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Hydrological and chemical budgets of a mire pool formed on alluvial lowland of Hokkaido, northern Japan

Author names and affiliations

Toshikazu Kizuka [a, b, *, 1], Hiroyuki Yamada [a], Takashi Hirano [a]

[a] Laboratory of Environmental Informatics, Graduate School of Agriculture, Hokkaido University, Kita-9 Nishi-9, Kita-ku, Sapporo, Hokkaido 060-8589, Japan

[b] Research Fellow of the Japan Society for the Promotion of Science, 6 Ichiban-cho, Chiyoda-ku, Tokyo 102-8471, Japan

* Corresponding author (Toshikazu Kizuka). Phone: +81(11)706-4175, Fax: +81(11)706-2494, Postal address: Laboratory of Environmental Informatics, Graduate School of Agriculture, Hokkaido University, Kita-9 Nishi-9, Kita-ku, Sapporo, Hokkaido 060-8589, Japan

[1] Present address. Phone: +81(52)747-6548, Postal address: Graduate School of Environmental Studies 101, Nagoya University, D2-1(510), Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan

E-mail addresses: kiduka.toshikazu@d.mbox.nagoya-u.ac.jp (Toshikazu Kizuka), hiroyama@env.agr.hokudai.ac.jp (Hiroyuki Yamada), hirano@env.agr.houdai.ac.jp (Takashi Hirano)

Abstract

Mire pools—permanently water-filled depressions on peatlands—provide important habitats for myriad organisms. Recently, water balance change and eutrophication resulting from agricultural development are

increasingly evident in mire pools of alluvial lowlands. Conservation of mire pool hydrochemistry is necessary. We investigated the hydrological and chemical budgets of a pristine mire pool, Akanuma Pool (95,280 m^2 area; 1.8 m mean depth), located in Kushiro Mire in Hokkaido, northern Japan, during its ice-free period (April–November) in 2007–2008. Thereby we elucidated the hydrochemical characteristics of mire pools formed on alluvial lowlands. Surface water inflow and surface water outflow dominated the hydrological budget, respectively representing 18.3 and 20.2 mm day^{-1}. Groundwater seepage through the pool bottom and surface water inflow mainly supplied the lake water with total nitrogen and Ca^{2+}. Total phosphorus was supplied mostly by groundwater seepage through the bottom. These chemical constituents were run off from the pool mostly by surface water outflow. The input and output fluxes of water were 16–20 times greater than those of North American mire pools because of Hokkaido's higher values of precipitation minus evapotranspiration (*P*–*ET*). Moreover, the Ca^{2+} input into the Akanuma Pool was several times greater than those reported from North American studies. Alluvial mineral soil under the peat layer supplied large amounts of nutrients and mineral ions including Ca^{2+}. These results demonstrate that Hokkaido mire pools' hydrochemical characteristics differ greatly from those of pools in North America. Furthermore, each hydrological budget component maintained a constant fraction throughout the two year study period, although the absolute flow rate varied concomitantly with the precipitation level. Maintaining this budget stability is important for the conservation of mire pool hydrochemistry.

Abbreviations

V = lake water volume (m^3); P = precipitation (m^3 day^{-1}); E = lake water evaporation (m^3 day^{-1}); S = surface water flow (m^3 day^{-1}); G = horizontal groundwater flow (m^3 day^{-1}); D = vertical groundwater flow through the deeper pool bottom (m^3 day^{-1}); subscripts i and o = inflow and outflow, respectively; subscripts (n) and (n+1) = the values of (n)th and (n+1)th days, respectively; H and W = height and width of the cross-sectional area of horizontal groundwater inflow, respectively (m); K_g and K_d = hydraulic conductivity at the peatland area and the pool bottom, respectively (m day^{-1}); i_g and i_d = hydraulic gradient at the peatland area and the

pool bottom, respectively (dimensionless); A = cross-sectional area of vertical groundwater flow (m^2); h = water depth of surface flow (m); a = inverse parameter of surface flow resistance ($m^{-1}day^{-1}$); C_L,C_P, C_{Si}, C_{Gi}, and C_{Di} = chemical constituent concentration of lake water, precipitation, surface water flow, horizontal groundwater flow, and vertical groundwater flow, respectively (mg l^{-1}); Ca^{2+}, nitrogen, and phosphorous concentrations were applied to C when each constituent was calculated.

Keywords

Hydrochemistry; Mineral ion; Mire pool; Nutrient; Peatland; Surface water flow

1. Introduction

The water chemistry of mire pools, defined as permanently water-filled depressions formed on peatlands, is characterized by acidic conditions, abundant dissolved organic compounds, and poor nutrients and mineral ions (Kilroy et al., 2008; Proctor, 1994; Proctor, 2006; Sharma and Bhattarai, 2005). The water chemistry differs greatly from those of lakes or other bodies of water (e.g., lakes formed by volcanic activity or obstructive depositional processes of river sediments). Mire pools play an important role in biodiversity because they are the chief habitats of the various endemic aquatic organisms which have adapted to their unique chemistry (Kilroy et al., 2007). Moreover, peatlands including pools provide numerous ecosystem services as carbon and nutrient sinks and flood regulators (Devito and Dillon, 1993; Roulet et al., 2007). Therefore, social demands for their conservation are very strong.

Around 16% (473,000 km^2) of all peatland area, however, has been lost to agricultural and forestry development in temperate and cold climate regions, where more than 80% of the global peatland area exists (Joosten, 1999). In Japan, about 61% (1,290 km^2) of the total wetlands area (including peat-forming mires, freshwater marshes, and salt marshes) has been converted to other land uses (Japan Geographical Survey Institute, 2001). Consequently, many mire pools have disappeared because of drainage or reclamation of the lake water. Recently, changes of water balance and water chemistry are increasingly evident at the remaining

mire pools formed on alluvial lowlands, which are liable to be affected by human activities (Hokkaido Institute of Environmental Sciences, 2005; Kizuka and Yazawa, 2004). In particular, agricultural development of pool catchment areas has caused eutrophication of the lake water because of the inflow of chemical fertilizers (Kizuka et al., 2008). Such hydrochemical deterioration of mires would change the fish species there (H. Yamada et al., unpublished). Rehabilitation of the hydrochemical conditions is urgently necessary for conservation of the mire pools' ecosystems.

Generally speaking, for rehabilitating lake hydrochemistry, reversion of the hydrological and chemical budgets of lakes to natural conditions, with no artificial disturbance, is important (National Research Council, 1992). However, only one study (Ferone and Devito, 2004) has been conducted in North America on hydrological and chemical budgets of mire pools. Furthermore, none has addressed the nutrient budget. In Japan, although the water chemistry of some mire pools has been investigated (Hokkaido Institute of Environmental Sciences, 2005; Tachibana et al., 2002a; Tachibana et al., 2002b), the pools' hydrological and chemical budgets have not been estimated quantitatively. Their budget characteristics remain unknown.

Mire pools developed on kettle-hole peatlands in North America have lower flow rates of water input and output because their hydrological budgets depend on precipitation and evaporation (Ferone and Devito, 2004; Mouser et al., 2005). In contrast, Japanese peatlands have a larger surface water flow rate because of the greater precipitation there than in North America (Nakamura et al., 2002; Yabe and Onimaru, 1997). Surface water flow would therefore be a larger hydrological budget component for Japanese mire pools.

Regarding chemical budgets, groundwater flow supplies large shares of chemical constituent inputs (Ferone and Devito, 2004). The chemical constituent flux depends on the groundwater flow rate and the characteristics of soils and rocks under the peat layer, which supplies chemical constituents to the groundwater (Bendell-Young, 2003; Bragazza and Gerdol, 1999; Reeve et al., 1996). The groundwater flow rate and the geological conditions differ among peatland locations. Most studies that have investigated the hydrochemistry of mire pools have targeted peatlands formed on tilled plains or small platforms in mountainous areas; none has examined alluvial lowlands.

The objective of this study was to estimate the hydrological and chemical budgets including the nutrient budget of a mire pool, Akanuma Pool, located in Kushiro Mire of Hokkaido, northern Japan, which remains in a more or less natural condition among Japanese mire pools formed on alluvial lowland. Furthermore, we characterized the budgets of mire pools formed on alluvial lowlands in Hokkaido through comparison with the budgets of North American mire pools.

