Retention time of lakes in the Larsemann Hills oasis, East Antarctica

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Abstract. The study gives first estimates of water transport time scales for five lakes located in the Larsemann Hills oasis (69º23´S, 76º20´E) in East Antarctica. We estimated the lake retention time (LRT) as a ratio of the lake volume to the inflow and outflow terms of a lake water balance equation. The LRT was evaluated for lakes of epiglacial and land-locked types, and it was assumed that these lakes are monomictic with water exchange existing during the warm season only. We used hydrological observations collected in 4 seasonal field campaigns to evaluate the LRT. For the epiglacial lakes Progress and Nella/Scandrett, the LRT was estimated at 12–13 and 4–5 years, respectively. For the land-locked lakes Stepped, Sarah Tarn and Reid, our results show a big difference in the LRT calculated from the outflow and inflow terms of the water balance equation. The LRT for these lakes vary depending on the methods and errors inherent to them. We suggest to rely on the estimations from the outflow terms since they are based on the hydrological measurements with better quality. Lake Stepped exchange water within less then 1.5 years. Lake Sarah Tarn and Lake Reid are endorheic ponds with the water loss mainly through evaporation, their LRT was estimated as 21–22 years and 8–9 years, respectively. To improve the estimates of the LRT, the special hydrological observations are needed to monitor the lakes and streams during the warm season with the uniform observational program.

1 Introduction

Antarctica is the continent, where most of water is frozen and deposited in the ice sheets, glaciers and permafrost. It makes the continent sensitive to climate warming by enhancing a transition of water from solid to liquid phase (melting). Melted water accumulates in lakes and streams, which appear on the surface of the continental ice sheet, at its contact with rocks and in local depressions in ice free areas (oases). Antarctic lakes exist under the ice sheet (subglacial type lakes) and on top of it (supraglacial type). Many lakes are located on the boundary between the rocks and continental/shelf ice sheets (epiglacial and epishelf types). In oases, lakes of the land-locked or closed basin type occupy local relief depressions (Govil et al., 2016; Hodgson, 2012).

In warm seasons, numerous supraglacial lakes appear on the surface of the continental ice sheet over its edges, in “blue ice” regions, and in the vicinity of rock islands or nunataks (Leppäranta et al., 2020; Bell et al., 2017). These lakes may be up to

80 km long, and accumulate large amounts of liquid water potentially affecting the ice discharge, ice calving and hydro-stability of the continental ice sheet (Stokes et al., 2019;). Lakes of the epiglacial type are situated at glacier edges, and melting of the glacier ice is the main source of water inflow to them. These lakes may be perennially frozen, or partially free of ice during the austral summer lasting from December to February. Land-locked lakes appear after retreat of the continental ice sheet in local depressions. Precipitation and melting of seasonal snow cover are two main sources of water inflow for these lakes. Precipitation over the lake surface usually contributes insignificantly to the water inflow compared to the snow melting (Klokov, 1979). Land locked lakes are ice-free for a period of 2–3 months in summer, and they mostly lose water through the surface runoff in the outlet streams, and/or through evaporation over their surface. In our study, we focus on two types of lakes, namely epiglacial and land-locked, located in the ice free area of the Larsemann Hills oasis, East Antarctic coast.

Water chemical composition and presence of living forms in Antarctic lakes are strongly linked to their thermal regime and water balance (Castendyk et al., 2016; Bomblies et al., 2001). Among other parameters, water transport/exchange time scales are needed to study lake eutrophication, bio production and geochemical processes by numerical modelling (Nuruzzama et al., 2020; Geyer et al., 2000; Foy, 1992; Burton, 1981). The lake retention time (LRT), also called "the flushing time" in Geyer et al. (2000) or "the coefficient of water external exchange" in Doganovsky and Myakisheva (2015), is among other transport scales to be taken into account while modeling the water exchange and mixing processes in lakes and estuaries (Monsen et. al., 2002; Lincoln et al., 1998). It indicates the time period of water renewing in the lake (Pilotti et al., 2014; Rueda et al., 2006) and is usually expressed in years. There are only few studies addressing estimates of water transport scales for the Antarctic lakes, mostly due to lack on the hydrological observations. For example, Foreman et al. (2004) give the hydraulic residence time (which is the same as the LRT) for three lakes located in the Dry Valleys, West Antarctica; Loopman and Klokov (1988) suggest estimations of the coefficient of water external exchange (which is the inverse of the LRT) of six lakes located in the Schirmacher oasis, East Antarctica.

This study contributes to estimations of the LRT of lakes located in the Larsemann Hills oasis, East Antarctica. Water temperature regime, chemical composition, and biota of the local lakes have been actively studied since 1990s (Hodgson et al., 2006 and 2005; Verleyen et al., 2004 and 2003; Saabe et al., 2004 and 2003; Kaup and Burgess, 2002; Gasparon et al., 2002; Burgess and Kaup, 1997). However, understanding of the seasonal water cycle of these lakes is still weak due to serious gaps in the hydrological measurements on the lakes. It limits the applicability of mass/water balance and biogeochemical models (Nuruzamma et al., 2020; Kaup, 2005). This study focuses on the lakes Stepped, Nella/Scandrett, Progress, Sarah Tarn and Reid since their water resources and biogeochemistry are important for human activity (Sokratova, 2011; Burgess and Kaup, 1997; Burgess et al., 1992). Hydrological data collected during four summer seasons in years 2011–2017 were used to calculate the LRT.

1. Study area

The Larsemann Hills occupy an area of approximately 50 square kilometres on the sea shore of the Princess Elizabeth Land, East Antarctica. The area consists of the Stornes, Broknes and Mirror peninsulas, together with a number of small islands in Prydz Bay. The peninsulas are rocks exposed by glacial retreat since the Last Glacial Maximum (Hodgson et al., 2005). The basement geology consists of the composite of orthogneisses overlying various pegmatites and granites (Geological map, 2018; Carson et al., 1995).

Climate of the Larsemann Hills is influanced by katabatic winds blowing from the north-east during most of austral summer. In this period, the daytime air temperatures frequently exceed 10 ℃, with the mean monthly temperature of about 0 ℃. Mean monthly winter temperatures range between –15 ℃ and –18 ℃. The annual precipitation amount is 159 mm (statistics is taken from the Russian Arctic and Antarctic Research Institute, http://www.aari.aq). Rain is rarely observed over the ice free areas also known as oases. There are two meteorological stations in the Larsemann Hills. Zhongshan station (WMO index 89573) started operating in 1989, and Progress station (89574) operated intermittently from 1988–1998, and since 1999 started to provide continuous observations (Turner and Pendlebury, 2004). Local climatology for the period of 1988–2010 is reported by the Russian Arctic and Antarctic Research Institute from the Progress station, see Table 1 in Shevnina and Kourzeneva (2017). Yu et al. (2018) notice the increasing trends for the annual precipitation for the period of 2003–2016.

