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

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Abstract. The study gives first estimates of water transport scale for five lakes located in the Larsemann Hills oasis (69º23´S, 76º20´E) in the 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 a warm season only. We used hydrological observations collected in 4 seasonal field campaigns to evaluate the LRT from the outflow and inflow terms of the water balance equation. For the epiglacial lakes Progress/LH57 and Nella/Scandrett/LH72, the LRT was estimated of 12–13 and 4–5 years, respectively. For the land-locked lakes Stepped/LH68, Sarah Tarn/LH71 and Reid/LH70, 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 suggested to rely on the estimations from the outflow terms since they are based on the hydrological measurements with better quality. Lake Stepped/LH68 exchange water within less then 1.5 years. Lake Sarah Tarn/LH71 and Lake Reid/LH70 are the endorheic ponds with the water exchange through mostly evaporation, their LRT was estimated as 21–22 years and from 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 consisting 80 % of frozen water deposited in the ice sheets, glaciers and permafrost (Word atlas, 1997). It makes the continent extremely 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 surface (subglacial type lakes) and over it (supraglacial type). Many lakes are located on the boundary between the rocks and continental/shelf ice sheets (epiglacial and epishelph 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). These lakes may be up to 80 km long, and

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accumulate tremendous amount of liquid water affecting the ice discharge and calving of the continental ice sheet (Stokes et al., 2019; Bell et al., 2017). Lakes of the epiglacial type are situated on 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 for December–January. Land-locked lakes appear after retreating of the continental ice sheet in local depressions. Precipitation and seasonal snow cover melting are two main sources of water inflow for these lakes. The precipitation over the lake surface usually contributes insignificantly to the water inflow comparing to the snow melting (Klokov, 1979). Land locked lakes are ice-free for a period of 3–4 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 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 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). There are only few studies addressing estimates of water transport scales for the Antarctic lakes. Foreman et al. (2004) gives 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, the understanding of the seasonal water cycle on these lakes still weak due to serious gaps in the hydrological measurements on the lakes. It limits the applicability of the biogeochemical models (Nuruzamma et al., 2020). This study aims to estimate the LRT of five lakes in the Larsemann Hills oasis. We focus on the lakes Stepped, Nella/Scandrett, Progress, Sarah Tarn and Reid since their water resources and bio geo chemistry 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, and to answer the question “how fast water exchanges in the lakes located in the Larsemann oasis?”

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1. Study area

The Larsemann Hills occupy the 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 the Prydz Bay. The peninsulas are rocks exposed by glacial retrieving during 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 featured by katabatic winds blowing from the north-east during most of austral summer days. In this period, the daytime air temperatures frequently exceeds 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 (AARI), http://www.aari.aq), and 85 % of precipitation falls as snow (Word atlas, 1997). There are two meteorological stations in the Larsemann Hills. Zhongshan station (WMO index 89573) started operating in 1989, and Progress station (89574) operated occasionally from 1988–1998, and since 1999 started to provide continued observations (Turner and Pendlebury, 2004). Local climatology for the period of 1988–2010 is reported by the Russian Arctic and Antarctic Research Institute (AARI) according to the Progress station. We refer to Shevnina and Kourzeneva (2017), Table 1 to describe it. 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, mostly occupying 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). Most 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 us 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:

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A: the red box indicates the location of the oasis; B: the red areas represent the lakes considered in this study (LIMA composite is on the background map, see detail in 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. In warm period, the outlet stream starts to operate in the north-eastern corner of the lake to release 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 melting of snow cover, precipitation and sea sprays (Kaup and Burgess, 2002). Water level of the lakes Stepped, Sarah Tarn and Reid varies of 0.2–0.4 m during the austral summers.

