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Lake El'gygytgyn water and sediment balance components overview and its implications for the sedimentary record

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Abstract

Modern process studies of the hydrologic balance and sediment flux into and out of Lake El'gygytgyn, central Chukotka, provide important quantitative estimates for better understanding the lacustrine paleoclimate record from this basin. Formed ca. 3.6 Ma as a result of a meteorite impact, the basin contains one of the longest paleoclimate records in the Arctic. Fluvial activity into the basin today is concentrated over the short snowmelt period. Recent lake-level changes have a slow regressive character due to active underground runoff, even during winter. The residence time of the lake-water is estimated to be about 100 yr. The main source of clastic material are incoming steams. The amount of sediment discharge through the outflow river is insignificant and completely compensated even by little aeolian input.

1 Introduction

Lake El'gygytgyn is located in Central Chukotka, Far East Russian Arctic (67°30′ N and 172°5′ E; Fig. 1), approximately 100 km north of the Arctic Circle. The lake has an almost square shape and a diameter of about 12 km in filling a portion of a meteorite impact crater that is 18 km in diameter. The crater formed 3.6 million yr ago (Layer, 2000). Based upon previous geomorphologic and geological research (Glushkova, 1993) this territory was never glaciated and sedimentation in the lake presumably has been continuous since its formation. In winter season of 2008–2009, deep drilling of Lake El'gygytgyn recovered long cores embracing both the entire lacustrine sediment sequence (318 m) from the center of the basin and a companion core 141.5 m long, into permafrost from outside the talik surrounding the lake (Melles et al., 2012; Brigham-Grette et al., 2012). These cores now provide the science community with the longest terrestrial paleoenvironmental record from the Arctic, starting in the warm middle Pliocene (Melles et al., 2012; Brigham-Grette et al., 2012).

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This paper provides the results of water and sediment balance investigations at Lake El'gygytgyn obtained during pre-site surveys (expeditions in 2000 and 2003). Knowledge of modern hydrological and sediment supply processes is critically important as a baseline to inform us concerning the sensitivity of basin sedimentology to climate forcing in the past.

An overview of the lake's setting, basin morphologic parameters, modern meteorological characteristics and lake crater hydrology were first provided by Nolan and Brigham-Grette (2007). Lake El'gygytgyn with an area of 110 km^2 and volume of 14.1 km^3 is today 175 m deep surrounded by a watershed measuring 293 km^2 (Nolan and Brigham-Grette, 2007). The lake has approximately 50 inlet streams and an outlet, the Enmyvaam River (Fig. 1) that belongs to the Anadyr River drainage basin leading to the Bering Sea. The lake level elevation is 492.4 m according to recent topographic maps.

Data from an automated meteorological station installed at the southern lake shore near the outflow river in 2000 (Nolan and Brigham-Grette, 2007; Nolan, 2012) shows that over the period from 2001 to 2009 the average air temperature was −10.2 °C with extremes from −40 °C to +28 °C, and liquid precipitation averaged 73 mm (summer rainfall) in the region. The mean annual amount of liquid precipitation during 6 yr over the period from 2002–2007 was 126 mm with extremes from 70 mm in 2002 to 200 mm in 2006 (Nolan, 2012).

The onset of the spring flooding and first motes of open water typically appear along the lake shore in the beginning of June. The lake ice completely disappears in the middle of July and freezing starts again by the middle of October (Nolan et al., 2003).

A first appraisal of the Enmyvaam River discharge velocity at its the head was done by Glotov and Zuev (1993), which was nearly equal to 1 $m\,s^{-1}$. These data allowed them to estimate a water discharge of 50 $m^3\,s^{-1}$ at a maximum, but with an average in the range of 20 $m^3\,s^{-1}$ (Glotov and Zuev, 1995). First instrumental measurements of water discharge were performed in summer 2000 (Nolan and Brigham-Grette, 2007). For this updated study, measurements were done three times in the Enmyvaam River head and once in most of the inlet streams. Water discharge in the Enmyvaam River was 19.8 $m^3 s^{-1}$ on 16 August, 14.2 $m^3 s^{-1}$ on 23 August, and 11.6 $m^3 s^{-1}$ on 1 September and in each inlet streams less than 1 $m^3 s^{-1}$. Notably timing is everything, given that the outlet is closed until late June when the lake level rises enough to breach and quickly downcut through fall season longshore drift choking the outlet. Moreover, during summers inlet streams are largely reduced to a trickle or dry up completely after the late spring freshet.

2 Methods

The following formula can be applied to estimate Lake El'gygytgyn water balance:

$$Y = Y_1 + Y_2 + P + Z_1 - Z_2 - E$$

- Y = Enmyvaam River runoff;
- Y_1 = main lake tributaries runoff;
- Y_2 = remaining stream network runoff;
- P = precipitation over the lake surface;
- Z_1 = ground water influx;
- Z_2 = underground runoff;
- E = evaporation from the open water surface.