There are more than 150 lakes in the Larsemann Hills oasis. Many of them occupy local depressions formed after melting of the continental ice sheet (Gillieson et al., 1990). The lake water chemical composition is affected by sea sprays, local geology and periodic seawater surges caused by calving of the Dålk glacier situated next to the east corner of the oasis (Kaup and Burgess, 2002; Stüwe et al., 1989). The majority of lakes are monomictic, which means that they are thermally homogeneous during summer, also due to persistent katabatic winds (Bian et al., 1994). The land-locked and epiglacial lakes are typical for the coastal ice free areas such as the Larsemann Hills oasis. The land-locked lakes are usually small ponds (Lake Stepped, Lake Sarah Tarn and Lake Reid in the Fig. 1).

Figure 1: Lakes on the Mirror peninsula, the Larsemann Hills, East Antarctica:

A: the red box indicates the location of the oasis; B: the red lines outline the catchment areas represent the lakes considered in this study according to the digital map scale of 1:25000, AAD, 2005;t he LIMA composite is on the background map(Bindschadler et al., 2008).

Land locked lakes are free of ice in December–February, and their water temperatures reach 10.0–11.0 °C in January (Boronina et al., 2019; Gillieson et al., 1990). Lake Stepped is located in the old coastal lagoon, and connected to the sea through the underground leakage of water. During the warm period, on outlet stream in the north-eastern corner of the lake releases water surplus. Water surplus occurs due to melting of the seasonal snow cover in the lake catchment. Lake Sarah Tarn and Lake Reid are endorheic ponds with no (or minor) outflow surface/ground runoff. The land-locked lakes are fed by seasonal snow cover melting, precipitation and sea sprays (Kaup and Burgess, 2002). Water level of the lakes Stepped, Sarah Tarn and Reid varies by 0.2–0.4 m during the austral summers. According to observations and modelling results, these lakes are well mixed during the summer seasons (Shevnina and Kourzeneva, 2017). A special case is Lake Reid, which has brackish water. In this lake, the thermal stratification resistant to the katabatic winds of over 14 ms^{-1} was observed by Kaup and Burgess (2003) in January 1994. Assumption about mixed state is important for our calculations of the LRT. We don't exclude Lake Reid from our calculations assuming it to be mixed, because this was shown by modelling results in Shevnina and Kourzeneva, (2017) by the fresh water lake model, however.

The epiglacial lakes are situated at the boundary between the glaciated and rock areas, and they are mostly fed by melting of the ice/snow of the lowest (ablation) zone of the glaciers (Klokov, 1979). Lake Progress and Lake Nella/Scandrett are the two biggest epiglacial lakes located on the Mirror peninsula of the Larsemann Hills oasis. Both lakes are fed by the melting of the Dålk glacier, however the portion of the glaciated area differ for these lakes: it is more than 50% for Lake Progress (Fig. 1). However, it is less than 10 % in case of Lake Nella/Scadrett. Table 1 shows the available estimates for the actual volumes of the studied lakes. Here and after, the lake name is given together with the lake index according to the Atlas of Lakes (Gillieson et al., 1990).

Table 1. The volume (V, x10^3 m^3) and area (A, x10^3 m^2), of five lakes located in the Larsemann Hills oasis: estimated after (Shevnina and Kourzeneva, 2017) / (Pryakhina et al., 2020). No estimates are indicated by "–" .

Parameter	Epiglacial lakes		Land-locked lakes		
	Lake Progress /LH57	Lake Nella/Scandrett /LH72	Lake Stepped /LH68	Lake Reid /LH70	Lake Sarah Tarn / LH71
V, x10^3 m^3	1812.4 / 1526.75	1033.2 / 1490.7	40.5 / 51.03	25.5 / 40.45	10.5 / –
A, x10^3 m^2	160.6 / 125.7	155.9 / 157.9	47.3 / 44.4	33.1 / 35.5	6.1 / –

The newest estimates of the actual volume of the lakes Stepped/LH68, Nella/Scandrett/LH72 and Reid/LH70 are given by Pryakhina et al. (2020). The authors use bathymetric surveys performed on these lakes in two seasons of 2017–2018 and 2018–2019, reported also in Boronina et al., (2019). These estimates of volume are larger by 44–50 % than those given in Shevnina and Kourzeneva (2017), which are in turn partly based on the surveys of 2011–2012 made by Fedorova et al., (2012). In our study we use the estimates provided both by Shevnina and Kourzeneva, (2017) and Boronina et al., (2019), depending on the lake studied (see Section Methods and Data)

2. Methods and data

2.1 Data

Our estimations of the LRT were obtained from the inflow and outflow terms of the lake water balance equation. The outflow terms are evaporation and surface outflow runoff; and the inflow terms are water inflow due to melting of seasonal snow cover and precipitation over the lake surface. The components were calculated from the hydrological observations on the lakes and streams collected during four field campaigns carried out at the Larsemann Hills.

Two campaigns lasting from 25.12.2012 to 28.02.2013 and from 03.01.2014 to 10.03.2014 were focused on measuring the water level/stage and water surface temperature, water discharges and levels at the inlet/outlet streams and collecting the water samples (Naumov, 2014; Vershinin and Shevnina, 2013). These observations were used to estimate the outflow terms namely surface runoff and evaporation for lakes in the Larsemann Hills oasis (Shevnina and Kourzeneva, 2017). In this study, we used results from (Shevnina and Kourzeneva, 2017) to evaluate the LRT from the outflow terms of the water balance equation.

Two campaigns lasted from 27.12.2011 to 05.02.2012 and from 05.01.2017 to 20.02.2017. They were mostly centred on the study of the water chemical composition in local lakes, but the snow properties were also measured, by means of the snow surveys on the watersheds of selected lakes (Dvornikov and Evdokimov, 2017; Fedorova et al., 2012). During each campaign, two consecutive snow surveys were performed: at 12 January and 5 February during year 2012, and at 8–10 January and 31 January – 1 February during year 2017. At the time of first snow surveys during both campaigns, snow had partly melted in the Larsemann Hills oasis. The snow cover consisted of several stand-alone snow packs (snow fields). These snow packs contain deep dense snow. They are persistent from year to year and probably belong to the permanent (multi-annual) cryosphere. Surveys were organized to measure the properties of the largest snow packs: their area, snow density and snow depth. In 2011–2012, snow surveys were carried out on the catchment of Lake Stepped/LH68 (2 biggest snow packs). In 2016–2017, the snow surveys were performed on the catchments of Lake Stepped/LH68 (9 snow packs), Lake Reid/LH70 (7 snow packs) and Lake Sarah Tarn/LH71 (one snow pack). The map of the snow surveys is displayed in Fig. 2. In these series of snow surveys, the snow depth was measured by the metal probe with the accuracy of 0.01 m; the snow density was measured by the snow tube VS–43 (Slabovich, 1985), and the snow edge was delineated using the Garmin Etrex 30 handheld GPS/Glonass receiver.