2. Study area

In alluvial lowlands of Hokkaido, climate cooling and the sea level falling after the Jomon transgression (about 6,000 years ago) led to the terrestrialization of coastal lakes and lagoons and commonly formed mires, which were peat-accumulating wetlands (Matsushita et al., 1985). Kushiro Mire is the largest mire (about 190 km^2) in Hokkaido. Conserved since ancient times, it has been designated as one of the Wetlands of International Importance by the Ramsar Convention in 1980 (Ramsar Secretariat, 2009), and has been a National Park since 1987.

A study pool, Akanuma Pool (N 43°6'30", E 144°21'35"), is located in western Kushiro Mire (Figs. 1a and 1b). The natural mire conditions remain around the pool as a special protection area for the National Park. The pool surface water area is 95,280 m^2, and its maximum water depth, mean water depth (water volume / surface water area), and water volume during the ice-free period (April–November) are, respectively, 2.1 m, 1.8 m, and 171,300 m^3. Similarly to many other mire pools, the Akanuma Pool bathymetry is a shallow pan shape with a near-vertical shore and a gently sloping bottom. The ground surface around the pool slopes gently down from the southwest to the northeast, forming an approximately 0.25% gradient (Fig. 1c). Although the pool has no inflow or outflow channel, surface water inflow and surface water outflow occur respectively at the southwestern and northeastern sides of the pool shoreline when the water table around the pool is high. The surface water outflow drains into the Hororo River, running approximately 300 m northeast of the pool (Fig. 1c).

Thirty-year average values (1971–2000) for summer (August) and winter (January) air temperatures are

17.9 and -5.6°C, respectively; the annual mean temperature is 5.9°C according to data of Kushiro Meteorological Station, located approximately 14 km south of the study area (Japan Meteorological Agency, 2009). The mean annual precipitation is 1,045 mm, with around 17% (177 mm) falling as snow.

The mire area around Akanuma Pool consists mainly of bogs with hummock–hollow microtopographies (Fig. 1c). The dominant plant species are peat mosses (*Sphagnum* spp.), sedges (*Carex* spp.), small cranberry (*Vaccinium oxycoccus*), bog-bean (*Menyanthes trifoliata*), crowberry (*Empetrum nigrum* var. *japonicum*), bog rosemary (*Andromeda polifolia*), sweet gale (*Myrica gale* var. *tomentosa*), and reed (*Phragmites australis*) (Tanaka et al., 1973). The peat depth around the pool is 3–4 m, consisting mainly of weakly decomposed sphagnum peat (Hokkaido Development Agency, 1963; Okazaki and Suzuki, 1977). The peat layer overlies alluvial mineral soil, which consists of clay and silt.

3. Materials and methods

3.1 Hydrological budget

The hydrological budget of Akanuma Pool is expressed as the following equation.

$$V_{(n+1)} = V_{(n)} + P_{(n)} + S_{i(n)} + G_{i(n)} + D_{(n)} - E_{(n)} - S_{o(n)} - G_{o(n)} \quad (1)$$

Therein, V denotes the lake water volume (m^3), P is precipitation, E signifies lake water evaporation, S stands for the surface water flow, G represents horizontal groundwater flow, and D denotes vertical groundwater flow through the deeper pool bottom (units of each component are m^3 day^{-1}). Subscripts i and o respectively represent inflow and outflow. Subscripts (n) and (n+1) respectively denote the values of the (n)th and (n+1)th days. The value of S_o was determined as the residual of Eq. (1) because it was difficult to measure S_o directly where no readily apparent outflow channel existed. To estimate other budget components, the following hydrometric measurements were conducted.

We surveyed the ground elevation of 50 m grid points, located within approximately 200 m from the

Akanuma Pool shoreline, using an electronic level (AL-50; Nikon Corp., Tokyo, Japan). Furthermore, we measured the pool's water depth and the geographic coordinates at 56 points including the shoreline using a tape measure and a GPS (MobileMapper; Magellan Navigation Inc., Santa Clara, CA, USA). The water depth data were converted to elevation data and integrated with a topographic map around the pool. These elevation data were used to construct a triangle irregular network (TIN) model of the pool bathymetry using geographic information system software (ArcGIS 9.3; ESRI, Redlands, CA, USA). A relation equation between the lake water level and water volume was produced by analyzing the water volume change with the lake water level gradations in the TIN model.

The lake water level was measured at 10 min intervals using a pressure transducer (HTV-020KP; Hi-Net Co., Ltd., Tokyo, Japan) and a data logger (VR71; T and D Corp., Matsumoto, Japan) at the southwest point of the pool during its ice-free period (April–November 2007 and May–November 2008) (Fig. 1d). To prevent the influences of waves, 30-min moving averages of the lake water level data were calculated. The lake water level data were converted to lake water volume using the level–volume relations.

A line transect was set across shoreline perpendicularly. Wells (40 mm inner diameter, polyvinyl chloride (PVC) pipe) were installed at each point located at distances of 5, 10, and 40 m from the shoreline (T1, T2, and T3, respectively; Fig. 1d) to monitor horizontal surfaces and groundwater flow systems between the peatland and pool. A pressure transducer (HTV-020KP) was inserted at each well. Pool bottom pore water pressure meters were installed at 0.5 and 1.0 m depths under the pool bottom at the point (P1) located at 14 m distance from the shoreline along the transect to monitor the vertical groundwater flow between the lake water and the bottom pore water (Fig. 1d). The pore water pressure meters were constructed with pressure transducers (HTV-050KP; Hi-Net Co., Ltd., Tokyo, Japan) attached to 0.1-m-long pressure-sensing compartments; the compartments were PVC pipes with 25-mm inner diameter with 0.1 m screens (6-mm inlet holes). The groundwater table and pore water pressure were measured at 10 min intervals using data loggers (VR71 and UIZ3635; Uizin, Tokyo, Japan) during the same period of the lake water level measurement.

Hydraulic conductivities were calculated for 0.2, 0.5, 1.0, and 1.5 m depths at T1, T2, and T3, and for 0.2, 0.5, and 1.0 m depths under pool bottoms at P1 and the point (P2) located 4 m distant from the shoreline using the Hvorslev piezometer test (Hvorslev, 1951), with 30-mm inner diameter PVC pipes with a screened section of 0.2 m at the lower end (6 mm inlet holes). Water recovery was recorded at one-second intervals using pressure transducers (HTV-020KP) and data loggers (VR71).

The horizontal groundwater inflow rate from the peatland to the pool, G_i, was calculated employing Dupuit–Forchheimer theory (Freeze and Cherry, 1979) on the assumption that the groundwater influx across the southwestern shoreline was equal to the flux along the line transect, as

$$G_i = HWK_g i_g , \tag{2}$$

where H and W respectively signify the height (m) and width (m) of the cross-sectional area of inflow, K_g is the hydraulic conductivity at the peatland area (m day^{-1}), and i_g is the hydraulic gradient (dimensionless). The value of i_g was calculated using the groundwater table gradient between T2 and T3. The cross-sectional area was estimated at T2. We estimated a length of perimeter line at T2 using a GIS buffer tool (ESRI, 2006), referencing to the pool's shoreline. The southwestern side of the perimeter length (935 m), where the surface ground sloped down to the pool, stands for W in Eq. (2). The vertical length from P1 bottom (2.46 m a.s.l.) to groundwater level at T2 was applied to H. Because K_g values varied with depth, H was divided to four peat depth profiles: the ground surface to 0.35 m, 0.35–0.75 m, 0.75–1.25 m, and 1.25 m to the base of groundwater flow (the altitude of P1 bottom). The K_g values of the four depths of 0.2, 0.5, 1.0, and 1.5 m (35, 31, 26, and 6.4 m day^{-1}, respectively), obtained using mean values for T1–T3, were applied to each profile. The horizontal groundwater outflow rate, G_o, occurs at the northeastern shoreline (Fig. 1d). To calculate G_o, the width (482 m) of the outflow cross-sectional area was given to W in Eq. (2). We used i_g, which was the same as that for the G_i calculation.