2.1 Enmyvaam River, main lake tributaries and remaining stream network runoffs

Methods of measurement and subsequent calculations were done in accordance with Russian hydrometeorological survey standards (Guide to Hydrometeorological stations, 1978).

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During summer 2003 the water discharge in the Enmyvaam River (outflow) and main inlet streams (Fig. 1) were measured three times at the beginning, middle and end of the summer season. A standard current velocity meter was used to measure flowrates.

The water discharge was calculated according to the prescribed analytical method (Guide to hydrometeorological stations, 1978). Average seasonal water discharge and subsequently seasonal runoff were then calculated for each measured stream. The stream's watershed area provided by Nolan and Brigham-Grette (2007) was used to calculate the seasonal unit area discharge (ratio between the water runoff and watershed area) for those main streams. For the unmeasured streams we used the average unit area discharge of the measured steams. Thus, we can calculate the seasonal unit area discharge for the entire drainage basin except of the lake itself. The total seasonal water runoff is calculated as the seasonal unit area discharge multiplied by total watershed area. The Enmyvaam River total runoff is estimated as average water discharge multiplied by time period of outflow activity.

2.2 Precipitation over the lake surface

Precipitation over the lake surface was estimated as the sum of liquid precipitation directly to the lake water surface during summer plus the melted snow supply from the seasonal lake ice. The data about summer liquid precipitations was extrapolated from the automatic weather station installed in southern lake shore in 2000 (Nolan and Brigham-Grette, 2007). To estimate the supply of the melted snow on top of the lake ice, a snow survey on the lake ice surface was performed in spring 2003. Two profiles across the lake were completed (Fig. 1). At intervals of 1 km the snow thickness was measured and snow samples were taken using an express volume sampling device (Guide to hydrometeorological stations, 1978).

2.3 Ground components of the water balance

The most difficult parameters to estimate in this basin are the ground water components. We have no data to estimate underground water supply from the catchment directly into the lake, however, it could be quite significant, given what was measured at Lake Levinson-Lessing located in similar climate and permafrost conditions on the Taymyr Peninsula, Central Siberia (Zimichev et al., 1999). For Levinson-Lessing Lake the ground water supply was about 15 % of total water yield. This was calculated as the difference in the outflow river runoff plus evaporation and all the other components of water income (Zimichev et al., 1999). At Lake El'gygytgyn however, both positive and negative portions of the water balance have ground components. In this case, as a first approximation, the volume of underground runoff was estimated as difference between the Enmyvaam River runoff and evaporation from one side of the equation and all the components of water input from another side, acknowledging that underground supply is really unknown.

2.4 Evaporation from the open water surface

Evaporation from the lake surface was also difficult to quantify. Within the accuracy of our empirical data we chose to use regional open water evaporation data from Sokolov (1964).

2.5 Lake level change measurements

During spring and summer field work in 2003 measurements of the water level were carried out at the south-eastern shore of the lake (Fig. 1). A temporary graduated staff gage for visual water level observations was installed after the first motes and leads of ice-free water appeared along the lake shore (10–15 June). The lake level changes were monitored from 14 June to 19 August (Fig. 2). Measurement gaps happened during ice jams at the beginning and strong storms at the end of the field campaign. The lake ice disappeared finally on 19 July.

2.6 Fluvial sediment supply and Enmyvaam River sediment runoff

Water samples were collected simultaneously with water discharge measurements where ever possible. Turbidity was determined after filtration through paper filters at the bottom of a "Kuprin" gadget having a diameter of 10 cm. The filters were preweighed before the expedition and repeatedly after with foregoing drying. Knowledge about turbidity and water discharge allowed us to calculate sediment discharges. Estimations of the total seasonal fluvial sediment supply and Enmyvaam River sediment runoff followed the same approach as that used to calculate total water runoff (see Sect. 2.1).

2.7 Aeolian sediment input

Aeolian input to the lake surface was estimated only for the winter season by measuring particle concentrations in the snow cover on the lake ice. The collected snow samples (see Sect. 2.2) were melted and filtered through paper filters as described earlier.

2.8 The period of the Lake water exchange

The residence time of the water in Lake El'gygytgyn was estimated as a ratio between the total lake water volume and the water supply volume for one year (using the data for 2003). While one year of data is a weak standard and more data are desired, the data are sufficient to allow estimates of the major parameters controlling the hydrological regime of Lake El'gygytgyn.

3 Results and discussion

3.1 Water and sediment input and output due to fluvial activity

During the summer 2003 water and sediment discharge was measured at the head of the Enmyvaam River and in selected inlet streams around the Lake El'gygytgyn basin three times on (Table 1). The lake and Enmyvaam River level changes were monitored from 14 June to 19 August (Fig. 2).