The epiglacial lakes are situated at the boundary between the glaciated and rocked 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 two biggest epiglacial lakes located in the Mirror peninsula of the Larsemann Hills oasis (Fig. 1). Table 1 shows the available estimations 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 estimations 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 estimations 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. These estimates of volume are larger for 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). Pryakhina et al. (2020) provide the absolute heights of the water level/stage of these lakes measured together with the volume of the lakes. These absolute heights of water levels are 14.5–15.0 m higher then those given in Dvornikov and Evdokimov (2017) and Vershinin and Shevnina (2013). We trust more the estimates provided by Shevnina and Kourzeneva (2017), and used these actual lake volumes given in the our calculations.

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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, precipitation, 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 therms 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 and were mostly centred on the study of the water chemical composition in the 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 gone in the Larsemann Hills oasis. The snow cover was already non-solid , and 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 on 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.

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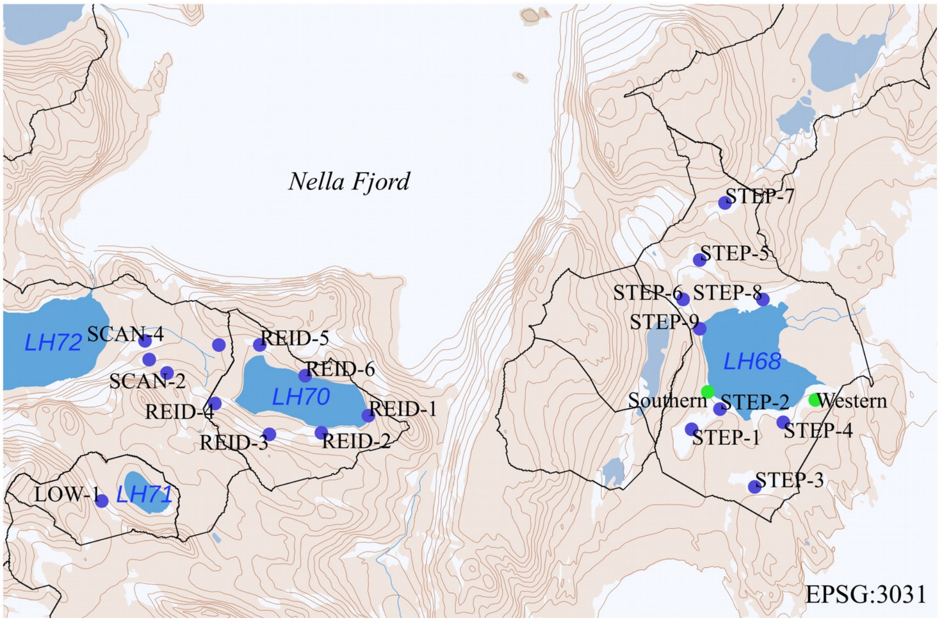

Figure 2. Snow surveys on the lake catchments during the campaigns of 2011-2012 (green dots) and 2016 – 2017 (blue dots). Stand-alone snow packs are identified by names for the campaign of 2011-2012 and by ID numbers for the campaign of 2017 (e.g., STEP-1 means the first snow pack in the catchment of Lake Stepped/LH68). Black 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 the 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 retreatment 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

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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), V is the lake volume (m^3), 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 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:

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

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:

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

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). The equation may be continued with adding

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more inflow/outflow (or accumulation/dissipation) terms depending on the lake type, the specific case of the study and the time scale of the processes considered (Chebotarev, 1975). Contributions of some equation terms (or 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 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 a subject of discussion in the Section 3.2.

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

$$0 = M - Q_{out} + (P - E)A \pm \ldots, \tag{2a}$$

where M, (m^3) is the amount of water due to snow melting per this time period (e.g. per a year). Then, the inflow and outflow terms in the Eq. (2) can be separated:

$$\ldots Q_{out} + E \cdot A = M + P \cdot A \tag{3}$$

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

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

and

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

Now $\bar{V}$, (m^3) is the mean lake volume during the considered time period (1 year).