Vertical water flow rates between the lake water and the bottom pore water (D) were calculated using

Darcy's Law as

$$D = AK_d i_d , \quad (3)$$

where A represents the cross-sectional area of flow (m^2), K_d denotes the hydraulic conductivity at the pool bottom (m day^{-1}), and i_d is the hydraulic gradient between 0.5 and 1.0 m depths under the pool bottom at P1 (dimensionless). Actually, A can be presumed as a flat area because the pool's shape is a bucket, as described above. The pool bottom area (49,560 m^2) was applied as A. The mean value for the hydraulic conductivities at 0.5 and 1.0 m depths under P1 bottom (5.0×10^{-2} m day^{-1}) was given to K_d. Furthermore, D was estimated as inflow, D_i, when i_d was upward, and as outflow, D_o, when i_d was downward.

The surface water inflow rate, S_i, was calculated using a power law model (Kadlec, 1990; Kadlec and Knight, 1996) as

$$S_i = aWh^3 i_g , \quad (4)$$

where h represents the water depth of surface flow at T2 (m), and a is an inverse parameter of flow resistance ($m^{-1}day^{-1}$). The value of a was calibrated using the method described below. The value of S_i was calculated when the water table at T2 was higher than the ground surface. The flow rate per day was estimated by averaging the S_i values that were calculated hourly with 1-hour averages of h and i_g.

Precipitation (P) was measured using a tipping bucket gauge (RG2; Onset Computer Corp., Barnstable-Yarmouth, MA, USA) at T2 (Fig. 1d). The daily lake water evaporation (E) was calculated using the modified Penman equation (Linacre, 1993) with daily mean meteorological values observed at the Kushiro Meteorological Station (Japan Meteorological Agency, 2009). Solar irradiance of the pool's surface was estimated using data of cloud cover and extraterrestrial solar irradiance (Linacre, 1992; Penman, 1948).

3.2 Chemical budget

The chemical budget of a well-mixed pool such as Akanuma Pool can be expressed as

$$V_{(n+1)}C_{L(n+1)} = V_{(n)}C_{L(n)} + P_{(n)}C_{P(n)} + S_{i(n)}C_{Si(n)} + G_{i(n)}C_{Gi(n)} + D_{i(n)}C_{Di(n)} - S_{o(n)}C_{L(n)} - G_{o(n)}C_{L(n)} - D_{o(n)}C_{L(n)}, \quad (5)$$

where $C_{subscript}$ signifies the chemical constituent concentration (mg l^{-1}), subscript $_L$ represents lake water, and subscripts $_{P,\ Si,\ Gi,\ Di}$ represent each hydrological budget component. To estimate the chemical budget daily from the (n)th day to the next sampling day, ($n+N$)th day, the chemical constituent storage of the ($n+N$)th day, $V_{(n+N)}C_{L(n+N)}$ (g), was expressed as the following based on Eq. (5).

$$V_{(n+N)}C_{L(n+N)} = V_{(n)}C_{L(n)} + \sum_{k=0}^{N-1}(P_{(n+k)}C_{P(n+k)} + S_{i(n+k)}C_{Si(n+k)} + G_{i(n+k)}C_{Gi(n+k)} + D_{i(n+k)}C_{Di(n+k)} - S_{o(n+k)}C_{L(n+k)} - G_{o(n+k)}C_{L(n+k)} - D_{o(n+k)}C_{L(n+k)}) \quad (6)$$

To calculate the budget presented above, the tracer ion concentration that is not susceptible to chemical changes and vegetation uptake in lake water should be given to C. Although conservative tracers such as Cl^- and stable isotope have been generally used in many other budget studies (e.g., Drexler et al., 1999; Gurrieri and Furniss, 2004; Hayashi et al., 1998), we adopted Ca^{2+} as a tracer ion for comparison of Ca^{2+} budgets for two mire pools (Ferone and Devito, 2004). Then, the parameter a for S_i in Eq. (4) was calibrated to minimize the calculation error in the Ca^{2+} storage (ΔVC_L: calculation minus observation) by trial and error in the range of reported values for other peatlands (1.0×10^7–2.4×10^8 $m^{-1}day^{-1}$) (Kadlec, 1990; Kadlec and Knight, 1996).

The budgets of total nitrogen (TN) and total phosphorous (TP) were regarded as important substances indicating a eutrophic state in these ecosystems. After the Ca^{2+} and hydrological budget calculations, we estimated TN and TP budgets.

Daily values of C_P, C_{Si}, C_{Gi}, and C_{Di} were linearly interpolated between the (n)th and the ($n+N$)th days. Then they were input into Eq. 6. In addition, the daily values of C_L, as linearly interpolated, were used to calculate the TN and TP budgets. We surmised that nutrients flowing into the pool via precipitation, surface water, and groundwater were dissolved components. Dissolved TN (DTN) and dissolved TP (DTP) concentrations were given for C_P, C_{Si}, C_{Gi}, and C_{Di}.

3.3 Monitoring of water chemistry

Lake water, groundwater, bottom pore water, and precipitation were sampled on a monthly basis. To assess the spatial variation of lake water concentration (C_L), water samples were collected from the surface and middle water layers at each point including P1 and the center of the pool. During April–July 2007 only, the surface lake water at the P1 site was used because of missing values.

Piezometers were installed at 0.5, 1.0, and 1.5 m depths at every T1, T2, and T3 for groundwater sampling (Fig. 1d). The piezometers were PVC pipe with 20 mm internal diameter with a screened section of 0.1 m at the lower end (4 mm inlet holes), which was covered with polypropylene (PP) net of 1 mm^2 square mesh to prevent sediment from entering. The concentration of groundwater at T1, which was nearest to the pool, was used as C_{Gi}. Groundwater concentrations of 0.5, 1.0, and 1.5 m depths were applied, respectively, to flow layers of the ground surface to 0.75 m, 0.75–1.25 m, and 1.25 m to the base. To sample the bottom pore water, the same type of piezometers as the groundwater sampling were installed at 0.1, 0.5, and 1.0 m depths under the P1 bottom, and 0.1, 0.5, 1.0, and 1.5 m depths under the P2 bottom (Fig. 1d). The concentration of the pore water sampled at 1.0 m depth under the P1 bottom, which was the deepest point, was applied to C_{Di} to avoid the influence of solute diffusion between the pore water and the lake water (Kang et al., 2005). The refilled water sample of about 400 cm^3 was collected using a cylinder from every piezometer after pumping out stagnant water.

Precipitation was collected near T2 for C_P using a 0.21-m-diameter PP funnel and a PVC bucket (Fig. 1d). A plastic ball was placed in the funnel to prevent the sample from evaporating. In general, the solute

concentration of surface water in the bog area strongly reflects that of precipitation because the source of the solute was limited to the precipitation around it (Proctor, 1994). Particularly at bog peatlands, where surface-water flow occurs easily because precipitation is much greater than evapotranspiration, the solute concentration of surface water is reported as comparable to that of precipitation (Proctor, 2006). For that reason, C_P was applied to C_{Si}.

For chemical analyses, we transported water samples back to the laboratory in a cooled box. First, TN and TP were analyzed for lake water. Then all water samples were filtered using 0.45 μm membrane filters (Mixed Cellulose Ester A045A; Toyo Roshi Kaisha Ltd., Tokyo, Japan) in the laboratory for DTN, DTP, and ion analyses. The values of TN, DTN and TP, DTP were determined using the persulfate method and the ascorbic acid method with an absorption spectrophotometer (UVmini-1240; Shimadzu Corp., Kyoto, Japan), respectively (APHA et al., 1992). To check the accuracy of ion analysis by calculating the cation–anion balance, major anion and cation concentrations were analyzed. Using an ion chromatograph (IA-300; DKK-TOA Corp., Tokyo, Japan), NO_3^-, NO_2^-, Cl^-, SO_4^{2-}, Na^+, K^+, Ca^{2+}, and Mg^{2+} were analyzed. NH_4^+ was analyzed using the indophenol blue method. The HCO_3^- concentration was determined by measuring the alkalinity of a solution with pH of 4.8.

4. Results

4.1 Calibration of parameter and budget's error

Results of calibration of parameter *a*, which represents the inverse value of flow resistance, show that the parameter was within the range of $1.00 \times 10^7 – 2.40 \times 10^8$ m^{-1} day^{-1}; it tended to decrease in summer and autumn (July–October) (Table 1). It represented the minimum values during July–October in 2007 and during July–August in 2008. The Ca^{2+} storage calculated using this calibrated parameter coincided approximately with the observed value. Calculation errors for Ca^{2+} storage were -19 to 28% for observed values of each calculation interval.

4.2 Temporal variations of water and chemical constituents fluxes

Focusing on temporal variations of the lake water level and water fluxes (Fig. 2), heavy precipitation (P) events of more than 30 mm day^{-1} occurred occasionally, especially during May 2007 (Fig. 2a). The lake water level increased with precipitation events and remained at a higher level during May 2007, which had many heavy precipitation events. Lake water evaporation (E) declined gradually toward late autumn (November), reflecting the attenuation of solar radiation. Surface water inflow (S_i) and outflow (S_o) exhibited the largest values among all components (Figs. 2c and 2d). Both S_i and S_o indicated higher values with large precipitation and high lake water level and often reached over 300 mm day^{-1} in May 2007. The absolute values and the occurrence timings of S_i and S_o approximately coincided. Groundwater inflow (G_i) and outflow (G_o) were less than 1 mm day^{-1}. They were lower than other components including P, E, S_i, and S_o (Figs. 2e and 2f). It is noteworthy that groundwater seepage flow through the pool bottom (D) showed a higher inflow value next after S_i and P among input components. This fact suggests that groundwater infiltrating into the catchment of Akanuma Pool was discharged into the pool through the bottom. Although such groundwater seepage inflow was observed, water fluxes occurring aboveground such as S_i, S_o, and P predominated the hydrological budget of Akanuma Pool. The temporal variations of the aboveground fluxes depended on precipitation events.

Temporal variations of Ca^{2+} fluxes were similar to those of each component of water flux (Fig. 3). The Ca^{2+} fluxes with S_i and S_o (S_iC_{Si} and S_oC_L, respectively) tended to occur corresponding to precipitation events (Figs. 3c and 3d). The values of S_iC_{Si} and S_oC_L were higher during May 2007, when water fluxes including P, S_i, and S_o were large (Figs. 2c and 3c). At that time, S_oC_L was much higher than S_iC_{Si}, indicating that the Ca^{2+} output was larger than the input. In response, the Ca^{2+} concentration of lake water declined markedly from 11 to 2 mg l^{-1} (Fig. 3a). The Ca^{2+} fluxes with G_i and G_o (G_iC_{Gi} and G_oC_L, respectively) were lower than the other flux components, representing less than 5 mg m^{-2}day^{-1} (Figs. 3e and 3f). The Ca^{2+} input with D_i (D_iC_{Di}) was largest among subsurface Ca^{2+} fluxes and occurred constantly except in October 2008, when D_i was almost zero. These data suggest that Ca^{2+} was supplied continuously to the lake water by groundwater seepage

inflow through the pool bottom, although Ca^{2+} was run off suddenly, but for a short time, by the surface water outflow.

4.3 Hydrological and chemical budgets

Daily mean water fluxes during 2007–2008 indicated that total water input and output were 23.5 and 23.6 mm day^{-1}, respectively (Table 2). The hydrological budget was dominated by S_i and S_o, respectively representing 78% (18.3 mm day^{-1}) for total input and 86% (20.2 mm day^{-1}) for total output. In addition, P, D_i, and G_i respectively represented 16% (3.8 mm day^{-1}), 4% (1.0 mm day^{-1}), and 2% (0.46 mm day^{-1}) for total input, and E, G_o, and D_o respectively represented 13% (3.1 mm day^{-1}), 1% (0.24 mm day^{-1}), and 0% (0.0 mm day^{-1}) for total output. The contributions of G_i or D_i to the total water input and G_o or D_o to the total water output were very slight.

Chemical budget calculations indicated that total Ca^{2+} input and output during 2007–2008 were, respectively, 33 and 68 mg m^{-2} day^{-1} (Table 3). Actually, D_iC_{Di}, S_iC_{Si}, PC_P and G_iC_{Gi} respectively represented 51% (17 mg m^{-2} day^{-1}), 39% (13 mg m^{-2} day^{-1}), 7% (2.2 mg m^{-2} day^{-1}), and 4% (1.2 mg m^{-2} day^{-1}) for the total Ca^{2+} input. Nutrient budget calculations in 2007 indicated that D_iC_{Di}, S_iC_{Si}, PC_P and G_iC_{Gi} represented 47% (15 mg m^{-2} day^{-1}), 43% (14 mg m^{-2} day^{-1}), 7% (2.1 mg m^{-2} day^{-1}), and 2% (0.74 mg m^{-2} day^{-1}) for the total TN input, respectively. In addition, D_iC_{Di} represented 97% (4.1 mg m^{-2} day^{-1}) for the total TP input. Consequently, chemical constituents were supplied to the lake water mainly by groundwater seepage through the pool bottom. In addition, surface water inflow contributed in large part to the total input for Ca^{2+} and TN. Regarding outputs, S_oC_L represented 99% (68 mg $m^{-2}day^{-1}$), 98% (23 mg $m^{-2}day^{-1}$), and 99% (1.2 mg $m^{-2}day^{-1}$) for the total outputs of Ca^{2+}, TN, and TP, respectively, indicating that these chemical constituents were removed from the pool mostly by surface water outflow.

Specifically regarding the difference of hydrological budgets between 2007 and 2008, P of 2007, representing 4.6 mm day^{-1}, was greater than that of 2008, representing 2.9 mm day^{-1} (Table 2). According to the Kushiro Meteorological Station data, total precipitation data during April–November in 2007 and 2008

were 974 and 732 mm, which were respectively more and less than the 30-year averages (1971–2000) of 868 mm (Japan Meteorological Agency, 2009). Similarly to P, both S_i and S_o were greater in 2007 than 2008, and both total water input and output of 2007 were approximately twice as large as those of 2008. Similarly to the hydrological budget, Ca^{2+} fluxes of 2007 were greater than those of 2008 for most components of Ca^{2+} budget (Table 3). These data reflect that absolute amounts of water and Ca^{2+} fluxes varied with the precipitation level, although the percentages of each input and output component for the total input and output amounts, respectively, were comparable in the two years for both hydrological and Ca^{2+} budgets.

4.4 Groundwater chemistry

Chemical budget calculations revealed that chemical constituents were supplied to lake water mainly by groundwater seepage through the pool bottom. Therefore, we particularly examined the relations between the altitudes of the sampling points for groundwater as well as bottom pore water and solute concentrations including Ca^{2+} and dissolved nutrients (Fig. 4). Concentrations of Ca^{2+}, DTN, and DTP tended to increase concomitantly with decreasing altitude and tended to be higher for bottom pore water than for groundwater. Concentrations of Ca^{2+}, DTN, and DTP for bottom pore water were, respectively, 1.5–6.6, 1.8–14, and 4.7–203 times higher than each mean concentration of lake water during the study period (2.49, 0.91, 0.018 mg l^{-1}, respectively).

5. Discussion

5.1 Evaluation of parameter a and accuracy of budget calculation

Manning's n, representing flow resistance for surface water, increases from spring to autumn in wetlands, which results from the increase of flow resistance with the increase of stem size and density of vegetation (Kadlec and Knight, 1996). In the present study, parameter a was used to calculate the flow rate of surface water. Results show that parameter a tended to decrease in summer and autumn (July–October), apparently reflecting the influence of vegetation growth.

Ferone and Devito (2004) estimated the annual budget of Ca^{2+}, which was the tracer ion of their hydrological and chemical budgets calculations, for two mire pools in central North America, with errors of 7% and 9% for the observed Ca^{2+} storage in lake water. In the present study, Ca^{2+} storage was calculated with errors of -19 to 28% for observed values, which were larger than the estimates reported by Ferone and Devito (2004). This error for Ca^{2+} storage calculation was attributed to the measurement uncertainty for the flow rate of each hydrological budget component and the capability of applied Ca^{2+} concentrations to represent actual concentrations of the components (Winter, 1981). Although these uncertainties were not evaluated in the present study, past reports described that errors were about 5% or less for annual precipitation estimates and about 15% for lake water evaporation estimates using the Penman method when instrumentation was located near the shore (Gibson et al., 1998). We measured groundwater fluxes through the pool shore or the bottom at a representative line transect. For that reason, spatial variations of the fluxes might cause errors in our budget estimate.