Figure 2. Snow surveys on the lake catchments during the campaigns of 2011-2012 (green dots) and 2016 – 2017 (orange dots). Stand-alone snow packs are identified by names for the campaign of 2011-2012 and by ID numbers for the campaign of 2017 (e.g., STEP-1 means the first snow pack in the catchment of Lake Stepped/LH68). Red line outlines the catchments, the background map is given according to AAD (2005).

The snow depth and density were used to calculate the snow water equivalent (SWE) accumulated in the stand-alone snow packs. An example of the SWE map obtained from the snow survey of 08–10.01.2017 in the catchment of Lake Stepped (LH68) is given on Fig. A1 in the Annex. Then, the volume of water incoming from the lake watersheds due to melting of seasonal snow cover was calculated as the SWE difference between two consecutive snow surveys. This is the amount of melted water which comes to the lakes from the permanent snowfields during the period between two surveys. Table A1 in the Annex provides the example of these calculations for the campaigns of 2011–2012 and 2016–2017 for Lake Stepped

(LH68). This table shows also the area retreat of the stand-alone snow packs. Details and the full data-sets from two field campaigns may be found in the reports by Dvornikov and Evdokimov (2017) and Fedorova et al. (2012).

2.2 Methods

Imboden (1974) suggests the LRT as a ratio between the volume of lake epilimnion and the outflow water flux, to estimate *the time scale* of water renewing in lakes. Znamensky (1981) suggests the inverse of the LTR known as "the coefficient of external water exchange" to characterize water renewal time in the lakes and reservoirs. For the lakes with thermal homogeneity, the LRT can be calculated using the lake total volume instead of the volume of lake epilimnion (Pilotti et al., 2014; Rossi et al., 1975). Both the lake volume and outflow water flux vary in time, depending on atmospheric conditions (climate and weather), topography changes, human activities and other factors. Generally speaking, this means that the LRT is also time-dependent. However the idea of *the time scale* suggests that averaging over some time period should be applied. We consider the equation for the LRT for the monomictic lakes as follows:

$$LRT = \frac{\bar{V}}{\bar{O}}, \quad (1)$$

where LRT is the lake retention time, (s), $\bar{V}$ is the lake volume (m^3), $\bar{O}$ is the outflow water flux (m^3 s^{-1}), $\bar{f} = \frac{1}{T}\int_0^T f(t)\,dt$ is the averaging operator, $f = \begin{bmatrix} V \\ O \end{bmatrix}$, t is time, (s), T is the averaging time period, (s).

The averaging time period should be large enough. It should be larger than the LRT itself, known from its typical value or preliminary studies. For large lakes, the LRT typical value is several (tens of) years. For example, Pilotti et al., (2014) estimated the LRT from the long-term average of the water discharge calculated from yearly discharges. However long time series of hydrological observations over lakes are often unavailable. If shorter time periods are considered, the result is less reliable and more time-dependent. An example of the LRT estimations from series of seasonal, monthly or daily outlet stream water discharges may be found in (Andradóttir et al., 2012). Generally speaking, for the lakes with a well pronounced annual hydrological cycle, the shortest averaging time period should be one year.

The lake volume can be estimated from the height–area–volume curve depending on the lake water level/stage (Strahler, 1952). To estimate the outflow water flux, usually the outflow surface runoff flux is used (Pilotti et al., 2014, Andradóttir et al., 2012), and also evaporation (Quinn, 1992). If no long-term changes in the lake volume can be suggested, the outflow water flux in the LRT estimations can be replaced by the inflow water flux, as it is done, e. g. in (Doganovskiy and Myakisheva, 2015). Let us consider this in detail.

The lake water balance equation describes an evolution of the lake volume:

$$\frac{dV(t)}{dt} = Q_{\text{in}}(t) - Q_{\text{out}}(t) + (P(t) - E(t))A(t) \pm ...,$$

where Q_{in} and Q_{out} are the surface inflow and outflow runoff (m^3 s^{-1}), P and E are precipitation and evaporation (m s^{-1}) over the lake surface area A (m^2). This equation is usually applied in the integrated form, with integration time period depending on application, e. g. one year time period:

$$\frac{\Delta V}{\Delta t} = Q_{\text{in}} - Q_{\text{out}} + (P - E)A \pm D, \tag{2}$$

where now ΔV (m^3) is the volume change during the time period Δt (e.g. 1 year), Q_{in} and Q_{out} are the inflow and outflow surface runoff per this time period (e.g., yearly surface inflow and outflow runoff), P and E are precipitation and evaporation during this time period (e.g. annual precipitation and evaporation); and D is discrepancies. The equation may be continued with adding more inflow/outflow (or accumulation/dissipation) terms depending on the lake type, the specific case of the study and the time scale of processes considered (Chebotarev, 1975). Contributions of some components to the total lake volume change may be minor, whereas other terms may be essential, depending on a particular case. Therefore, additional components may need to be included into the water balance equation, *i.e.* artificial water withdrawal, underground inflow/outflow runoff, water inflow/outflow due to melting/freezing processes, etc. In our case, we apply this equation differently for the epiglacial lakes and for the land-locked lakes. For both lake types, we do not consider the underground water runoff, because most of lakes are located on the rock-covered catchments. The special case is Lake Stepped/LH68, which is situated in the sandy valley closed to the sea. Including no underground inflow/outflow runoff for this lake will affect the results; this is discussed in Section 3.2.

For the land-locked lakes considered in our study, the annual volume changes do not exceed 1–2 % (Boronina et al. 2019; Dvornikov and Evdokimov, 2017; Shevnina and Kourzeneva, 2017). All the land-locked lakes in our study have no inlet streams. Therefore, the surface inflow due to melting of snow cover over the catchment area is the most important inflow term for their water balance (Shevnina and Kourzeneva, 2017). Then, Eq. (2) for the land-locked lakes may be written as follows:

$$D = M - Q_{\text{out}} + (P - E)A, \tag{2a}$$

where D, (m^3) is the discrepancies including non-known outflow terms i.e. water withdrawal (D_{out}) and inflow terms (D_{in}); M, (m^3) is the amount of water due to snow melting for this time period (e.g. per a year). Then, the inflow and outflow terms in the Eq. (2) can be separated:

$$D_{\text{out}} + Q_{\text{out}} + E \cdot A = D_{\text{in}} + M + P \cdot A \tag{3}$$

This allows to calculate the LTR both from the outflow or dissipation (LRT^{o}) and inflow or accumulation (LRT^{i}) terms of the water balance for the land-locked lakes:

$$LRT^{o} = \frac{\bar{V}}{Q_{\text{out}} + D_{\text{out}} + E \cdot A} \tag{4}$$

and

$$LRT^{i} = \frac{\bar{V}}{M + D_{\text{in}} + P \cdot A}. \tag{5}$$

Now $\bar{V}$, (m^3) is the mean lake volume during the considered time period (1 year). Lake Stepped/LH68 provides water supply for the polar base Progress (Russia), thus the Eq.(2) needs to be extended with the water withdrawal added to the outflow terms of the water balance equation for this lake. In this study this term was not accounted due to lack of data, and we consider it as a discrepancy.