The water level in both the river and the lake basin are at a maximum at the end of the snowmelt period coincident with the opening of the Enmyvaam River near the end of June. During autumn (August/September), with the general lowering of the lake level accompanied by northern winds, storms form a levee along the southern shore that impedes the outflow into the Enmyvaam River. In springtime this levee is destroyed by similar storms with the rise of the lake level, leading to the restitution of the river flow.

The total amplitude of lake-level changes during the measurement period was 26.5 cm (Fig. 2). However, it is obvious that lake-level change directly controls the levels of the Enmyvaam River, which fluctuated in amplitude by almost 90 cm during the measurement period. During summer 2003, before breaching of the outlet levee (i.e. prior to 3 July) the level of Lake El'gygytgyn rose steadily at a rate of about 0.8 cm per day. The highest rates (3 cm and 1.2–1.8 cm per day) were recorded on 16 June and 23–26 June. With the onset of the annual discharge through the river, the level of the lake subsequently dropped at an average rate of 0.7 cm per day with downcutting of the outlet channel.

Notably the maximum water discharge down the Enmyvaam River (15.27 $m^3 s^{-1}$), documented during the middle of July, did not coincide with the peak of lake level or that of the river itself (Fig. 2 and Table 1). Instead, the maximum discharge occurred during the lake level lowering. This discrepancy is due to the active erosion and enlargement of the outlet channel during the period of major water discharge into the Enmyvaam River.

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This interpretation is supported by the data illustrated in Fig. 3, showing a general drop of the lake/river level coincident with a significant deepening of the riverbed. Suspended load also tracked in parallel with discharge (106.02 $g\,s^{-1}$). This took place in early July, with the initiation of riverbed erosion.

The 50 major streams entering Lake El'gygytgyn are numbered according to a system first proposed by O. Yu. Glushkova (unpublished data). The first measurements of water and sediment discharge in selected inlet streams were initiated at the onset of snowmelt in the middle of June, in July, and then at the end of the field season in the middle of August. The results illustrate two important points. First, that water and sediment discharge vary widely between individual streams, and over time (Table 1). Secondly, both the water and sediment delivery into the lake takes place over a short interval of time span during the snowmelt, when the input of both water and suspended sediment load is an order of magnitude higher than that during summer.

Sediment supply to the lake by inlet streams during spring and summer is estimated at roughly 350 t, whereas the entire sediment discharge through the Enmyvaam River channel can be estimated to be 5 t (Fig. 4), suggesting that nearly all of the sediments eroded within the crater are eventually deposited on the lake floor. The total water yield by inlet streams is 0.11 km^3 and runoff at the Enmyvaam River headwaters is 0.05 km^3, indicating that either the lake was storing more water or that evaporation and groundwater leakage are important fluxes in the lake mass balance.

3.2 Water supply from the lake ice surface and aeolian sediment input

During spring 2003 (16 May and 23 May) two snow sampling profiles were performed (see Fig. 1), to estimate water and aeolian sediment supply derived from the lake ice surface. The snow thickness averaged 35.6 cm within a range from 13 cm to 75 cm with a snow density averaging 0.29 $g\,l^{-1}$ within a range from 0.1 to 0.4 $g\,l^{-1}$. The average concentration of solids in the snow pack was about 0.6 mg per litre of melted water. The values ranged from 0.05 $mg\,l^{-1}$ to 1.32 $mg\,l^{-1}$. The same data was also collected from two lake ice cores (see Fig. 1) yielding a solid concentration in the ice of only

$0.012\,\mathrm{mg\,l^{-1}}$. These data provided a means of estimating the water supply from the snowpack and ice at $0.01\,\mathrm{km}^3$ with the capacity of supplying as much as 6 t of sediment to the lake. This is a maximal estimate, because commonly some small portions of the lake ice surface are blown free of winter snow accumulation. Recalculation with 10 % smaller lake area yields a slightly smaller estimate of $0.009\,\mathrm{km}^3$ and 5.5 t (Fig. 4), which is still in excess of that estimated for lake outflow.

The aeolian sediment supply during summer is unknown, because we were not prepared and equipped for this type of complicated measurements. However, the summer season in central Chukotka is very short (4 months at maximum for open water period and even less time for positive temperatures), aeolian income can be still very high because of large snow-free area. Main portion of aeolian input in summer is most likely associate with Lake El'gygytgyn storm events then fine-grained, shoreline material is fed into the lake by strong wind as shown, for example, around the Baltic Sea (Chechko and Kurchenko, 2008). Even with this process, aeolian material is still derived from the crater and reworked by fluvial and coastal processes. On the other hand, original aeolian material accumulates every year in the catchment and is subsequently transported into the lake by fluvial processes. Based on our data we can not subdivide aeolian input from total fluvial supply, but based on the material measured in the snowpack and lake ice, we are confident that the amount is not very significant. In total, we assume that total aeolian supply amounts to 4–5 % of total sediment input; that is, the bulk of the sediments entering the lake basin are derived from the 50 inlet streams within the crater catchment.