For the calculations of TN and TP budgets, the biochemical changes such as vegetation uptake, oxidation–reduction reaction, and denitrification must be considered (Horne and Goldman, 1994; Schernewski, 2003). However, the present study did not address the biochemical changes. For that reason, the results of TN and TP budgets might have larger errors than those of Ca^{2+} budget which is not susceptible to biochemical changes.

5.2 Characteristics of the hydrological budget

The hydrological budget of Akanuma Pool was dominated by surface water inflow (S_i) and outflow (S_o). The absolute values as well as the occurrence timings of S_i and S_o mutually corresponded to an approximate degree. This is probably true because lake water, whose volume is the same as S_i, is immediately run off as S_o.

The amounts of S_i and S_o as well as total water input and output showed interannual variations because S_i and S_o depended strongly on the precipitation level. However, the respective percentages of water input and output components for the total input and output were the same every year. Schindler et al. (1976) estimated

the four-year hydrological budget of a glacial lake in Ontario, central Canada, and reported that input water via channels increased concomitantly with increased precipitation, although the contribution of each flow to the water balance did not change among years. A caldera lake in Japan showed a similar trend, except when artificial water was supplied (Ito et al., 2009). Such a hydrological feature—those by which the absolute values of water input and output vary depending on precipitation level into the catchment while keeping the flow rate balance for hydrological budget—is regarded as common for many natural lakes, including Akanuma Pool.

Previous studies targeting the hydrological budget of mire pools are limited to a study conducted in central North America (Ferone and Devito, 2004). They investigated the annual hydrological budgets of two mire pools (Moraine Pond and Clay Plain Pond) that originated from a kettle hole, and reported that precipitation and evaporation accounted for approximately 90% of the total water inputs and outputs, respectively, for both pools during their ice-free period (April–December). In contrast, the hydrological budget of Akanuma Pool was dominated by S_i and S_o. Specifically examining the flow rate for Moraine Pond and Clay Plain Pond, total water inputs were 1.40 and 1.21 mm day^{-1}, respectively, and the total water outputs were 1.47 and 1.50 mm day^{-1}, respectively during the ice-free period. In the case of Akanuma Pool, the total water input and output were, respectively, 23.5 and 23.6 mm day^{-1} on average during the ice-free period of 2007 and 2008. Those values are 16–20 times greater than the values of the reported mire pools in North America. Consequently, the amounts of water input and output as well as the main components of water fluxes of Akanuma Pool differ vastly from those of mire pools reported previously.

When precipitation (*P*) exceeds evapotranspiration (*ET*) to some degree, peat soils are saturated easily with precipitation events, and surface water flows occur (Evans et al., 1999; Holden and Burt, 2003). Ingram (1983) reported that surface water flows occur when *P–ET* (precipitation minus evapotranspiration) is higher than 0.7 mm day^{-1} for a blanket bog, although the threshold value of *P–ET* depended on the initial groundwater level. The annual value of *P–ET* for the kettle-hole peatland, where the two North American mire pools were located, was 0 mm day^{-1} (estimated from Ferone and Devito, 2004). In contrast, the annual

value of *P–ET* for Kushiro Mire, where Akanuma Pool was located, was 2.63 (estimated from Okazaki and Itoh, 1977) or 2.28 mm day^{-1} (estimated from K. Kudo and M. Nakatsugawa, unpublished), which are much higher than those of the kettle-hole peatland in North America or the 0.7 mm day^{-1} described by Ingram (1983). Therefore, the reason for the greater amount of S_i for Akanuma Pool is probably the higher value of *P–ET* at the mire area.

According to data of 22 meteorological stations located throughout Hokkaido, 30-year averages (1971–2000) for annual precipitation are 2.20–4.77 mm day^{-1}. These precipitation values for most stations (16 stations) are higher than those recorded at the Kushiro Meteorological Station (2.86 mm day^{-1}), which is the present study area (Japan Meteorological Agency, 2009). On the other hand, evapotranspiration of the bog area in Sarobetsu Mire, which is one of the peatlands formed on alluvial lowlands in northern Hokkaido, was 1.86 mm day^{-1} during June–August (Takahashi, 2002). This value is comparable to the evapotranspiration (2.2 mm day^{-1}, estimated from Y. Sasaka et al., unpublished) observed at the bog area in Kushiro Mire during August–September in 2006. The value of *P–ET* was 4.48 mm day^{-1} during the growing season (June–August) in Fuhrengawa Mire of eastern Hokkaido (Yazaki, 2006). These results suggest that other peatlands in Hokkaido have *P–ET* that are equal to or greater than that of Kushiro Mire. Accordingly, other mire pools in Hokkaido might have as large or larger amounts of surface water inflow as Anakuma Pool, because higher *P–ET* would cause surface water flow.

5.3 Characteristics of chemical budget

Chemical budget calculations indicated that Ca^{2+} and TN were supplied to the lake water mainly by groundwater seepage through the pool bottom (D_i) and by S_i. Furthermore, TP was supplied mostly by D_i. These chemical constituents were run off from the pool mostly by S_o. Results of temporal variations for water fluxes suggest that the occurrence of S_o resulted from S_i. Moreover, the Ca^{2+} concentration of the lake water declined markedly with a large amount of S_i in May 2007. Accordingly, the inflow and outflow of surface water are thought to have a role in inhibiting the chemical constituents from accumulating in the lake water.

For the Moraine Pond and Clay Plain Pond in North America, the total Ca^{2+} inputs were estimated as 4.70 and 1.89 mg $m^{-2}day^{-1}$, respectively, and the total Ca^{2+} outputs were estimated as 1.27 and 1.62 mg $m^{-2}day^{-1}$, respectively (estimated from Ferone and Devito, 2004). In contrast, the respective total Ca^{2+} input and output for Akanuma Pool were 33 and 68 mg $m^{-2}day^{-1}$, on average, during the ice-free period of 2007 and 2008. Those values are several to dozens of times greater than those reported from North America study. Similarly to the water fluxes, Akanuma Pool has greater fluxes of chemical constituents.

Specifically regarding the vertical groundwater flux through the pool bottom, which affects the chemical constituent supply, the Moraine Pond and Clay Plain Pond respectively had leakage water losses of 0.007 and 0.004 mm day^{-1} (estimated from Ferone and Devito, 2004) during the ice-free period, presumably because kettle-hole peatlands formed on glacial deposits, where groundwater readily recharges (Dempster et al., 2006). Akanuma Pool showed input seepage water of 1.0 mm day^{-1} through the bottom, on average, during the ice-free period of 2007 and 2008, resulting in greater input fluxes of chemical constituents. For pools that formed on alluvial lowland, groundwater usually flows into pools because alluvial lowlands are located on the groundwater discharge area (Brock et al., 1982; Schneider et al., 2005; Yamamoto, 1992).

On the other hand, solute concentrations such as those of Ca^{2+}, DTN, and DTP for groundwater and bottom pore water tended to increase along with the decrease of the sampling altitude. Alluvial mineral soils including clay and silt exist around Akanuma Pool (Hokkaido Development Agency, 1963; Okazaki and Suzuki, 1977). The altitude of the mineral soil layer is lower than our sampling positions for groundwater and bottom pore water. The groundwater and the bottom pore water that are closer to the mineral soils can receive larger amounts of mineral ions and nutrients from the mineral soil by advection and diffusion (Glaser et al., 1997; Bragazza and Gerdol, 1999; Reeve et al., 1996).

