Preliminary estimation of Lake El`gygytgyn water balance and sediment income

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Abstract

Modern process studies of the hydrologic balance of Lake El'gygytgyn, central Chukotka, and the sediment income from the catchment provide important quantitative estimates for better understanding the lacustrine paleoclimate record from this basin. Formed ca. 3.6 million years ago 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 (about 20 days in second part of June). Underground outflow plays a very important role in the water balance and predominates over surface outflow. The residence time of the lake-water is estimated to be about 100 yr. The main source of clastic material are incoming streams (about 350 t in 2003). The atmospheric deposition contributes only few % to the total sediment income. All the numbers provided here based on limited measurements during only one season (2003).

As a result there are quite high uncertainties but even preliminary character of results provide an important basis for understanding the modern and past sedimentation processes in the crater.

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 141.5m 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).

This paper provides the results of water balance and sediment income 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 interpret the sensitivity of basin sedimentology to climate forcing in the past.

The crater rim hills rise up to 600-930 m a.s.l. (above sea level) and formed by Upper Cretaceous rocks of volcanic origin (Belyi, 1998). The lake level elevation is 492.4 m a.s.l. according to recent topographic maps.

Lake El'gygytgyn located in zone of continuous permafrost (Yershov, 1998; Schwamborn et al., 2012). The thickness of permafrost in the crater is estimated to be about 350 m (Mottaghy et al., 2012, Schwamborn et al., 2012). In 2003 the active layer varied between 0.4 m in silty material and 0.8 in sand and gravel (Schwamborn et al., 2012).

The Crater belongs to the hypoarctic tundra vegetation zone (Yurtsev, 1973). Modern vegetation cover is discontinuous and dominated by lichen and herbaceous taxa (Kohzevnikov, 1993; Minyuk, 2005; Lozhkin et al., 2006, Wilkie et al., 2013).

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 is monomictic, ultra oligotrophic lake with an area of 110 km^2 and volume of 14.1 km^3 is today 175 m at maximum deep surrounded by a watershed measuring 293 km^2 (Nolan and Brigham-Grette, 2007). The lake has approximately 50 inlet streams and one outlet, the Enmyvaam River (Fig. 1) that belongs to the Anadyr River drainage basin leading to the Bering Sea.

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. 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). 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.

A first appraisal of the Enmyvaam River discharge velocity at its head was done by Glotov and Zuev (1993), which was nearly equal to 1m s^{-1}. These data allowed them to estimate a water discharge of 50m^3 s^{-1} at a maximum, but with an average in the range of 20m^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 19.8m^3 s^{-1} on 16 August, 14.2m^3 s^{-1} on 23 August, and 11.6m^3 s^{-1} on 1 September and less than 1m^3 s^{-1} in all the inlet streams.

2 Methods

2.1 Water balance

The following equation can be applied to estimate Lake El`gygytgyn water balance:

$$\frac{dV}{dt} = (Y_1 + Y_2) + P + Z_1 - Z_2 - E - Y, \ (1)$$

Y= outflow by Enmyvaam River

Y_1= inflow by main lake tributaries

Y_2= inflow by remaining stream network

P= precipitation over the lake surface

Z_1= underground inflow

Z_2= underground outflow

E= evaporation from the open water surface

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

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 (see table 1). 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 unit area discharge (ratio between the water runoff and watershed area) for those main streams.

Below provided the sequence of total seasonal surface inflow ($W=Y_1+Y_2$, see equation 1) estimation:

$$M_{i_j} = \frac{Q_{i_j}}{F_i}, \quad (2)$$

Where: Mi_j – unit area discharge from the watershed area of stream-"i" for measurement series-"j" ($m^3\ s^{-1}$ sq. km^{-1}); Q_{ij} – water discharge of stream -"i" for measurement series -"j" ($m^3\ s^{-1}$); i – ordinal number of incoming stream; j – ordinal number of water discharge measurements series; F_i – watershed area of stream -"i" (km^2).

$$M_{m_j} = \frac{1}{n_j}\sum_{i=1}^{n_j} M_{i_j}, \quad (3)$$

Where: Mm_j- average unit area discharge for measurement series-"j" ($m^3\ s^{-1}$ sq. km^{-1}); n_j – number of measured streams for measurement series -"j" ($n_1=9$, $n_2=21$, $n_3=28$).

$$Q_j = F * \frac{1}{3}\sum_{j=1}^{3} M_{m_j} \text{ , (4)}$$

Where Q_j is water discharge from entire lake watershed area (F) for measurement series-“j” (m^3 s^{-1})

$$W = T * \frac{1}{3}\sum_{j=1}^{3} Q_j \text{, (5)}$$

Where T is duration of the estimate period. As a beginning of the estimate period we took the dates of first visual recognition of the water flow in stream mouths in 2003 (June 10-12). Very beginning of October then automated meteorological station recorded onset of active layer freezing (see Fig. 2) considered to be the end of estimate period. Thus, duration of estimate period considered to be 110 days.

The Enmyvaam River total runoff is estimated as average water discharge multiplied by time period of outflow activity. In 2003 the outflow into Enmyvaam River opened on 3 July and closed by storm on 14 August.

2.1.2 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).

2.1.3 Groundwater components of the water balance

The most difficult parameters to estimate in this basin are the groundwater components. We have no data to estimate underground inflow from the catchment directly into the lake, however, it could be quite significant as it is shown for different arias (Zhang et al., 2003, Woo et al., 2008)

For Levinson-Lessing Lake located in similar climate and permafrost conditions on the Taymyr Peninsula, Central Siberia (Zimichev et al., 1999) the underground inflow 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 can have unknown groundwater components. As a result, the contribution of underground in- or outflow to the water balance was estimated jointly as the difference between the known terms of the equation.

2.1.4 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). