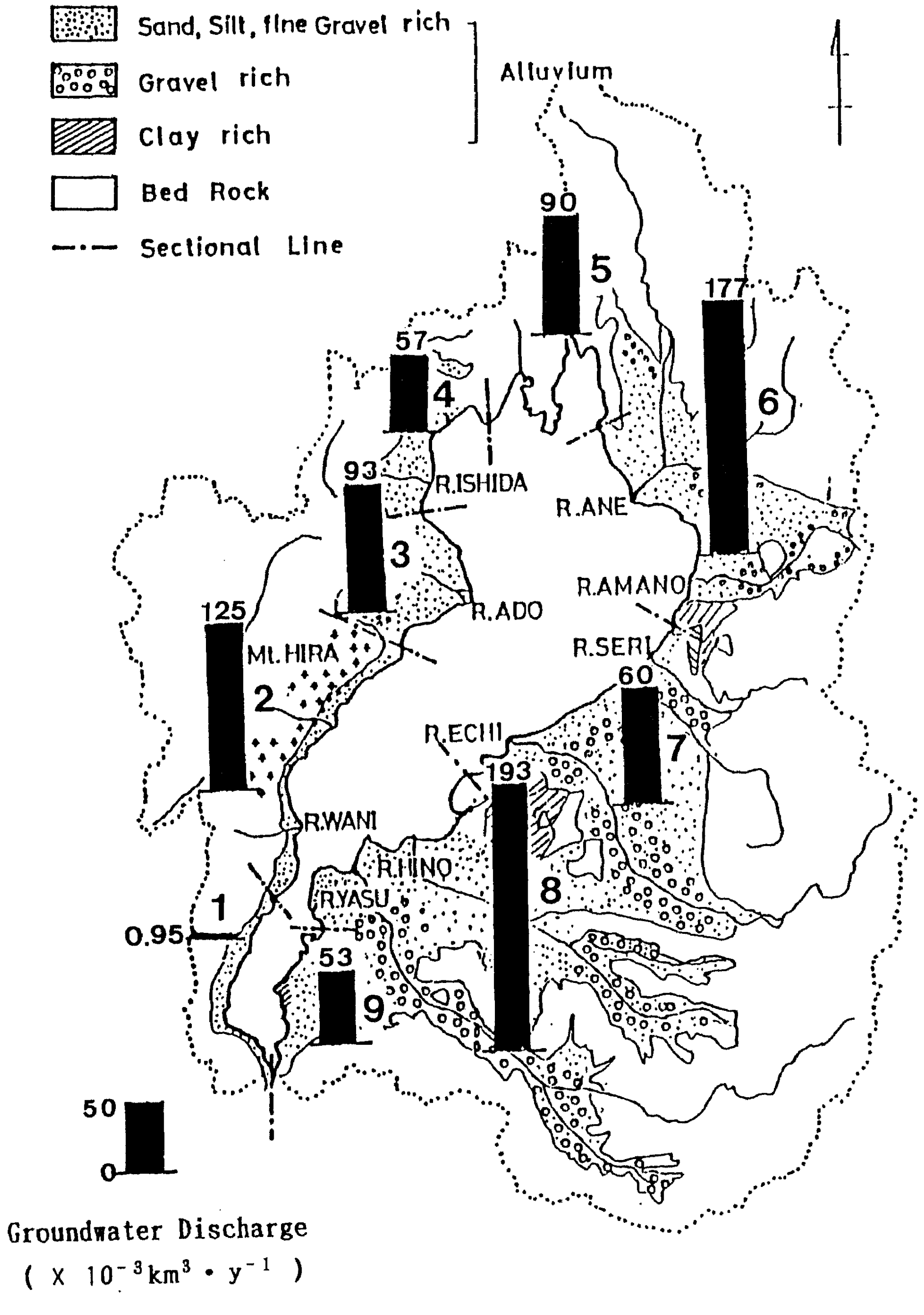


Figure 33. Groundwater discharge for each sectioned area around the lake. Annual amount of seepage into the lake for each sectioned area was summed up from the integrated the total amount of seepage at each of 76 seepage measurement sites.