Lakes of epiglacial type are located on the edge of ice sheets and have specific water balance due to that. Their volume can change a lot during the year. Epiglacial lakes may be connected to supraglacial lakes through the ephemeral hydrological network. Abrupt drops of water level/stage are reported to happen on many epiglacial lakes located in the Schirmacher, Thala Hills and Banger Hills oases (Gibson et al., 2002; Klokov, 1979). These drops lead to release of a huge amount of water into the sea. These events are known as water outbursts (Schomacker 1 and Benediktsson, 2017; Klokov, 1979). In the Larsemann Hills oasis, the water drop of the level/height were reported for Lake Progress/LH57 in years 2013 and 2014, and this drop resulted in the outflow of 7.5–8.1 % of the total lake volume (Shevnina and Kourzeneva, 2017). The abrupt drop of the water level/stage was also reported for Lake Nella/Scandrett/LH72 in 2018 with release of 5.7 % of the lake total volume (Boronina et al., 2019). In this study, the water outburst due to the abrupt drops should be accounted for in the Eq.(2) as the outflow term of the water balance equation for the epiglacial lakes. At the same time, the resulting change in the water volume between the end t_2 and the beginning t_1 of the time period (annual change) $\Delta V = V(t_2) - V(t_1)$ is minor. Then the Eq. (2) for the epiglacial lakes can be written:

$$D = Q_{\text{out}} + Q_{\text{abr}} + E \cdot A, \tag{2b}$$

where Q_{abr}, (m^3) is the surface outflow runoff due to the abrupt drop. This term can be calculated from the lake volume (water levels/stage) observations during dates before and after the drop, ΔV_{abr}:

$$Q_{\text{abr}} = \frac{\Delta V_{\text{abr}}}{\Delta t} \tag{6}$$

For the epiglacial lakes, in our study the LRT was estimated only from the outflow terms of the water balance equation Eq. (2b):

$$LRT^{o} = \frac{\bar{V}}{Q_{\text{out}} + Q_{\text{abr}} + D + E \cdot A}. \tag{7}$$

The observations from the measurement campaigns of 2012–2013 and 2013–2014 were used to calculate the LRT^i and LRT^o for the land locked and epiglacial lakes applying the Eqs. (4, 5 and 7). For the evaporation term, we used the estimates given in (Shevnina and Kourzeneva, 2017). These estimates are obtained with different methods: from the empirical equation after (Odrova, 1978) and from the modeling results by the lake model FLake (Mironov et al., 2005).

Data from measurement campaigns of 2011–2012 and 2016–2017 described in Dvornikov and Evdokimov (2017), and Fedorova et al. (2012) were used to calculate the LRT^i for the land-locked lakes applying Eq. (5). From these observations, the annual inflow due to melting of snow cover was evaluated. In addition, the annual precipitation amount was calculated using the observations on the nearest meteorological site Progress located about 700 m form the lake Stepped/LH68. The monthly sum of the precipitation observed at this site is available at www.aari.aq/data/progress/prec.txt. We used the precipitation sum for three summer months in the Eq. (5) because the lakes are covered by ice during the rest of the year. The precipitation during this period is usually blown away from the lake surface.

Table 2 summarizes methods used in our study to estimate the LRT for various lakes together with years of measurement campaigns which provided data for that, and also shows some data. We used the estimates of lake volume/area given by Boronina et al. (2019) for Lake Stepped/LH68 and Lake Reid/LH70, because they use measurements performed on the next season after the latest measurement campaign. The volume/area of Lake Nella/Scandrett/LH72 were also taken after Boronina et al. (2019) because of using the bathimetric survey, which promises good accuracy. For the rest of lakes, the volume/area estimates were taken from Shevnina and Kourzeneva (2017).

Table 2. The volume (V, x10^3 m^3) and area (A, x10^3 m^2) and the methods used to evaluate the LRT of five lakes located in the Larsemann Hills oasis.

Parameter	Epiglacial lakes		Land-locked lakes		
	Lake Progress /LH57	Lake Nella/Scandrett /LH72	Lake Stepped /LH68	Lake Reid /LH70	Lake Sarah Tarn / LH71
V, x10^3 m^3	1812.4	1490.7	51.03	40.45	10.5
A, x10^3 m^2	160.6	157.9	44.4	35.5	6.1
Equation for LRT^o / LRT^i	(7)/-	(7)/-	(4)/(5)	(4)/(5)	(4)/(5)
Years of campaign for LRT^o	2012-2013 2013-2014	2012-2013 2013-2014	2012-2013 2013-2014	2012-2013 2013-2014	2012-2013 2013-2014
Years of campaign for LRT^i	–	–	2011–2012 2016–2017	2016–2017	2016–2017

Shevnina and Kourzeneva (2017) provide some details on errors and discrepancies of the water balance components. In our study, the discrepancies (D) were not accounted in the estimates of the LRT. It leads to over- estimation for the LRT in our calculations since the discrepancies of the water balance equation are always in the denominator. The polar environment limits the water exchange in local lakes to the warm season usually coinciding with the austral summer (December–February/June–August in the South/Northern Hemisphere). In our calculations we used the seasonal estimates of the outflow and inflow terms referring them for the whole year because, we suggested no water flux during the frozen period for Antarctic lakes. Evaporation during the frozen period was also assumed to be small. The hydrological observations during field campaigns covered almost, but not exactly the whole warm season. They lasted 38–65 days in December–March, depending on the available logistic for a field campaign. The length difference between the observation period and warm season leads to an over- estimation of the LRT, in case of the land-locked lakes mostly. Also, non-accounting for the water withdrawal from Lake Stepped/LH68 leads to an over-estimation of the LRT^{o} for this lake.

3. Results

3.1 Retention time of the epiglacial lakes

The epiglacial lakes Progress/LH57 and Nella/Scandrett/LH72 are among the biggest water bodies of the Larsemann Hills oasis (Gillieson et al., 1990). Their seasonal water cycle starts in December with the water accumulation due to melting of the seasonal snow/ice cover in the lake watersheds. In the first week of January, the volume of these lakes reaches a maximum, and then rapidly decreases due to the water outburst into the sea (Boronina et al., 2019; Shevnina and Kourzeneva, 2017), leading to an abrupt drop of the water level/stage in these lakes. The seasonal cycle ends in mid February with freezing of these lakes. During the warm season, the surface area of these lakes is up to 60–80 % free of ice.