Shevchenko and Lisitzin (2003) suggest aeolian input into the Arctic Ocean is much more significant than realized before, however, this is obviously not the case for Lake El'gygytgyn. From our point of view there are two main reasons. First, Lake El'gygytgyn Crater is comparably small and a closed trap for aeolian material and secondly, the predominant wind directions either from the Arctic or Pacific Oceans excludes widespread source areas for aeolian material.

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3.3 Liquid precipitation to the lake water surface

The contribution of rainfall precipitation to the lake during summer can be estimated using data from an automatic weather station on southern lake shore (Nolan, this special issue). According to these data, during summer 2003 the amount of rainfall was 73 mm, suggesting a total of 0.008 km^3 of additional water to the lake surface (Fig. 4). Over the 7 yr of instrumental measurements at the lake, the maximum recorded summer rainfall was 200 mm, or nearly 3 times larger than observed in 2003. Given that the rain gage was not shielded for wind, these numbers are probably conservative.

3.4 Underground runoff and evaporation

The complete 2003 annual water input was approximately 0.13 km^3 excluding an unknown amount of underground input, but the total Enmyvaam River outflow was only 0.05 km^3 (Fig. 4), which means that significantly higher volume of water must be lost due to underground runoff and/or evaporation, since lake levels (and therefore water storage) dropped during the observation period.

According to Sokolov (1964) the annual evaporation from lakes like El'gygytgyn across this territory is estimated to be 10 cm per year. Thus, we can roughly estimate the annual evaporation for Lake El'gygytgyn as 0.01 km^3; i.e. up to 10 % of the total water discharge.

The water level observations in Lake El'gygytgyn and the Enmyvaam River (Fig. 2) demonstrate the important role of underground runoff. It is important to note that for a raising or lowering of the lake water level by 1 cm, about 0.001 km^3 of water is required. Thus, using available daily lake water level dynamics and calculated average daily water supply we can estimate the average daily total lake water discharge by all factors.

During the spring the Enmyvaam River headwaters is not active, in other words, evaporation and underground runoff were the only possible processes for water to escape the basin. Water level continually increased at ca. 0.8 cm per day (ranging from 3 cm to 0 cm), but the daily water supply ranged from 0.001 to 0.004 km^3 plus an unknown volume of underground supply. This means that the lake lost more than 0.001 km^3 of water per day by underground runoff and some portion to evaporation.

During summer the Enmyvaam River was open and the water level decreased by a mean rate of 0.7 cm per day (ranging from 0 to 2.9 cm per day). This requires daily Lake water discharge roughly 0.0007–0.0008 km^3 plus entire volume of daily water income. The variability of water volume supplied through the inlet streams was dependent mostly on rainfall events and some modest flux from active layer melting in the range from 0.0003 to 0.0005 km^3. Also we should take into account unknown volume of daily underground supply. Thus, total daily Lake water discharge in summer 2003 was definitely higher than 0.001–0.0013 but daily discharge of the outflow was around 0.001–0.0009 km^3. This means that underground runoff was still active in summer time.

It is also important to note that if precipitation is low during winter time and, hence, there is little rise of the lake level in spring, and without strong northerly winds in spring or summer, there may be some years without direct outflow from the lake into the Enmyvaam River at all.

Given that the lake has a relatively small catchment area compared to the size of the lake itself (roughly 3:1), and geomorphologic evidence exists for several generations of coastal shorelines above the modern lake (Schwamborn et al., 2008; Fedorov et al., 2008), we can infer that in general, lake level has mostly fallen in recent times. The recent erosion rate of the outflow threshold can be assumed to be minor, because it is covered by several metres of lacustrine-fluvial sediments (Fedorov et al., 2008). Never the less, the lake does lose water through these porous deposits even during winter time as is indicated by the annual formation of aufeis (ice body that forms as a result of ground water discharging onto the surface during freezing temperatures) observed both in the field (2008/2009) and on satellite images.