Table 14. Specific groundwater discharge of the sectioned area around Lake Biwa.

Number of Sectioned area	1	2	3	4	5	6	7	8	9
Drainage area(km^2)	68	124	428	173	137	658	643	803	113
Groundwater discharge ($\times 10^{-3} km^3 \cdot y^{-1}$)	0.95	125	93	57	90	177	60	193	53
Water depth($mm \cdot d^{-1}$)	0.04	2.76	0.59	0.90	1.8	0.74	0.25	0.66	1.28

the other regions(0.7~1.0 mm$\cdot$d^{-1}) around the lake except with areas NO.1 and NO.7. The high SD may be due to the high amount of surface water seepage for the area NO.1 and of precipitation for the area NO.5. Because, alluvial fan are distributed widely around the Hira mountains and seepage amount from the rice paddy field in this area is high. For example, the seepage amount from the paddy field is maximum 50mm$\cdot$d^{-1} in the irrigation season(Sugawara, 1973). Also high amount of precipitation occurs on the northern end of the lake.

Relatively low values on the Echi and Seri river basins may be due to the following reason. That is, a confined aquifer with high permeability is distributed in this region, however, confined groundwater seepage into the lake was ignored in the calculations of seepage amount.

The annual total amount of seepage into the lake was estimated at 270mm$\cdot$y^{-1} (0.85km$^3\cdot$y^{-1}) which is calculated for the land surface area and the total seepage area of the lake bottom calculated was 97.24km^2 which is 14% of the lake surface area (674 km^2). This result suggests that groundwater contributed about 25% of the annual inflow(including of the surface water and groundwater) into the lake(about 1000~1200mm$\cdot$y^{-1} (4~4.5km$^3\cdot$y^{-1}, Table 1). This seepage value is quite close to the average value of 322mm $\cdot$y^{-1} (1.0km$^3\cdot$ y^{-1}) by Fujino (1980). Our estimation is smaller than that of Kawabata (1982b) by 10~15%(Table 1). Kyoto Agricultural Land Administration Office(1951) estimated the groundwater inflow by hydraulic calculations of about 1500mm ($5.7km^3 \cdot y^{-1}$), about 7-fold higher than our value(Table 1).

The calculated amount of seepage into the whole lake may be underestimated because of the following reasons:

(1) The point offshore where seepage flux decreased to insignificant amount was not measured. Even so, the width of the zone of active seepage flux for all sites was defined from the equation using average slopes at only six specific sites and was assumed to be within the depth shallower than 10m. Thus the seepage area seems to be underestimated.

(2) The confined aquifer with high permeability exposed to the lake bottom surface offshore around the eastern shore of the lake(Takatani and Nishida, 1964). However, it was ignored in the present calculation.

(3) Although seepage flux is very low in the bottom sediments which consists of mud and silty sand, groundwater seeps out evidently into the lake through an low permeable layer. In such a condition, the amounts of groundwater seepage could be expected to be significant because of the large bottom area (about 20% of the total bottom area of $677km^2$ is covered by mud and sandy mud to the depth shallower than 20m; Kotani, 1971).

Thus the groundwater discharge into the lake in the whole year would be higher than this value. However, it seems useful for providing a preliminary indication of the relative importance of groundwater contribution to the water balance of the lake based on the seepage calculations for the whole lake by using a comparatively large data set obtained from measurements around the periphery of the lake.

To estimate the amount of seepage into a lake accurately, it is desirable to define the point where seepage decrease to an insignificant amount and to determine the seepage patterns along the transects offshore at a number of sites.

CHAPTER 6

SUMMARY AND CONCLUSIONS

Field measurements were carried out to study the groundwater seepage into Lake Biwa using seepage meter, piezometer, core drilling and well water level techniques. Before regular data collections were started, several tests were firstly done to evaluate the usefulness of the seepage meter technique and secondly the process of groundwater flow into the lake was investigated. Thirdly, the spatial and temporal variations of seepage flux were determined around the lake. Using the results of seepage observations, the annual amount of seepage into the lake was obtained.