The main contribution to the volume changes of these epiglacial lakes during the warm season is the outflow runoff, and the role of the evaporation over the lake surface is considered to be minor. Table 3 shows the LRT^{o} of the epiglacial lakes for years 2012–2013 and 2013–2014, together with the measured outflow surface runoff and evaporation from the lake surface calculated by two methods: after (Odrova, 1978) and using the modeling results of the lake model FLake (Mironov et al., 2005). All the values in these calculations are taken from (Shevnina and Kourzeneva, 2017): the surface outflow runoff Q_{out}, runoff due to the abrupt drop Q_{abr}, and the evaporation $E \cdot A$ calculated by two methods. Note that Q_{out} and $E \cdot A$ provided in (Shevnina and Kourzeneva, 2017) and in Table 1 are integrated for the period of the measurement campaign/warm season, although we used them to characterize the whole year period (see explanations in Section 2.2). The estimated LRT^{o} of the biggest Lake Progress/LH57 is 12–13 years. For the second biggest Lake Nella/Scandrett/LH72, the LRT^{o} was estimated as 6–7 years. The estimations are very similar for data from both campaigns.

Table 3. The LRT^{o} (years) of two epiglacial lakes, calculated from the measurement campaign data of years 2012–2013 and 2013–2014, the measured outflow surface runoff $Q_{out}+Q_{abr}$ (x10^3 m^3 per season) and evaporation from the lake surface $E \cdot A$ in the volumetric rate (x10^3 m^3 per season) calculated after (Odrova, 1978) / (Mironov et al., 2005). No observations are indicated by "–" .

Lake	Year of campaign	$Q_{out}+Q_{abr}$	$E \cdot A$	$Q_{out}+Q_{abr}+E \cdot A$	LRT^{o}
Nella/Scandrett/LH72	2012–2013	246	–	~246	6
	2013–2014	190	7.6 / 18.3	198 / 209	7 / 7
Progress/LH57	2012–2013	150	–	~150	12
	2013–2014	128	7.7 / 18.8	136 / 147	13 / 12

The errors of the LRT estimates, depend on the errors of both hydrological/meteorological measurements and calculation methods. Here, the LRT^{o} of two epiglacial lakes was estimated from the hydrological measurements collected by various methods. The program of the hydrological observations varies from season to season. The field campaigns of 2012–2013 and 2013–2014 covered only 60–66 days in the austral summer. Therefore, the over-estimation may be expected due to lack of data in the start and end of the warm season. In both seasons, the water exchange cycle in the epiglacial lakes started in already December, thus it is longer than the periods covered by the observations. In both seasons, the hydrological observations were done with same methods and tools: the daily outflow water discharges were calculated from the water discharges and water level/stages measured in the outlet streams (Guidelines, 1978). The water discharge in the stream was calculated from the flow velocity measured at a one chosen point, and its maximum error is estimated as *ca.* 10 % (Zhelezhnjakov and Danilevich, 1966). The actual volumes of these lakes were estimated from the bathymetric surveys in years 2011 and 2018 with similar measurement tools and data-processing technique 3D Analyst by ESRI (https://www.esri.com). We can expect the 10% accuracy for the volume estimations. It actually leads to the 10% accuracy for the estimates of the LRT^{o} in case of the epiglacial lakes. To further improve the estimates of the LRT^{o}, long term hydrological observations covering the whole warm season are needed. Observations during the campaign of 2012–2013 did not allow to calculate the evaporation over the lake surface. The LRT^{o} was estimated without taking it into account, which leads to an over-estimation. However for the season 2013–2014, different methods to calculate the evaporation, namely after the empirical formula by (Odrova, 1978) and from the modelling results with the lake model FLake (Mironov et al., 2005), do not affect much the LRT^{o} estimates for epiglacial lakes, resulting in a difference of only 1 year for Lake Progress/LH57. This is because the outflow surface runoff from these lakes is much larger than the evaporation, and uncertainties in the evaporation calculation do not affect much the accuracy of the LRT^{o} estimations.

3.2 Retention time of the land-locked lakes

We estimated the LRT^o using Eq.(4) for three land locked lakes: Lake Stepped/LH68, Lake Reid/LH70 and Lake Sarah Tarn/LH71. Lake Stepped/LH68 is a source for the stream operating during almost 3–4 months in austral summer. Its water discharge varies with the water level/stage. Lakes Reid/LH70 and Sarah Tarn/LH71 are the endorheic ponds, *i.e.* with minor contribution of the outflow surface/underground runoff to the changes in the lake volume. Therefore, the LRT^o was estimated with only seasonal evaporation, which was considered the main loss term of the water balance equation for these lakes. The hydrological observations collected during two field campaigns for years 2012–2013 and 2014 were used to calculate the LRT^o. Observations over Lakes Reid/LH70 and Sarah Tarn/LH71 were performed only during the field campaign of 2014.

All the values in the calculations were taken from (Shevnina and Kourzeneva, 2017): the lake mean volume $\bar{V}$, the surface outflow stream runoff Q_{out} and the evaporation $E \cdot A$. The errors inherent to the estimations from the uncertainty in the evaporation calculation are studied by the use of different methods to evaluate the evaporation: after the empirical equations by (Odrova, 1978) and from the modelling results of the lake model FLake (Mironov et al., 2005). Shevnina and Kourzeneva (2017) give more details on the methods applied. Table 4 shows the LRT^o of the land locked lakes calculated using Eq. (4) from the measurement campaign data of years 2012–2013 and 2014, together with the measured outflow surface runoff and evaporation from the lake surface calculated by two methods. All the outflow terms of the water balance equation provided in (Shevnina and Kourzeneva, 2017) and in Table 4 are integrated for the period of the measurement campaign/warm season, although we used them to characterize the whole year period (see explanations in Section 2.2).

Table 4. The LRT^o (years) of three land locked lakes, calculated from the measurement campaign data of years 2012–2013 and 2014, the measured outflow surface runoff Q_{out} (x10^3 m^3 per season) and evaporation from the lake surface $E \cdot A$ in the volumetric rate (x10^3 m^3 per season) calculated after (Odrova, 1978) / (Mironov et al., 2005).

Lake	Year of campaign	Q_{out}	$E \cdot A$	$Q_{\text{out}} + E \cdot A$	LRT^o
Stepped/LH68	2012–2013	26.6	5.5	32.1	1.6
	2013–2014	20.7	5.7 / 5.5	26.4 / 26.2	2 / 1.6
Reid/LH70	2013–2014	0	4.6 / 6.4	4.6 / 6.4	9 / 4
Sarah Tarn/LH71	2013–2014	0	0.5 / 0.7	0.5 / 0.7	21 / 15

In this study, the land-locked Lake Reid/LH70 and Lake Sarah Tarn/LH71 were considered as endorheic ponds, thus only evaporation was accounted for the LRT^{o} as an outflow term. We estimated the LRT^{o} for Lake Sarah Tarn/LH71 of 15–21 years, and for Lake Reid/LH70 of 4–9 years, depending on the method applied to calculate the evaporation: after the simulations by the lake model FLake or after the empirical equation. The estimated LRT^{o} is sensitive to the method of calculating evaporation for these two endoheic lakes: the estimated LRT^{o} values differ by a factor of *ca.* 1.5 times when different evaporation calculation methods are used. The method with using the model FLake (Mironov et al., 2005) gives shorter time period of water exchange for these lakes compared to Odrova (1978).