Generally, alluvial lowland peatlands are formed on mineral soils which derive from marine and terrestrial sediments (Miyaji et al., 1995; Reeve et al., 1996; Yamada et al., 2004). Therefore, the alluvial lowland mire pools can receive larger amounts of mineral ions and nutrients from the underlying mineral soils. In contrast, some upland peatlands had thinner mineral soils than lowland areas, or none at all (Devito

and Hill, 1997; Okada, 2007). In fact, the concentrations of mineral ions and nutrients of upland mire pool's water were extremely lower than those of Akanuma Pool (e.g., pools of Bealey Spur Wetland, Ca^{2+} 0.43–1.48 mg l^{-1}, TN 0.221–0.296 mg l^{-1}, TP 0.0038–0.0065 mg l^{-1}, Kilroy et al., 2008; a pool of Miyatoko Mire, Ca^{2+} 0.61 mg l^{-1}, Watanabe et al., 2000; pools of Uryunuma Mire, Ca^{2+} 0.2–0.8 mg l^{-1}, Tachibana et al., 2002b; mean values of Akanuma Pool, Ca^{2+} 2.49 mg l^{-1}, TN 1.26 mg l^{-1}, TP 0.061 mg l^{-1}). Accordingly, higher solute concentration might be a general characteristic of lowland mire pools.

The fact that the chemical constituent flux differs so greatly between Akanuma Pool and North American pools described above suggests that the chemical budgets of mire pools depend strongly on the recharge and discharge regimes of groundwater as well as on the occurrence of mineral soils under the peat layer on which pools are located.

6. Conclusion

Meteorological and geological conditions, including precipitation minus evapotranspiration (*P–ET*), recharge and discharge regimes of groundwater, and the occurrence of mineral soils under the peat layer are regarded as important factors governing the hydrological and chemical budgets of mire pools. Japan has more precipitation under the influence of a temperate monsoon than central North America does. Furthermore, in Hokkaido, which is located in the cool temperate zone, mire pools are generally formed on alluvial lowland with mineral soils under a peat layer. Therefore, these pools can be expected to have large input and output fluxes of water and chemical constituents similarly to those of Akanuma Pool. It is noteworthy that each hydrological budget component maintains a constant fraction, although the absolute flow rate varies with precipitation levels, which suggests that the budget maintains some stability corresponding to precipitation levels. This mechanism plays an important role in inhibiting the chemical constituents from accumulating in the lake water by generating surface water outflow.

Recently, based on growing consideration of mire pool values, projects targeting conservation of remaining pools or rehabilitation of the ecosystem for degraded pools have been conducted worldwide (e.g.,

Higgins et al., 2006; Mazerolle et al., 2006). Results of hydrological and chemical budgets estimated in this study can provide important knowledge for quantitative determination of conservation and rehabilitation methods for the pool hydrochemistry. To conserve mire pools continuously, it is important to maintain some mechanism for stabilizing the hydrological budget. Failing to do so, it might be difficult to conserve the hydrochemistry of pools that have lost stability, i.e. a constant fraction of each budget's component. It is necessary to conserve, preferentially, those mire pools that have retained stability and to bring the hydrological budget to the natural conditions necessary for their rehabilitation.

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Figure captions

Fig. 1 Locations of Kushiro Mire (a) and Akanuma Pool (b), vegetation cover and topography around Akanuma Pool (c), and location of instrumentation (d). The distributional area of Kushiro Mire in (b) and vegetation cover in (c) are described using GIS data of the natural environment (Biodiversity Center of Japan, 2009). The contour in (c) represents the ground surface elevation (m a.s.l.).

Fig. 2 Temporal variations of the lake water level and water fluxes of hydrological budget (Eq. (1)). Lake water level, precipitation (P), and evaporation (E) for (a) and (b); surface water inflow and outflow (S_i, S_o) for (c) and (d); groundwater inflow and outflow (G_i, G_o), and groundwater seepage flow through the pool bottom (D) for (e) and (f). Every water flux represents flow rates per unit pool's surface water area (mm day^{-1}). Positive and negative values of fluxes respectively represent input and output.

Fig. 3 Temporal variations of Ca^{2+} concentration of lake water ([Ca^{2+}]) and Ca^{2+} fluxes. [Ca^{2+}] and the Ca^{2+} fluxes of precipitation (PC_P) for (a) and (b); surface water inflow and outflow (S_iC_{Si}, S_oC_L) for (c) and (d); groundwater inflow and outflow (G_iC_{Gi}, G_oC_L), and groundwater seepage inflow and outflow through the pool bottom (D_iC_{Di}, D_oC_L) for (e) and (f). Every Ca^{2+} flux represents values per unit pool's surface water area (mg $m^{-2}day^{-1}$). Positive and negative values of fluxes respectively represent input and output. The Ca^{2+} concentration of lake water represents mean±S.D. for all sampling points.

Fig. 4 Relation between the altitudes of the sampling point (m a.s.l.) and the solute concentrations of Ca^{2+}, DTN, and DTP (mg l^{-1}) in bottom pore water (filled circles) as well as groundwater (open circles). These concentrations represent mean values of all sampled water for each sampling point. The dashed line represents mean concentrations of lake water during the study period.

Table 1. Parameter *a*, calculated and observed Ca^{2+} storage and error

Calculation year and interval	Days	Parameter a ($m^{-1}day^{-1}$)	Calculated storage $V_{(n+N)}C_{L(n+N)}$ *cal.* (kg)	Observed storage $V_{(n+N)}C_{L(n+N)}$ *obs.* (kg)	ΔVC_L (kg)	Error $\Delta VC_L / V_{(n+N)}C_{L(n+N)}$ *obs.* ×100 (%)
2007						
28 Apr–12 May	15	1.86×10^8	402	402	0	0
13 May–3 Jun	22	3.72×10^7	324	324	0	0
4 Jun–23 Jun	20	6.87×10^7	340	340	0	0
24 Jun–21 Jul	28	9.18×10^7	367	367	0	0
22 Jul–28 Aug	38	1.00×10^7	409	484	-74	-15
29 Aug–17 Oct	50	1.00×10^7	549	682	-133	-19
18 Oct–1 Nov	15	2.40×10^8	682	566	116	20
2008						
23 May–19 Jun	28	2.40×10^8	212	166	46	28
20 Jun–20 Jul	31	2.40×10^8	215	183	32	17
21 Jul–10 Aug	21	1.00×10^7	208	212	-4	-2
11 Aug–12 Sep	33	1.09×10^8	215	215	0	0
13 Sep–23 Oct	41	1.14×10^8	219	219	0	0
24 Oct–17 Nov	25	2.40×10^8	233	207	26	12

Calculated and observed Ca^{2+} storage represent values for the end of each calculation interval.

Table 2. Hydrological budget and the percentage of each budget's component of total input or output flux