For the lakes of epiglacial type, changes in the total volume can be huge during the year due to releasing water into the see with outbreaks or outbursts (Klokov, 1979). Such outbursts lead to the abrupt drop downs of the lake water levels/stages and the volume shrinkage, and they have been reported for many lakes located in the Schirmacher, Thala Hills and Banger Hills oases (Gibson et al., 2002; Klokov, 1979). In the Larsemann Hills oasis, the water outbursts were reported for Lake Progress/LH57 in years 2013 and 2014, and these outbursts resulted in the outflow of about 7.5–8.1 % of the total lake

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volume (Shevnina and Kourzeneva, 2017). The abrupt drop down of the water level/stage was also reported for Lake Nella/Scandrett/LH72 in 2018 with releasing of the water outflow of 5.7 % of the lake total volume (Boronina et al., 2019). In this study, the water outburst due to the abrupt drop downs 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:

$$0 = Q_{\text{in}} - Q_{\text{out}} - Q_{\text{abr}} + (P - E)A, \tag{2b}$$

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

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

To calculate the LRT^{o} for the land locked and epiglacial lakes applying the Eq.(4), Eq.(5) and Eq.(7), observations from the measurement campaigns of 2012–2013 and 2013–2014 with the results described in (Shevnina and Kourzeneva, 2017) were used. Polar environment limits the water exchange in local lakes to the warm season usually coinciding with the austral summer (December–February). Then, in our calculations we considered 1 year time period but referred the seasonal ice-free observations of the outflow surface runoff for the whole year, suggesting 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 underestimation of the LRT, in case of the land-locked lakes mostly. Also, non-accounting for the water withdrawal from Lake Stepped/LH68 leads to underestimation of the LRT^{o} for this lake. For the evaporation term, we used different estimates obtained in (Shevnina and Kourzeneva, 2017) by different methods: from the empirical equation after (Odrova, 1978) and from the modeling results by the lake model FLake (Mironov et al., 2005).

To calculate the LRT^{i} for the land-locked lakes applying the Eq.(5), one year time period was considered and data from measurement campaigns of 2011–2012 and 2016–2017 described in Dvornikov and Evdokimov (2017), and Fedorova et al. (2012) were used. From these observations, the annual snow melt amount was evaluated. In addition, the annual precipitation amount was calculated using the observations on the nearest meteorological site Progress located about 700 m

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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 sum of precipitation 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.

3. Results and Discussion

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 maximum, and then rapidly decrease due to the water outburst into the sea (Boronina et al., 2019; Shevnina and Kourzeneva, 2017). It leads to the abrupt drop down of the water level/stage in these lakes. The seasonal cycle ends in mid February with freezing of the 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 surface runoff, and the role of the evaporation over the lake surface is considered to be minor. Table 2 shows the LRT^{o} of the epiglacial lakes calculated using Eq. (7) and Eq. (6) from the measurement campaign data of 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 lake mean volume $\bar{V}$, the surface outflow runoff Q_{out} and runoff due to the abrupt drop down 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 4–5 years. The estimations are very similar while using data from both campaigns.

Table 2. 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	4

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	2013–2014	190	7.6 / 18.3	198 / 209	5 / 5
Progress/LH57	2012–2013	150	–	~150	12
	2013–2014	128	7.7 / 18.8	136 / 147	13 / 12

Hydrological observations available over lakes and streams in Antarctica are extremely limited. They are mostly restricted with measurements collected during seasonal field campaigns. The longest hydrological observations (since 1991) on the lakes and streams are currently available only for the Dry Valleys region (West Antarctica). Foreman et al. (2004) apply these hydrological observations to evaluate the hydraulic residence time of three large epiglacial lakes: 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.

Episodic hydrological observations on the lakes and streams located in the Shirmacher oasis (East Antarctica) date back to late 1980s. Loopman and Klokov (1988) suggest the estimations for the water exchange coefficient (the inverse of the LRT) for two epiglacal lakes: Smirnova with the volume of 613x10^3 m^3, and Pomornik with the volume of 236x10^3 m^3. In these cases, the estimated LRT are 1 and 3 years for Lake Smirnova and Lake Pomornik correspondingly (Kaup, 2002 with the reference to Loopman and Klokov, 1988). These estimations are also difficult to compare with ours since the volume of the lakes in the Schirmacher oasis is much less than of Lake Nella/Scandrett/LH72 and Lake Progress/LH57.