The difference of the LRT^{o} estimates for the land-locked lakes gives an idea about the errors. There are no direct measurements of evaporation for these lakes, thereby it is difficult to quantify the errors and uncertainties for evaporation calculation for each method. Tanny et al. (2011) suggest that the difference between the directly measured daily evaporation and those calculated from the semi-empirical equations vary from 15 % to 45 %, and the energy budget method generally gives better accuracy. Therefore, we suggest to use the results after the lake model FLake (Mironov et al., 2005) while estimating the LRT^{o} for the land-locked lakes.

The lake retention time estimated from the water balance inflow (or accumulation) terms was calculated using Eq.(5). For that, the hydrological observations collected during the field campaigns in years 2011–2012 and 2016–2017 were used. The amount of water incoming due to melting of snow cover M was calculated from the snow surveys in the watersheds of Lake Stepped/LH68, Lake Reid/LH70 and Lake Sarah Tarn/LH71 (Dvornikov and Evdokimov, 2017; Fedorova et al., 2012). During the campaign of 2011–2012, observations were performed only over the watershed of Lake Stepped/LH68, and during 2017 over the watersheds of all considered lakes. Since melting occurs only during the spring period, this value characterizes the annual volume of water incoming due to the melting snow cover. Another inflow term in Eq. (5) is precipitation over the lakes surface $P \cdot A$. We consider only precipitation during the warm season, when lakes are free of ice, because during the cold season the solid precipitation is mostly blown away from the ice-covered lake surface by katabatic winds. In season 2016–2017, it was calculated as the sum of the monthly precipitation observed in December, 2016, and January – February, 2017 at the meteorological site Progress. In season 2011–2012, the monthly precipitation was not reported at this site, thus we used the average monthly values calculated for the period of 2003–2017. The mean volume $\bar{V}$ and area A of the considered lakes were taken from (Shevnina and Kourzeneva, 2017). Table 5 shows the LRT^{i} of the land locked lakes estimated from data of two field campaigns, together with accumulation terms: the inflow surface runoff due to melting of snow cover M and annual precipitation over the lake surface. All the accumulation terms in Table 5 reflect the period of the measurement campaign/warm season, although we used them to characterize the whole annual period (see explanations in Section 2.2).

Table 5. The LRT^{i} (years) of three land-locked lakes, calculated from the measurement campaign data of years 2011–2012 and 2016–2017, the inflow runoff due to melting of snow cover estimated from the snow surveys M (x10^3 m^3 per season) and precipitation over the lake surface $P \cdot A$ in the volumetric rate (x10^3 m^3 per season).

Lake	Year of campaign	M	$P \cdot A$	$M + P \cdot A$	LRT^{i}
Stepped/LH68	2011–2012	0.55	1.18	1.73	30
	2016–2017	2.56	1.32	3.88	13
Reid/LH70	2016–2017	1.02	0.92	1.95	21
Sarah Tarn/LH71	2016–2017	0.14	0.17	0.31	34

Tables 4 and 5 show a big difference in the LRT calculated from the outflow and inflow terms of the water balance equation for the land-locked lakes. In case of Lake Stepped/LH68, the estimated LRT^{o} is less than 2 years for both measurement campaigns and both methods to calculate evaporation, whereas the estimated LRT^{i} is 13–30 years, depending on the measurement campaign. For lakes Reid/LH70 and Sarah Tarn/LH71, the largest estimated LRT^{o} is *ca.* 2 times smaller than LRT^{i}. This difference is caused by the quality of the hydrological observations available for the analysis (the periods of the field campaigns and the hydrological characteristics measured in the particular campaign). The LRT^{o} was evaluated from the hydrological measurements covering the period of 60–66 days in the austral summers of 2012–2013 and 2013–2014. The hydrological observations include the water level/stage in the stream originated by Lake Stepped/LH68 as well as the water discharges in this stream. This allowed to estimate the outflow surface runoff with the accuracy of 7–10 % (Guidelines, 1978) within the observed periods. Therefore, we suggest that the LRT calculated from the outflow terms of the water balance equation are more reliable estimates. Lake Stepped/LH68 serves as the technical water supply for the Progress station (Russia), however this outflow term was not accounted for in this study. It leads to an over-estimation of the LRT^{o} for this lake. In the future, the measurements on the volumes of water extracted from Lake Stepped/LH68 will allow improving the estimations given in this study. Also, omitting of the outflow underground runoff affects the estimations of the LRT for Lake Stepped/LH68, and leads to its over-estimation. To improve the estimates, the special measurements are needed.

The LRT^{i} was evaluated from only two snow surveys in January–February 2012 and January-February 2017 with the interval of 20–23 day, and their dates were quite far from the beginning and the end of the astral summer. By the time of the first survey, much of the snow cover had already melted out on the catchments of the studied lakes (Dvornikov and

Evdokimov, 2017; Naumov, 2014; Vershinin and Shevnina, 2013). Only the snow melt from the remaining (perhaps, permanent) snow packs was estimated during these surveys. It leaded to significant under-estimations of the LRT^i . Also, the large difference between the water balance outflow terms and the inflow term, namely the surface inflow due to melting of seasonal snow cover (*M)* estimated from the measurements over remaining snow packs, means that these snow packs do not serve as a main source of water inflow to the considered lakes. We can suggest that melting of seasonal snow cover over the territory of the whole watershed is of higher importance. An earlier date of the first snow survey, and a larger area of measurements and remote sensing methods will be applied in the future studies. They will help to improve the LRT estimates from the inflow terms and to understand better how melting of seasonal/permanent snow contributes to the water balance of these lakes.

4. Discussion

It is recognized that liquid water presence in the Antarctic ice-sheet is more extensive now than ever observed previously (Stokes et al., 2019; Bell et al., 2019). The melted water feeds a population of lakes associated with glaciers and connected by ephemeral streamflows into the hydrological network which becomes well developed in warmest summers (Holgson, 2012; Klokov, 1979). The hydrological observations on these glacier-related lakes and streams are extremely limited, and they are restricted to the measurements collected in seasonal field campaigns. However, they provide irreplaceable data to fast detecting the amount liquid water melted over the ice sheets (Antarctic and Greenland). The hydrological observations include the bathymetric surveys on the lakes, the snow surveys on their catchments, the measurements of the lakes water level/stage, lake water temperature, and water discharges on the inlet/outlet streams.