The results indicated the followings:

(1) Seepage meter technique is found to be reliable when used with a large diameter tube(10mm I. D.) and with a baggie collector which is prefilled with 200ml of water. The quality of water collected by seepage meter is quite similar to that of groundwater in the aquifer in the lake only at the site where seepage flux is high, but did not provide a good indication of composition of groundwater entering the lake at the site where seepage flux is relatively low.

(2) The distributions of the groundwater potential in the lake, the quality of groundwater and the seepage flux show that the shallow groundwater moves horizontally toward the lake and the flow veers almost vertically upward on the shore line near the inflection point of the lakebed and seeps out within about 20m distance from the shore. Confined groundwater seeps out into the lake through a thin low permeable layer offshore. Furthermore, seepage patterns obtained also agree with the flow model predicted by a mathematical simulation (McBride and Pfannkuch, 1975).

(3) Seepage fluxes measured at 76 sites around the lake ranged from 0.01 to $4.9 \mu m \cdot s^{-1}$. The significant spatial variability can be attributed to either the heterogeneity of the lake bottom sediments or the difference of lakebed configuration or hydraulic gradient of groundwater near the shore. Discernible seasonal change in the total amounts of seepage is found and it might be caused by precipitation.

(4) The seepage distribution patterns can be classified into three groups: Type A in which the seepage decreases with increasing distance from the shore; Type B in which seepages are distributed uniformly offshore; Type C in which a uniform seepage nearshore area increases measurably at some distance from the shore then decreases

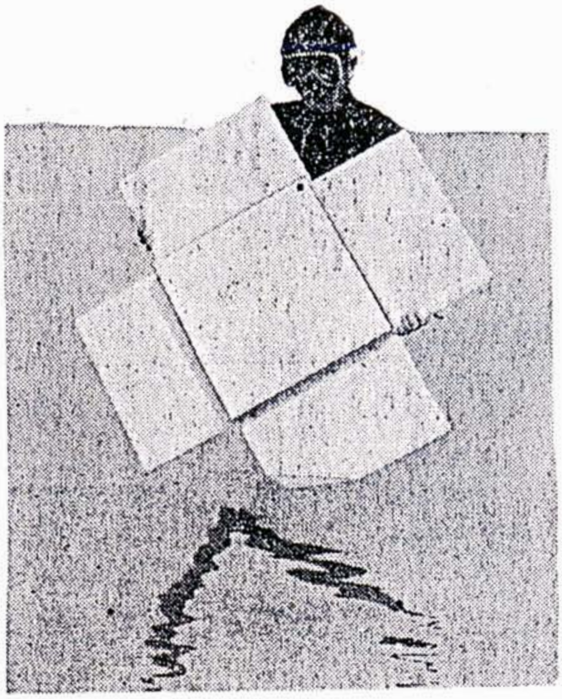
abruptly farther offshore. The Type B must be attributed to the heterogeneity of configuration of the lakebed because the slope of the lakebed is more gentle than the case of Type A. For Type C, the detailed coring data show that a perfect correlation between the distributions of seepage flux and the hydrogeological heterogeneity within the flow system in the lake.

(5) The groundwater discharge around the eastern shore was twofold larger than that around the western shore of the lake. However, the specific discharge in the areas around the Hira mountains and the northern end part of the lake was higher than that in the other areas around the lake. The amount of seepage into Lake Biwa is estimated to be $270\mathrm{mm}\cdot y^{-1}$ ($0.85\ \mathrm{km}^3\cdot y^{-1}$). This value accounted for about 25% of the annual total inflow(including of the surface water and groundwater) to the lake.

As a results, the seepage meter technique employed could be useful for investigating groundwater seepage into a lake, and the applicability of the theoretical models for investigating groundwater discharge into a lake with homogeneous lakebed sediments is confirmed through the field measurements, and also the shape of the bottom profile and the hydrogeological heterogeneity in the groundwater flow system have a significant effect on seepage pattern.