In our study, the LRT^o of two epiglacial lakes located in the Larsemann oasis was estimated only from the data collected during two seasons. The field campaigns of 2012–2013 and 2013–2014 covered 60–66 days in the austral summer. The estimations of the LRT^o from observations during both seasons are very similar, however some under-estimation may be expected due to lack of data in the begging and end of the warm season. In both seasons, the water exchange cycle in the epiglacial lakes already started in December, thus it is longer than periods covered by the observations. To further improve the estimations of the LRT^o, the 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. Then, the LRT^o was estimated without taking it into account, which leads to some over-estimation. Different methods to calculate the evaporation, namely after the empirical formula by (Odrova, 1978) and from the modeling results with the lake model FLake (Mironov et al., 2005), do not affect the LRT^o estimates for epiglacial lakes. This is because the outflow surface runoff from this lakes is much larger than the evaporation. Only slight difference of 1 year in the LRT^o estimates depending of different evaporation calculation methods is noted for Lake Progress/LH57, from data for the season 2013–2014.

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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 originates the stream operating during almost 3–4 months in austral summer. The amount of water in this stream depends on the volume of the lake, and its water discharges vary 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 considering as main dissipation 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 LRT^{o} 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 LRT^{o} 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 3 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 inflow 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 3 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 3. 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). No observations are indicated by "–".

Lake	Year of campaign	Q_{out}	$E \cdot A$	$Q_{out} + E \cdot A$	LRT^{o}
Stepped/LH68	2012–2013	26.6	–	26.6	1.5
	2013–2014	20.7	4.6 / 5.5	25.3 / 26.2	1.6 / 1.6
Reid/LH70	2013–2014	0	3.2 / 6.4	3.2 / 6.4	8 / 4
Sarah Tarn/LH71	2013–2014	0	0.5 / 0.7	0.5 / 0.7	21 / 15

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Different methods to calculate the evaporation, namely after the empirical formula by (Odrova, 1978) and from the modeling results with the lake model FLake (Mironov et al., 2005), do not affect the LRT^{o} estimates for epiglacial lakes. This is because the surface outflow runoff from this lakes is much larger than the evaporation. Only slight difference of 1 year in the LRT^{o} estimates depending of different evaporation calculation methods

The lake retention time estimated from the water balance inflow (or accumulation) terms LRT^{i} 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 years 2011–2012, observations were performed only over the watershed of Lake Stepped/LH68, and during year 2017 over the watersheds of all the considered lakes. Since melting occurs only during the spring period, this value characterizes the annual volume of water incoming due to 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 are not reported at the 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 is taken from (Shevnina and Kourzeneva, 2017). Table 4 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 4 reflect 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^{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 annual 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	23
	2016–2017	2.56	1.32	3.88	10
Reid/LH70	2016–2017	1.02	0.92	1.95	13
Sarah Tarn/LH71	2016–2017	0.14	0.17	0.31	34

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In this study, the land-locked Lake Reid/LH70 and Lake Sarah Tarn/LH71 were considered as endorheic ponds, thus only evaporation was accounted in 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 4–8 years, depending on the method applied to calculate the evaporation: after the empirical equation or after the simulations by the lake model FLake. The estimated LRT^{o} is sensitive to the method of calculating evaporation for endoheic lakes: the estimated LRT^{o} values *ca* 1.5 times differ when different evaporation calculation methods are used. The method with using the model FLake (Mironov et al., 2005) gives larger values of the LRT^{o} comparing with (Odrova, 1978). 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.