Our automated weather station provides some direct information of water transport and storage through the gravels. The station is sited about 200 m from the lake outlet, on an older floodplain about 20 cm higher than lake outlet. Soil moisture and soil temperature probes were placed in a pit to a depth of 60 cm and the pit back-filled;

these probes remained active for 7 yr and provide a record of local water table and the timing of subsurface thaw and water movement (Figs. 5 and 6). In each year, the ground thawed to 60 cm depth several weeks before the outlet river opened. Further, the deeper gravels were always fully saturated after spring snow melt, and this water drained laterally or to deeper layers by late June or early July, indicating that substantial subsurface flows of water occurred. By late summer, it was typically the case that the gravels were dry at all depths and froze this way. However, after the particularly wet summer of 2006, the soils at all depths were fully saturated and froze when filled with water. Winter freezing levels did not penetrate as deeply in this winter due to the heat released by freezing this water, and in spring the water thawed in place and remained saturated for several weeks until it drained off below the surface. Thus we have direct evidence for subsurface water movement and storage within this outwash plain related to rain and snow melt, and have no reason to doubt that similar water movement and storage is occurring at much larger volumes related to subsurface drainage of lake water at the outflow. We suspect that most of this flow is beneath the outlet river itself, because (1) the river bed is likely fully saturated and thus limits active layer thickness, (2) this is the topographical low, and (3) aufeis forms downstream within this channel where the pressure gradient brings the water to the surface again in the descending channel.

All the data provided above allow us to roughly estimate the period of the Lake water exchange to about 100 yr (Fig. 4).

3.5 Delivery of coarse-grained debris into the Lake

We have to clarify that we estimated only suspended fluvial sediments and did not measure river-bed sediment load. These kinds of measurements require complex equipment and much longer observation periods. During most of the active fluvial period, delivery of coarse-grained material into the coastal zone is a slow process, but, as observed in spring (June) 2003, it becomes significantly more active during the very short spring freshets. At the onset of the snow-melting period, streams immediately

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become active, at a time, when the lake is still covered by thick ice (up to 2 m). During these periods the largest catchments mouths formatting fans consists of gravel, sand and cobbles extending up to hundreds of meters onto the ice. This processe, certainly, influences the shallow water environment delivering coarse-grained material into subaquatic parts of the alluvial fans, but also, due to the active movement of the ice fields during summer (July), could melt out in deeper parts of the lake producing "drop-stones" in pelagic sediments.

3.6 Coastal zone as a trap for incoming sediments

Since lake level is largely regressive in character, the modern coastal zone is prograding except where it is annually deformed by ice shove events. Very common features for the modern shoreline are gravel berms formed by wave activity that effectively trap coarse-grained material supplied to the lake. Many of the stream mouths are impounded by such berms, causing lagoons to form behind them. These lagoons act as traps for fine-grain sediment as well. Total lagoon area calculated for 2000 (Nolan and Brigham-Grette, 2007) was $11.5 \pm 1.0\,\mathrm{km}^2$, which is just 10 times less than lake surface. The area was calculated for mid-summer and, of course, it is much larger during snowmelt. The slope mass wasting delivered into the Lake is also dammed by these berms (Schwamborn et al., 2008; Fedorov et al., 2008). This kind of coastal zone activity coincided with lake level lowering stages. During rising lake level stages erosion increases in the coastal zone evoking the destruction of the gravel berms and levees as the lagoons overflow. This provides a significant amount of debris in a short time period onto the proximal parts of alluvial fans which are otherwise the primary source for debris flows and turbidites recognized in lake sediment cores (Juschus et al., 2009; Kukkonen et al., 2012).

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4 Conclusions

1. Lake El'gygytgyn is a typical arctic nival hydrological regime. Surface drainage system is active only during the short summer and many of the inlet streams are active mostly during snowmelt when water and sediment input is an order of magnitude higher than that during summer.

2. Underground runoff from the lake is active in summer and persists even during winter time at the lake outlet. The latter is clearly indicated by aufeis formation. This occurs because modern lake level is higher than the bedrock outflow threshold, which had been eroded up to about 10 m below modern water level position during the Late Weichselian and is now covered by porous lacustrine-fluvial sediments (Schwamborn et al., 2008; Fedorov et al., 2008; Juschus et al., 2011).

3. The residence time of the lake under modern conditions is estimated to be about 100 yr.

4. The overwhelming amount of sediment transported into the lake is accomplished by the inlet streams. Aeolian input is not significant and likely ranges between 2 % and 5 % of total input. However, aeolian input is higher than sediment discharge through the outflow channel, indicating that by volume little, if any, of the sediment eroded within the crater is escaping through the outlet river.

5. In modern times the mass wasting and fluvial delivery of sediment into the lake is restricted by the trapping of material landward of coastal berms and levees in lagoons.

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Table 1. Water and sediment discharge measured during spring and summer 2003 in the outlet river and inlet streams, Lake El'gygytgyn.