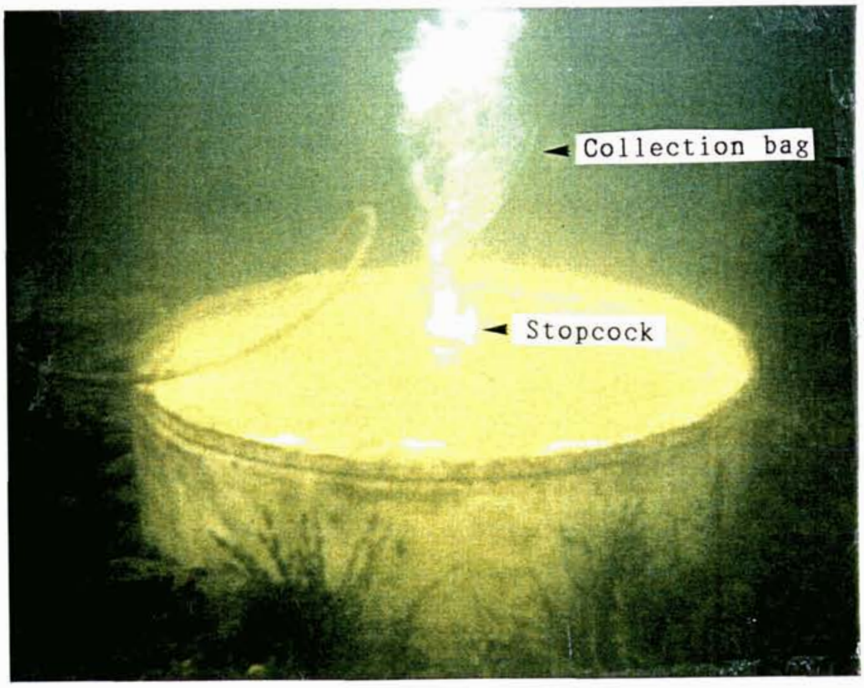
Appendix 1. Seepage meters.

1



◄ Box type

2



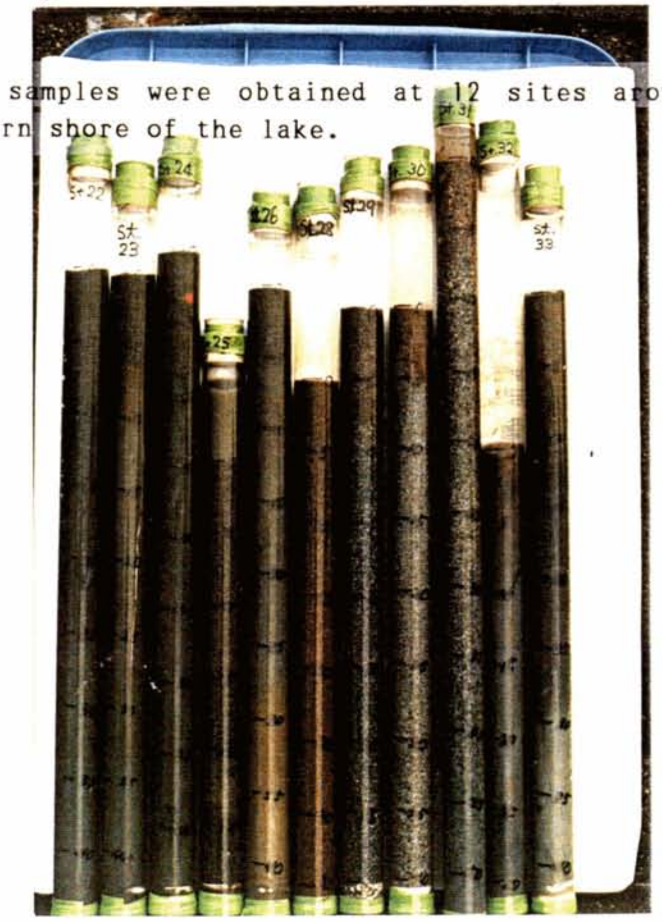
◄ Cylinder type

Appendix Ⅱ. Sample of water collected by seepage meter and the bottom sediments.