Our results show a big difference in the LRT calculated from the outflow and inflow terms of the water balance equation in 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 10–23 years, depending of the measurement campaign. For lakes Reid/LH70 and Sarah Tarn/LH71, the largest estimated LRT^{o} is *ca.* 1.5 times smaller than LRT^{i}. Such difference is mostly caused by the quality of the hydrological observations available to the analysis (the periods of the field campaigns and the hydrological characteristics measured in the particular field 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 allows to estimate the outflow surface runoff with the accuracy of 7–10 % (Guidelines, 1978) within the observed periods. Therefore, we would suggest that the LRT calculated from the outflow terms of the water balance equation are reliable estimates. Lake Stepped/LH68 serves the technical water supply for the Progress station (Russia), however this outflow term was not accounted for in this study. It leads to 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 estimations, 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 remained (perhaps,

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permanent) snow packs was estimated during these surveys. It leads 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 don 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. Earlier date of the first snow survey, larger area of measurements and remote sensing methods will be applied in the future studies. They will help to improve the LRT estimations from the inflow terms and, to understand better how melting of seasonal/permanent snow contributes to the water balance of these lakes.

It is very difficult to find estimations of the LRT for the land-locked lakes in the Antarctica for the comparison. The coefficient of external water exchange (the inverse of the LRT^{o}) is suggested for the land-locked Lake Glubokoe located in the Schirmacher oasis (Loopman et al., 1988). Authors use the hydrological observations on the lake and its inlet/outlet streams carried out in 1986–1987 to estimate the coefficient of external water exchange. The estimated coefficient for Lake Glubokoe is 0.38 (Kaup, 2002 with reference to Loopman et al., 1988), which corresponds to the estimate of 2.6 years of the LRT. It is difficult to compare this estimation with those obtained for the lakes located in the Larsemann Hills oasis, since the volume of Lake Glubokoe is much larger. Also, the surface outflow/inflow runoff for this lake is larger due to its specific location in the chain of epiglacial and epishelf lakes.

4 Conclusion

Water chemical composition and life presence in Antarctic lakes are strongly connected to lake thermal regime and water balance. For better understanding this connection, the modeling approach is applied to simulate the eutrophication, bio production and geochemical processes in the lakes. However, many models need characterization of water transport/exchange time scales. This study suggests the first estimations for water transport scale characteristics, namely the lake retention time (LRT) for five lakes located in the Larsemann oasis, East Antarctica. The LRT was evaluated depending on the lake type: separately for epiglacial and 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 and the surface runoff 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 during austral summer seasons of 2011–2017. The LRT was calculated from the observations covering most of the warm season.

The estimated LRT of two epiglacial lakes Progress/LH57 and Nella/Scandrett/LH72 is 12–13 and 4–5 years , respectively. Different methods applied to calculate the evaporation do not affect the estimates of the LRT for the epiglacial lakes, since the surface outflow runoff for these lakes is much larger than the evaporation. Some under-estimation may be expected due to lack of data in the begging and end of the warm season.

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For the land-locked lakes Stepped/LH68, Sarah Tarn/LH71 and Reid/LH70, our results show a big difference in the LRT calculated from the outflow and inflow terms of the water balance equation, depending on the methods and errors inherent to them. For Lake Stepped/LH68, the LRT estimated from the outflowe surface runoff thought the outlet stream is less than 2 years. However, calculations from the inflow surface runoff due to melting of seasonal snow cover suggested the LRT of this lake of over 10–23 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 empirical approach is used to calculate evaporation, the LRT time 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. On our opinion, such difference is caused by the quality of the hydrological observations available to the analysis. In particular, the length of the period and start/end dates depend on the schedule for seasonal logistic for each field campaign. We suggested to rely on the estimations from the outflow surface runoff since they are based on the hydrological measurements collected during longer periods (60–66 days). The 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.

In this study, we provided the first estimations of the LRT of the land-locked and epiglacial lakes located in the Larsemann oasis in the Antarctica. We would consider these estimates as preliminary attempt to answer the question "how fast water is renewing in the local lakes?" To improve these estimates, the hydrological observations are needed to monitor the lakes and streams during the warm season with the uniform observational program. In particular, to better estimate the seasonal inflow due to melting of snow cover, we recommend to carry out the first snow survey already at the begging of December and the second one at the end of February. On our opinion, it is especially important to install the hydrological network on Lake Stepped/LH68 and Lake Progress/LH57 due to importance of their water resources in water supply of Progress base.