Site	Date	Water discharge $m^3 s^{-1}$	Sediment discharge $g s^{-1}$	Date	Water discharge $m^3 s^{-1}$	Sediment discharge $g s^{-1}$	Date	Water discharge $m^3 s^{-1}$	Sediment discharge $g s^{-1}$
Enmyvaam River	3 Jul 2003	12.807	106.022	17 Jul 2003	15.271	75.670	10 Aug 2003	9.053	62.527
creek 50	12 Jun 2003	0.580	6.678	n			n		
creek 49	12 Jun 2003	6.094	23.955	23 Jul 2003	0.058	0.138	18 Aug 2003	0.359	0.329
creek 47	18 Jun 2003	0.140	0.351	23 Jul 2003	0.018	0.030	18 Aug 2003	0.018	
creek 44	n			23 Jul 2003	0.020	0.165	n		
creek 45	n			n			18 Aug 2003	0.158	0.164
creek 41	18 Jun 2003	0.220	0.266	23 Jul 2003	0.015	0.190	18 Aug 2003	0.013	0.010
creek 36	n			n			18 Aug 2003	0.034	0.113
creek 35	n			n			18 Aug 2003	0.064	0.260
creek 34	n			23 Jul 2003	0.019	0.021	18 Aug 2003	0.072	0.225
creek 33/1	n			n			18 Aug 2003	0.066	0.062
creek 33	18 Jun 2003	0.170	0.599	23 Jul 2003	0.022		18 Aug 2003	0.073	0.035
creek 32	n			23 Jul 2003	0.052	0.052	18 Aug 2003	0.116	0.133
creek 31	n			n			18 Aug 2003	0.249	0.333
creek 28	n			n			18 Aug 2003	0.048	0.083
creek 27	n			n			18 Aug 2003	0.028	0.026
creek 26	n			23 Jul 2003	0.006	0.583	18 Aug 2003	0.029	0.015
creek 25	n			23 Jul 2003	0.026	0.223	18 Aug 2003	0.055	0.114
creek 23	n			23 Jul 2003	0.516	1.351	18 Aug 2003	0.122	0.023
creek 21	19 Jun 2003	1.720	5.867	23 Jul 2003	0.044	0.083	19 Aug 2003	0.094	
creek 20	n			24 Jul 2003	0.068	0.298	19 Aug 2003	0.105	0.157
creek 19	n			n			19 Aug 2003	0.033	0.025
creek 16	n			24 Jul 2003	0.036	0.160	19 Aug 2003	0.072	0.206
creek 14	19 Jun 2003	1.305	17.879	24 Jul 2003	0.093	0.026	19 Aug 2003	0.152	0.397
creek 12	n			24 Jul 2003	0.010	0.017	19 Aug 2003	0.035	0.046
creek 10	n			24 Jul 2003	0.005	0.014	19 Aug 2003	0.083	0.162
creek 8	n			24 Jul 2003	0.017	1.248	19 Aug 2003	0.014	0.006
creek 7	n			24 Jul 2003	0.012		19 Aug 2003	0.003	0.009
creek 6	n			24 Jul 2003	0.003	0.013	19 Aug 2003	0.005	0.000
creek 5	n			24 Jul 2003	0.002		19 Aug 2003	0.009	0.020
creek 4	n			24 Jul 2003	0.002	0.002	19 Aug 2003	0.003	0.010
creek 3	15 Jun 2003	0.140	1.036	n			n		
creek 2	15 Jun 2003	0.060	0.107	n			n		

"n" – no measurements.

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Lake El'gygytgyn water and sediment balance components overview
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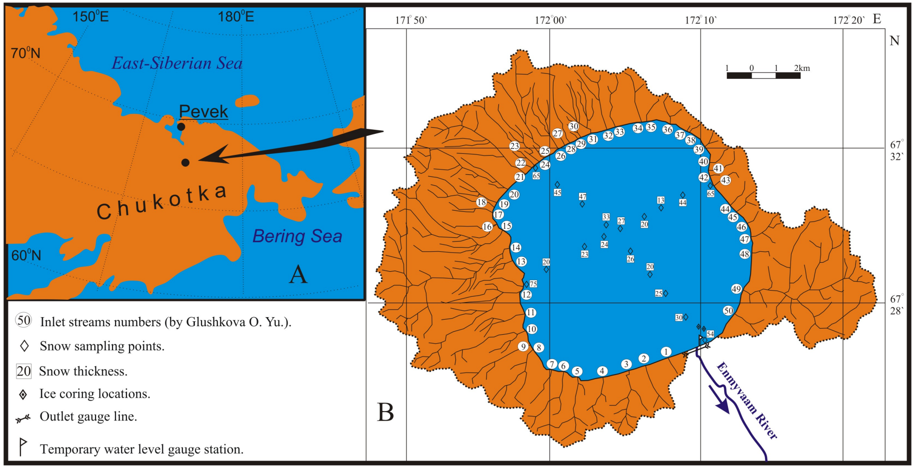

Fig. 1. Location **(a)** and scheme **(b)** of the Lake El'gygytgyn drainage basin.