1

Sample was collected at Sta. 4 (duration time is 12 hours).

2 Core samples were obtained at 12 sites around the eastern shore of the lake.



Appendix Ⅲ. Observation site(Imajyuku beach, Sta. W3) for groundwater flow into the lake.

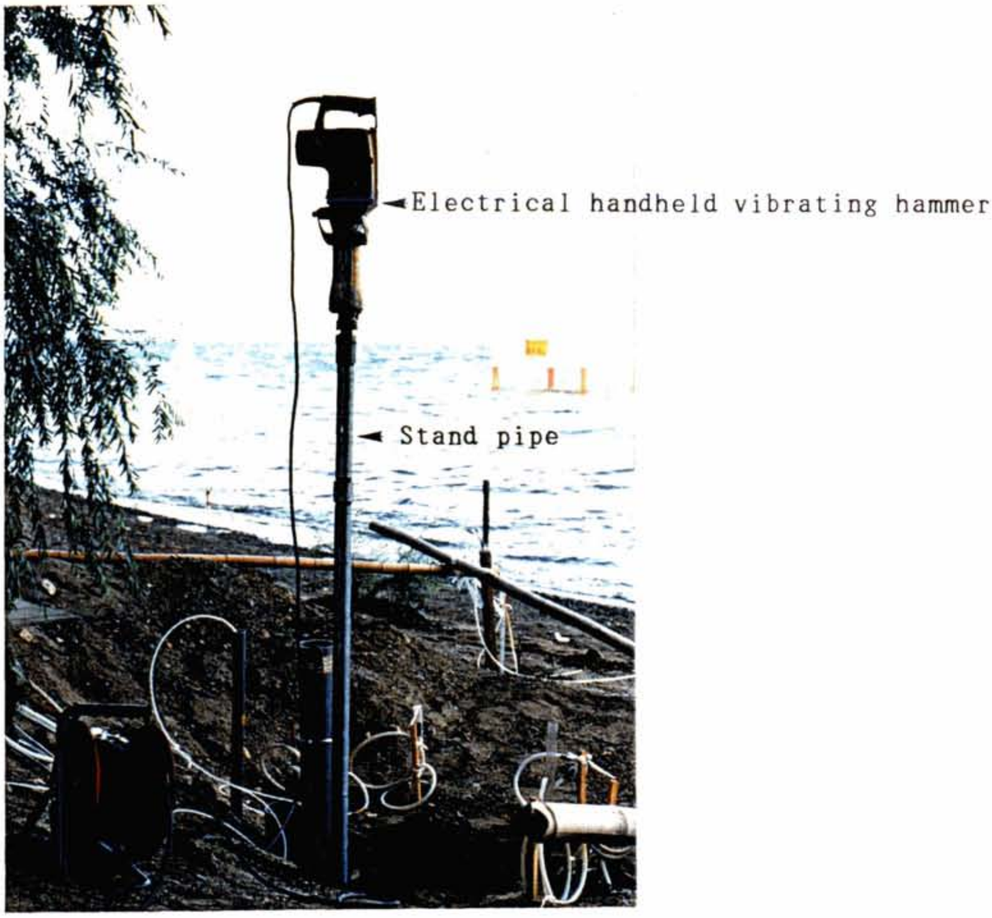
1

Transect line of Y-Y extended offshore along the poles in the lake.