Annex

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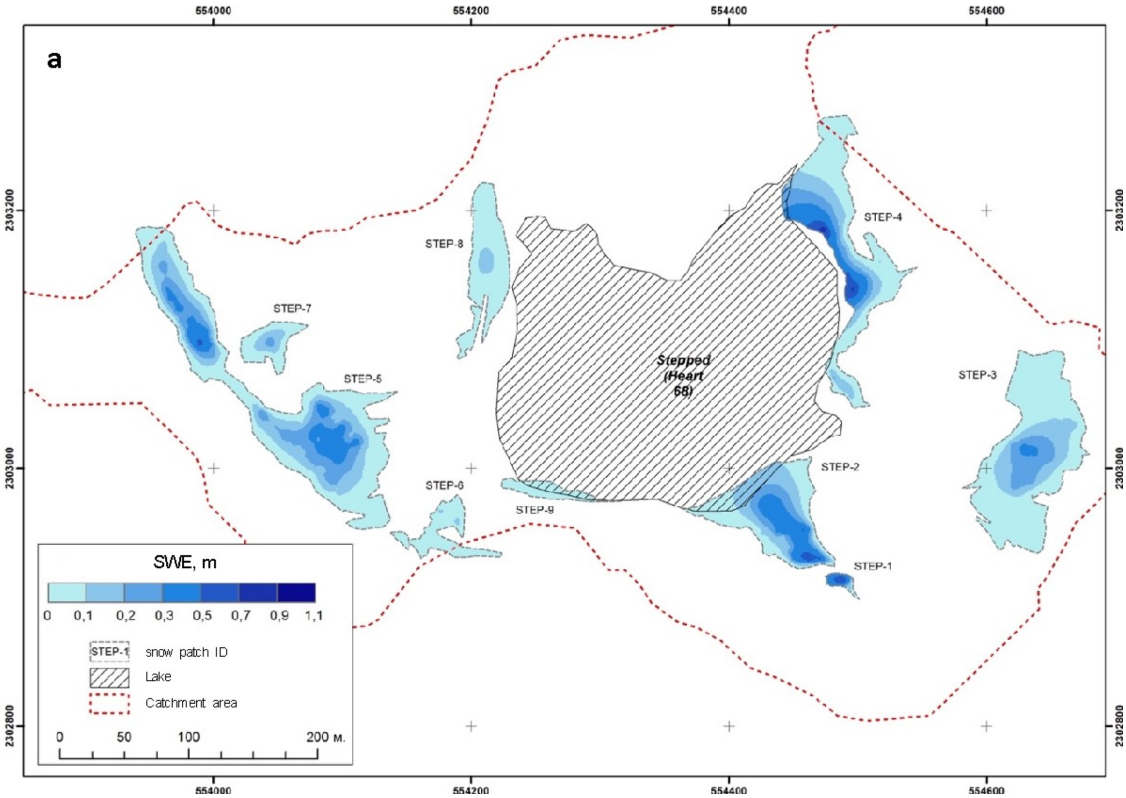

415 Figure A1: The map of SWE calculated from the snow surveys of 08–10.01.2017 over 9 stand-alone snow packs on the watershed of Lake Stepped, after (Dvornikov and Evdokimov, 2017).

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
2017	STEP-1	218	62
	STEP-2	2669	638
	STEP-3	2436	276
	STEP-4	2157	438
	STEP-5	4201	1020
	STEP-6	1293	28

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	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 is supplemented this manuscript (Supplement_Shevnina_etal2020.xlsx).

Authors' contributions

Elena Shevnina and Ekaterina Kourzeneva wrote the text with equal contribution. Elena Shevnina calculated the tables and prepared the figures. Yury Dvornikov and Irina Fedorova contribute 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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