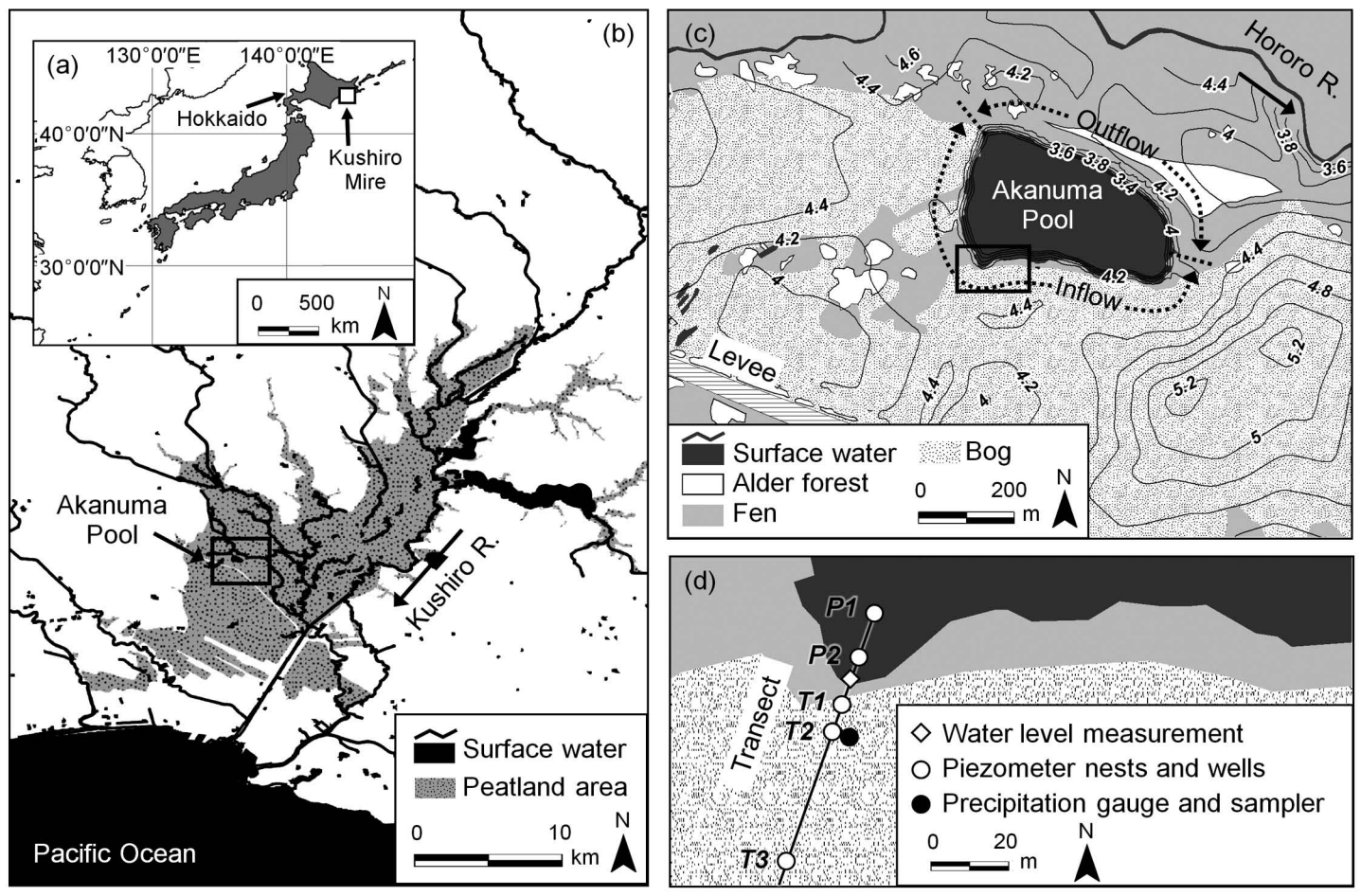
Calculation year	Days	Input (mm day^{-1})					Output (mm day^{-1})				
		P	S_i	G_i	D_i	Total	E	S_o	G_o	D_o	Total
2007	188	4.6 (16)	23.5 (79)	0.51 (2)	1.1 (4)	29.8	3.1 (10)	26.3 (89)	0.26 (1)	0.0 (0)	29.7
2008	179	2.9 (17)	12.9 (76)	0.40 (2)	0.85 (5)	17.0	3.1 (18)	13.8 (81)	0.21 (1)	0.0 (0)	17.2
2007–2008	367	3.8 (16)	18.3 (78)	0.46 (2)	1.0 (4)	23.5	3.1 (13)	20.2 (86)	0.24 (1)	0.0 (0)	23.6

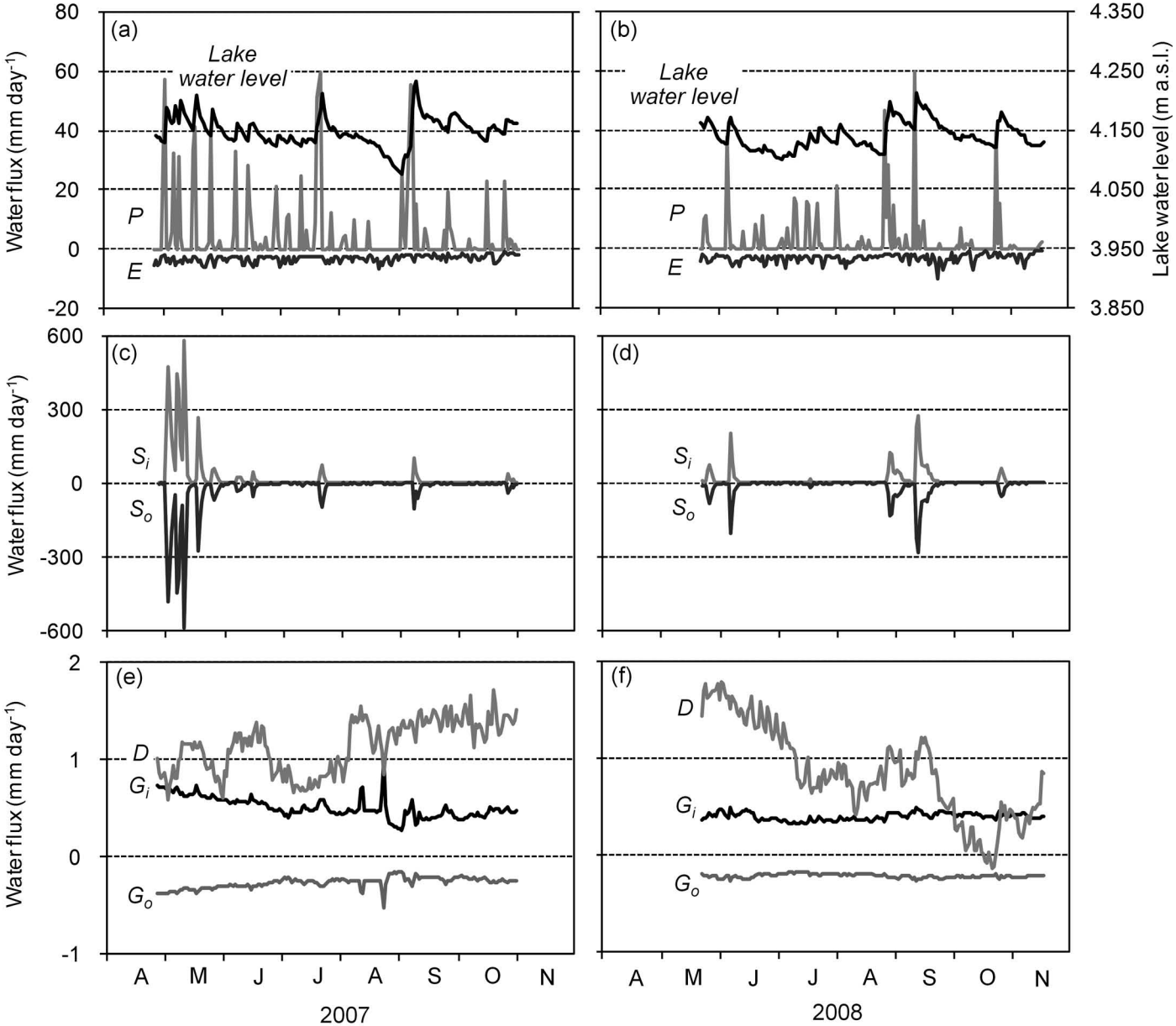
Water fluxes for precipitation (P), evaporation (E), surface water inflow and outflow (S_i, S_o), groundwater inflow and outflow (G_i, G_o), and groundwater seepage inflow and outflow through the pool bottom (D_i, D_o) represent means of daily values per unit of pool surface water area for each calculation year. Figures in parentheses represent the percentages of budget components for total input or output flux.