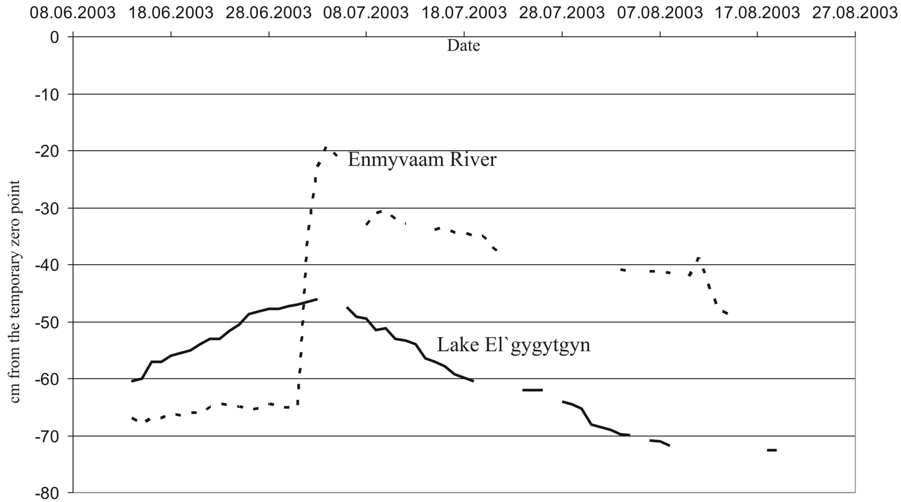

Fig. 2. Water level changes in Lake El'gygytgyn (solid line) and Enmyvaam River (dashed line) during summer 2003.

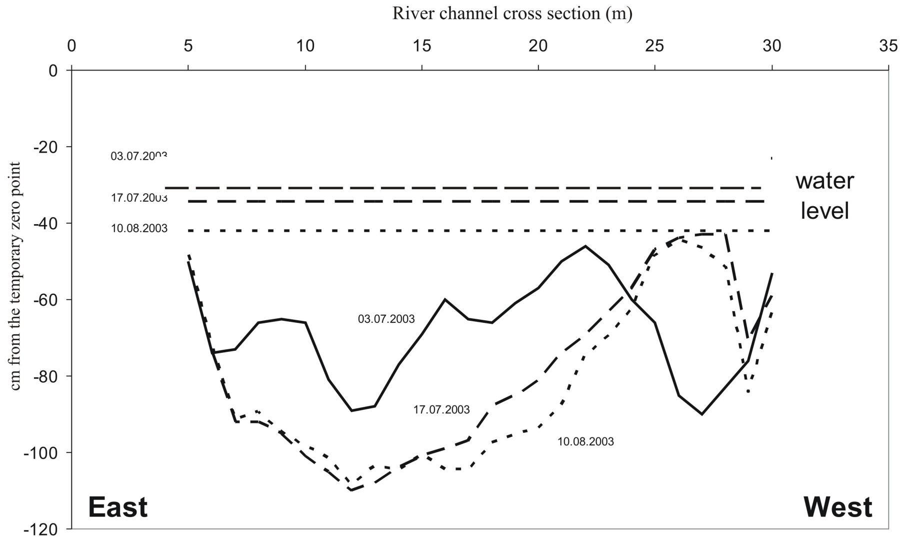

Fig. 3. Depth measurements at the head of Enmyvaam River during the summer 2003, compared to the river water levels at the respective times.

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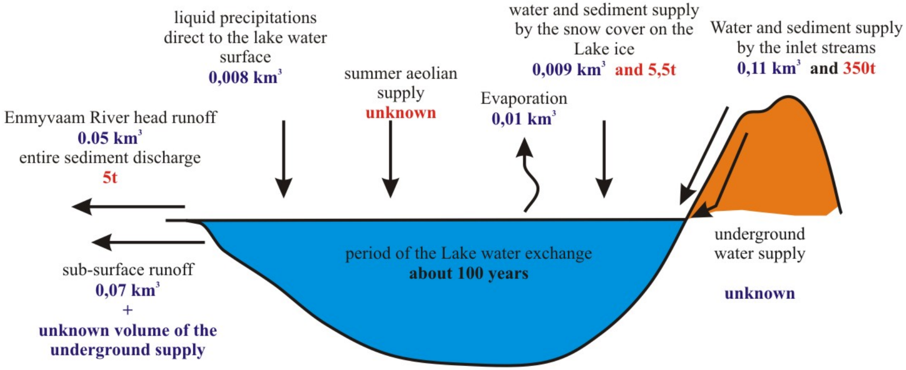

Fig. 4. Sketch of the water and sediment balance of Lake El'gygytgyn.

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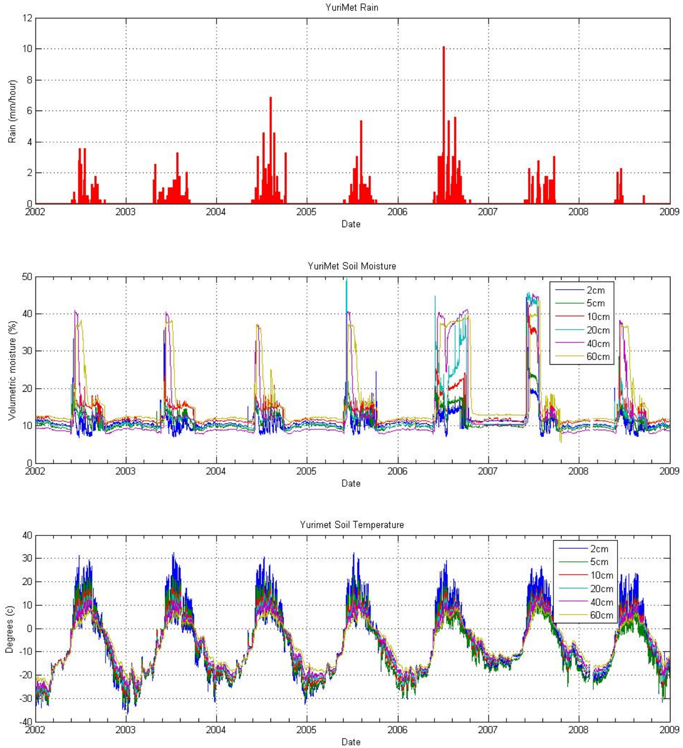

Fig. 5. Seven years of rain, soil moisture, and soil temperature data from the outwash plain of Lake El'gygytgyn. Rain fall, as measured by a tipping bucket, occurs mainly during the summer months of June, July and August, varying from 70 mm, 73 mm, 173 mm, 106 mm, 200 mm and 134 mm from 2002 to 2007 respectively. The gage apparently malfuctioned in June 2008. Soil moisture and soil temperature follow similar trends each year, except in 2006 when high rainfall left soils saturated at the end of summer. The moisture then froze and drained off the following summer. We believe these dynamics strongly support our conclusions that significant amounts of lake water can be stored in and migrate through these gravels, as described in the text.

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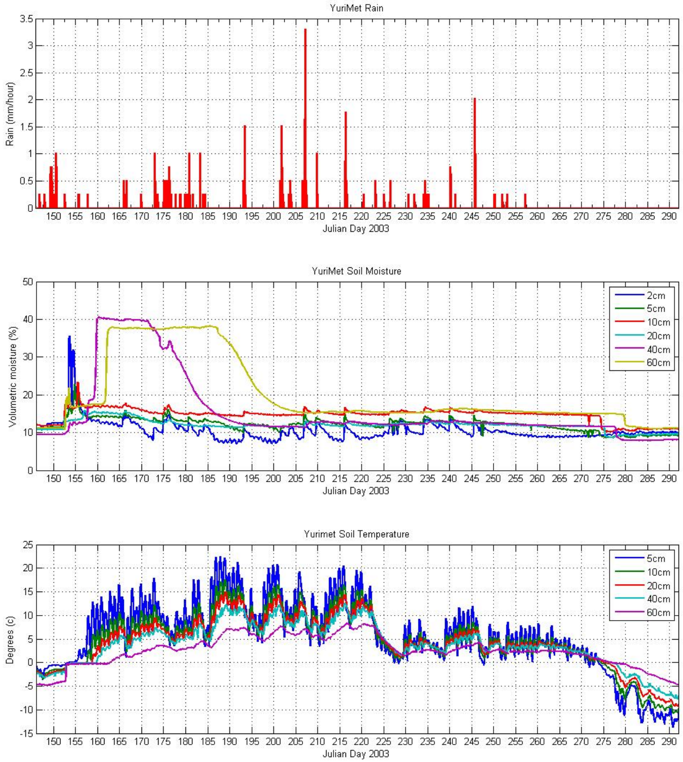

Fig. 6. Rain, soil moisture and soil temperature for 2003. Surface soils thaw between day 150–155 (end of May), with energy from the sun, snow melt, and rain. Within a week the deeper soils thaw. The surface soils begin drying out quickly once thawed, but a water table persists for several weeks between 20 and 40 cm depth, indicating water storage, likely from snow melt and early rain as the soils at depth were dry at the end of the previous summer. This water drains about the time the outlet river opens up in early July. Variations after this point are caused by rainfall, which do reach the 40 cm level quickly, indicating good hydraulic conductivity. Soils then freeze with little trapped moisture between days 273–280 (early October).