In Antarctica, the long hydrological observations (since late 1980s) are available only for several lakes located in Western part of the continent. In this study, the hydrological observations collected in four summer field campaigns in the Larsemann Hills oasis were used to estimate the components of the water balance equation: the lake volume, surface outflow runoff, evaporation, precipitation and inflow due to melting of snow cover. Then, the water transport time scale (namely the lake retention time) is evaluated from the components separately for the epiglacial and land-locked lakes. Among the lakes studied, two egiplacial lakes are biggest in volume with the LRT varying for 6–12 years. The LRT of the land-locked lakes takes from 2 to 15 years. The long water transport is common for the endoheic lakes since they loos water only by evaporation, which is expected be small in the cold polar environment. It should be noted that in this study we did not account for the sublimation from the lake surface during the ice covered period, although it could be a significant outflow term of the water balance for polar lakes (Huang et al., 2019; Faucher et al., 2019). This can lead to over-estimations of the LRT calculated from the outflow terms of the water balance equation both for the epiglacial and land-locked lakes.

By recent, it is little known about the water transport time scales of the glacial lakes located in the Antarctica, and it makes difficult to analyse our results comparing them with other studies. Foreman et al. (2004) apply the longest hydrological observations to evaluate the hydraulic residence time of three large epiglacial lakes located in the Dry Valley, West Antarctica (Lake Bonney, Lake Hoare and Lake Fryxell). The estimated hydraulic residence time for Lake Bonney is 77 years, for Lake Hoare is 281 years and for Lake Fryxell is 107 years. The authors notice that the estimations of the residence time depend on the series length and period of the hydrological observations included into the analyses. In case of Lake Fryxell, for example, the hydraulic residence time varies from 107 to 9 years being calculated from data for years 1995–2001 and year 2001–2002, respectively. The volumes of these lakes are much bigger then of the lakes located in the Larsemann Hills oasis. All this makes the comparison between our estimations and ones given by Foreman et al. (2004) difficult.

The hydrological observations on six lakes and streams located in the Shirmacher oasis (East Antarctica) date back to early 1980s. These observations covered the whole hydrological season lasting from November, 1983 to March, 1984. Further they were used by Loopman and Klokov (1988) to estimate the water exchange coefficient (the inverse of the LRT) for three epiglacal lakes: Lake Smirnova with the volume of $613x10^3$ m^3, Lake Pomornik with the volume of $236x10^3$ m^3, and Lake Glubokoe with the volume of $1930x10^3$ m^3. The estimated LRTs are 1 and 2.4 years for Lake Smirnova and Lake Pomornik correspondingly (Kaup, 2005). The volume of these lakes is much less than the volume of Lake Nella/Scandrett/LH72 and Lake Progress/LH57. The LRT of Lake Glubokoe, which is comparable in volume with Lake Progress/LH57, is estimated as 2.6 year, and it is almost three times less than for Lake Progress/LH57. It is interesting to note, that Lake Progress is connected with the epiglacial Lake Boulder, which got the outburst flood in January 2018 (Popov et al., 2020). It was the first observed outburst on this lake since start of instrumental observations in the Larseman Hills oasis in early 1990s.

The results show a big difference in the LRT estimated for the land-locked lakes Stepped/LH68, Sarah Tarn/LH71 and Reid/LH70. The LRT estimates depend much on the methods: for Lake Stepped/LH68, the LRT estimated from the outflow surface runoff is less than 2 years while from the inflow due to melting of seasonal snow cover is 13–30 years. For the endorheic Lake Sarah Tarn/LH71 and Lake Reid/LH70, the LRT estimated from the outflow term is also dependent on the method to calculate evaporation. If an empirical approach is used to calculate evaporation, the estimated LRT is smaller, it is 15 and 4 years for Lake Sarah Tarn/LH71 and Lake Reid/LH70, respectively. The LRT estimated from the inflow terms of the water balance is 34 years and 13 years for these lakes, respectively. We think that this difference is caused by the quality of the hydrological observations over snow. In particular, the length of the period and start/end dates depend on the schedule for seasonal logistic for each field campaign. We suggest to rely on the estimates from the outflow surface runoff since they are based on the hydrological measurements collected during longer periods (60–66 days). Data collected during the snow surveys in seasons 2011–2012 and 2016–2017 are not representative to estimate the inflow to the lakes due to melting of seasonal snow cover over their watersheds.

The LRT of three land-locked lakes vary from 2 to 15 years. The longest retention time is typical for the endoheic lakes loosing water with evaporation/sublimation. In this case, errors in the LRT estimates of depend on the methods used to evaluate the evaporation. By recent, there are still only few studies addressing the evaporation over the Antarctic lakes. Most of them use the energy budget or semi-empirical equations to evaluate the evaporation from the meteorological observations (Dhote et al., 2020; Faucher et al., 2019). Borghini et al. (2013) evaluate the evaporation over three shallow land-locked lakes located the Victoria Land, West Antarctica. The surface area does not substantially decrease since late 1980s for these endorheic lakes. Authors suggest that water loss through surface evaporation is *ca.* 40–45 % of total change in the lake volume. In the Larsemann Hills, no significant changes in the surface area of the endorheic lakes Sarah Tarn and Reid are found since late 1980s (Shevnina and Kourzeneva, 2017), and the contribution of the evaporation may be significant in the water balance of these lakes.

It should be noted that the direct measurements of the evaporation over the ice/snow and lakes are still rarely found for the remote polar regions, mostly due to specific measuring techniques. The traditional pan-evaporators are difficult to deploy and operate. The method of eddy covariance provides the best accurate estimates for the evaporation rate for the lakes. This method gives insight into the surface energy balance with the unique measurements, and allows improving the semi-empirical equations with best estimates of the regional coefficients (Tanny et al., 2011). We will address the future study of evaporation over the epiglacial and land locked lakes with different methods: the eddy covariance, energy budget and semi-empirical. The method of eddy covariance will provide the reference while analysing the uncertainties in evaporation and the LRT estimates of the Antarctic lakes (Shevnina et al., 2020).

5 Conclusion

Water chemical composition and life presence in Antarctic lakes are strongly connected to the lake water balance and thermal regime. The modelling approach is among others approaches applied in understanding eutrophication, bio production and geochemical processes in lakes. Many geochemical models need characterization of water transport/exchange time scales. This study provides the first estimates for water transport time scale characteristic, namely the lake retention time for five lakes located in the Larsemann Hills oasis, East Antarctica. The LRT was evaluated depending on a lake type: separately for the epiglacial and the land-locked lakes. The LRT was estimated with two methods based on the inflow and outflow terms of the water balance equation. The outflow terms are evaporation and surface outflow runoff; and the inflow terms are the water inflow due to melting of snow cover and precipitation over the lake surface. To calculate these components, we used the hydrological observations on the lakes and streams collected during four field campaigns in austral summers of 2011–2017.

Our study showed that the LRT of lakes in the Larsemann Hills oasis is very different, depending on the lake type. This is because the mechanisms of water exchange differ for the epiglacial and land-locked lakes. The epiglacial lakes loos water through the outflow surface runoff mostly. For these lakes, the surface runoff is much larger than the evaporation over the lake surface area. For the endorheic land-locked lakes, the evaporation over the surface area is the main loss term of the water balance equation. The obtained LRT indicates that water exchange in epiglacial lakes is faster than in land-locked endorheic lakes in the Larsemann Hills oasis, sometimes much faster. For example, the estimated LRT of large epiglacial lake Nella/Scandrett/LH72 is 6–7 years, and of small land-locked lake Sarah Tarn/LH71 is 15-21 years. Therefore, different strategies should be applied to monitor the hydrological cycle of these lakes in general, and to obtain better estimates of the LRT in particular. For the epiglacial lakes, the accurate measurements on water discharges on inlet/outlet streams are needed, covering most of the warm season. If data are missing in the start or end of the warm period, over-estimation of the LRT may be expected. For the endorheic land-locked lakes, methods applied to measure/calculate evaporation are of great importance. All these methods need meteorological observations. To choose the best technique to calculate evaporation, measurement campaign with eddy covariance flux observations would be very helpful. The role of sublimation over the ice-covered surface of the land-locked Antarctic lakes should be also clarified. For these lakes, the LRT may be calculated also from the inflow term of the water balance equation, namely from snow melting. However snow surveys for that should start early enough, before the on-set of the melting season, and also end late enough. We recommend to carry out the first snow survey already in early December and the second one at the end of February. Otherwise, we may over-estimate the LRT a lot, as it happened in this study.

Hydrological observations on the epiglacial lakes also allow to accurately evaluate the amount of liquid water seasonally melting from the margins of glaciers. Observations of the lake water level/stage and temperature are of especially importance, in additional to water discharges on inlet/outlet streams. These measurements complementing with in-situ bathymetric surveys will allow verification of remote sensing measurements of glacier melting. We would consider our LRT estimates as a preliminary attempt to answer the question “how rapidly water is renewing in the Antarctic lakes?” To improve these estimates, the hydrological and meteorological observations are needed on the lakes and streams, lasting for the whole warm season. We recommend to include the hydrological observations to the further field campaigns, which are planned for the Larsemann Hills oasis. The uniform observational program for the hydrological measurements will contribute to better estimations of the water transport time scale. We would especially suggested to install the hydrological monitoring network on Lake Stepped/LH68 and Lake Progress/LH57 due to their importance in water supply of Progress and Zhongshan scientific stations.

Annex

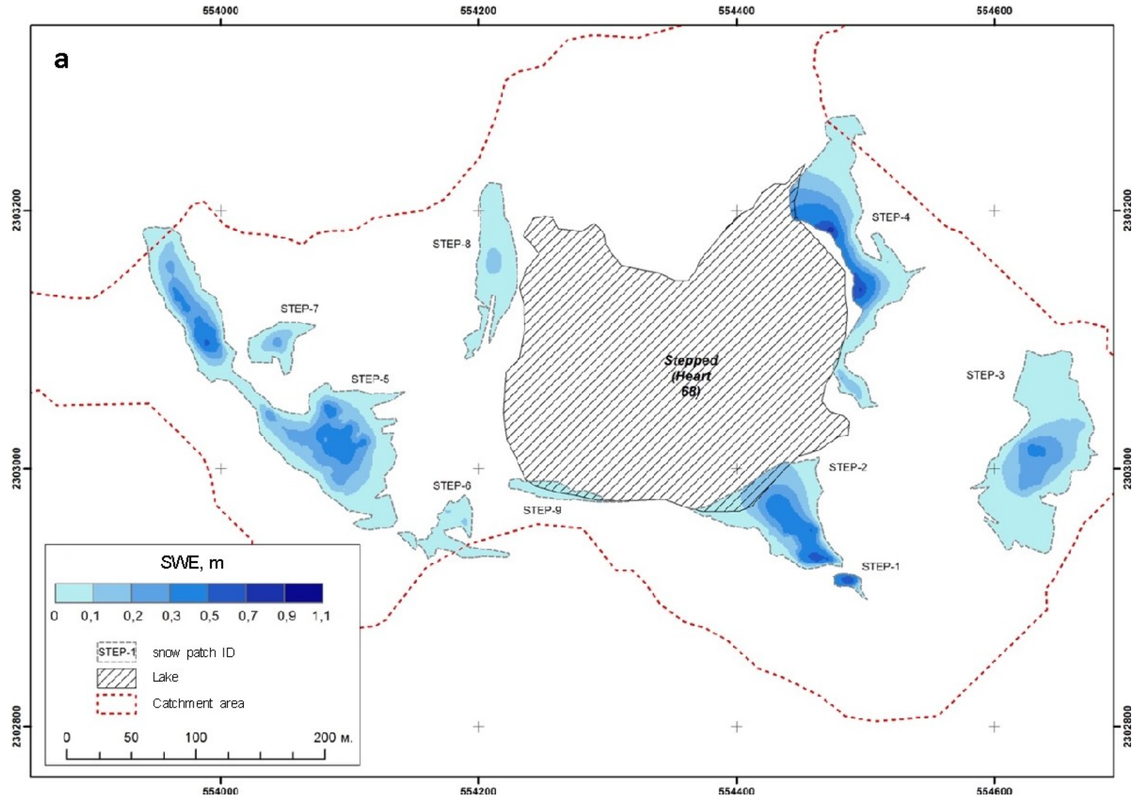

Figure A1: The map of SWE calculated from the snow surveys of 08–10.01.2017 over 9 stand-alone snow packs on the watershed of Lake Stepped, after (Dvornikov and Evdokimov, 2017).

Table A1. The volume of water from melting of the stand-alone snow packs and incoming into Lake Stepped/LH68 together with the melted area between 2 snow surveys for each stand-alone snow pack for 2 measurement campaigns during years 2011–2012 and 2016–2017 . Snow pack indexes can be known from Fig. 3 and Fig. A1.

Year/campaign	Snowfield index	Melted area , m^2	Volume of water melted, m^3
2012	Western	2484	260
	Southern	6929	286
	Total volume of water melted:		546
	STEP-1	218	62
	STEP-2	2669	638
	STEP-3	2436	276

2017	STEP-4	2157	438
	STEP-5	4201	1020
	STEP-6	1293	28
	STEP-7	419	32
	STEP-8	1971	64
	STEP-9	516	4
	Total volume of water melted:		2562

Data Availability

The data used in our calculations of the volume of water incoming due to melting of snow cover in January 2017 are provided as a supplement to this manuscript (Supplement_Shevnina_etal2020.xlsx).

Authors' contributions

The idea of the paper belongs to Elena Shevnina. Elena Shevnina and Ekaterina Kourzeneva wrote the text with equal contribution. Elena Shevnina performed calculations and prepared the tables and figures. Yury Dvornikov and Irina Fedorova contributed with the estimations of the volume of water incoming due to melting of seasonal snow cover in the seasons 2011–2012 and 2017.

Competing interest

No potential conflict of interest was reported by the authors.

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