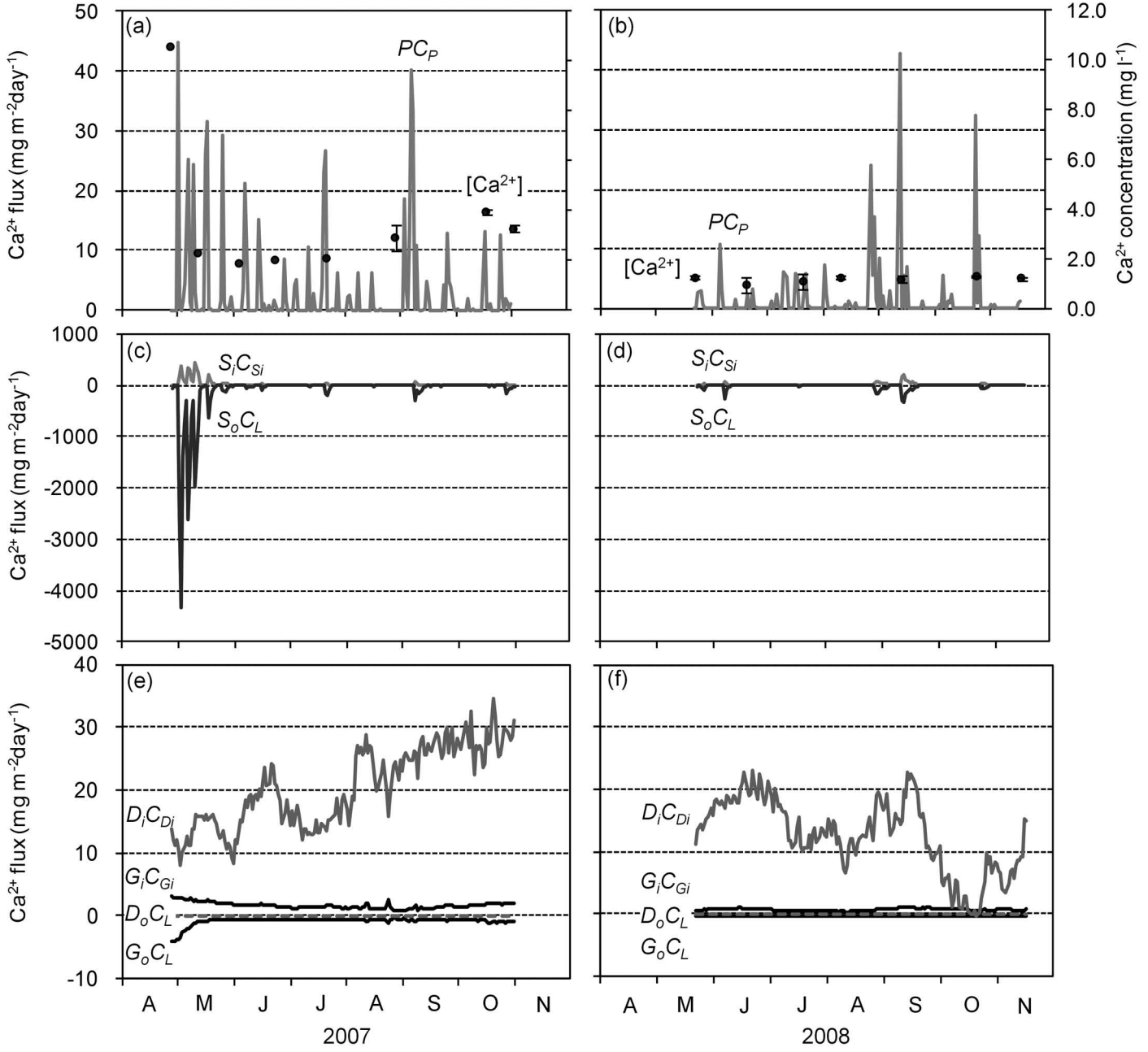
Table 3. Ca^{2+}, TN, and TP budgets and the percentage of each budget's component of total input or output flux

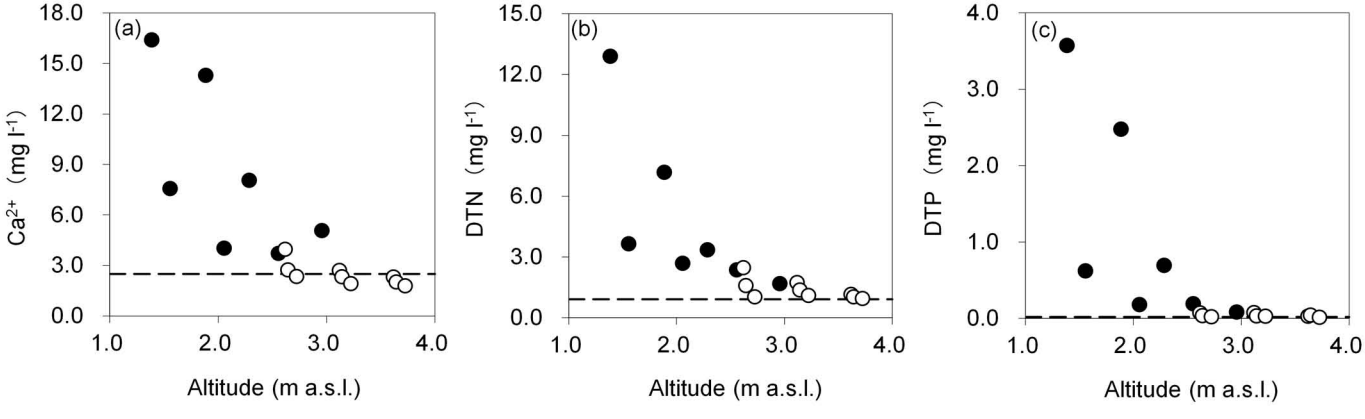
Chemical constituent and calculation year	Days	Input (mg $m^{-2}day^{-1}$)					Output (mg $m^{-2}day^{-1}$)			
		PC_P	S_iC_{Si}	G_iC_{Gi}	D_iC_{Di}	Total	S_oC_L	G_oC_L	D_oC_L	Total
Ca^{2+}										
2007	188	2.9 (7)	17 (41)	1.7 (4)	20 (48)	43	116 (99)	0.78 (1)	0.0 (0)	117
2008	179	1.5 (7)	7.6 (34)	0.73 (3)	13 (56)	22	17 (99)	0.25 (1)	0.0 (0)	17
2007–2008	367	2.2 (7)	13 (39)	1.2 (4)	17 (51)	33	68 (99)	0.52 (1)	0.0 (0)	68
TN										
2007	188	2.1 (7)	14 (43)	0.74 (2)	15 (47)	31	23 (98)	0.37 (2)	0.0 (0)	24
TP										
2007	188	0.02 (0)	0.06 (1)	0.025 (1)	4.1 (97)	4.2	1.2 (99)	0.015 (1)	0.0 (0)	1.2

Chemical constituent fluxes for precipitation (PC_P), surface water inflow and outflow (S_iC_{Si}, S_oC_L), groundwater inflow and outflow (G_iC_{Gi}, G_oC_L), and groundwater seepage inflow and outflow through the pool bottom (D_iC_{Di}, D_oC_L) represent means of daily values per unit of pool surface water area for each calculation year. Figures in parentheses represent percentages of budget components for total input or output flux.


(a)
130°0′0″E
140°0′0″E
40°0′0″N
30°0′0″N
Hokkaido
Kushiro Mire
0 500 km
N
(b)
Akanuma Pool
Kushiro R.
Surface water
Peatland area
0 10 km
N
Pacific Ocean
(c)
Hororo R.
Outflow
Inflow
Akanuma Pool
Levee
Surface water
Alder forest
Fen
Bog
0 200 m
N
(d)
P1
P2
T1
T2
T3
Transect
Water level measurement
Piezometer nests and wells
Precipitation gauge and sampler
0 20 m
N


(a)
Lake water level
P
E
(b)
Lake water level
P
E
Water flux (mm day-1)
Lake water level (m a.s.l.)
80
60
40
20
0
-20
4.350
4.250
4.150
4.050
3.950
3.850
(c)
Si
So
(d)
Si
So
600
300
0
-300
-600
(e)
D
Gi
Go
(f)
D
Gi
Go
2
1
0
-1
A
M
J
J
A
S
O
N
2007
2008


(a)
(b)
(c)
(d)
(e)
(f)
PC_P
[Ca^{2+}]
S_iC_{Si}
S_oC_L
D_iC_{Di}
G_iC_{Gi}
D_oC_L
G_oC_L
Ca^{2+} flux (mg m^{-2}day^{-1})
Ca^{2+} concentration (mg l^{-1})
A M J J A S O N
2007
2008


(a)
Ca2+ (mg l-1)
18.0
15.0
12.0
9.0
6.0
3.0
0.0
1.0
2.0
3.0
4.0
Altitude (m a.s.l.)
(b)
DTN (mg l-1)
15.0
12.0
9.0
6.0
3.0
0.0
1.0
2.0
3.0
4.0
Altitude (m a.s.l.)
(c)
DTP (mg l-1)
4.0
3.0
2.0
1.0
0.0
1.0
2.0
3.0
4.0
Altitude (m a.s.l.)