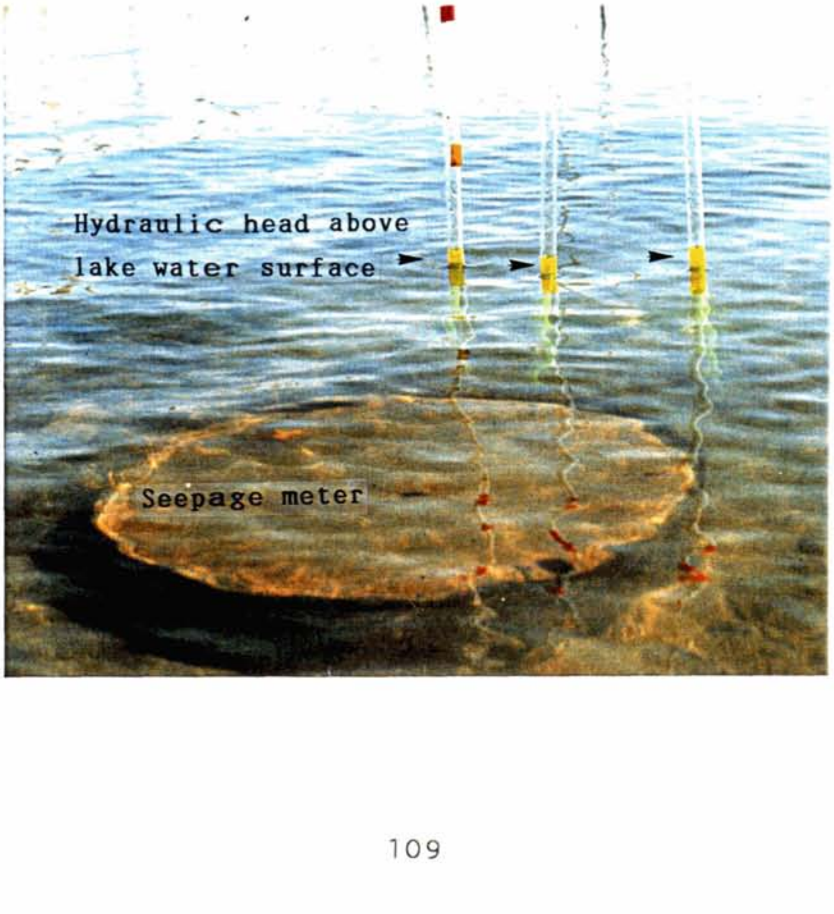
2

Appendix Ⅳ. Installation view of stand pipes and hydraulic heads of each piezometer near the shore.

1

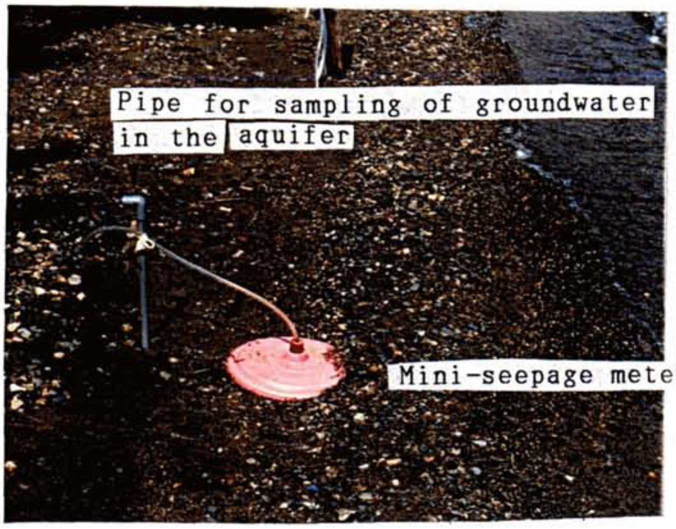


2



Appendix V. Mini-seepage meter and the view of sampling of groundwater in the lake(Wani beach). Seepage meters in the lake(white).

1



Bottom sediments were dug up by wave motion.

2

Samples of water were collected by gentle suction by vaccum.

Appendix Ⅵ. Lake water level change at Imajyuku beach(Sta. W3).

1

Heavy rainfall period(Baiu season)

2

Unusual light rainfall period

Appendix Ⅶ. Samples of water collected by seepage meter along the transect offshore at Wani beach(Sta. 4).

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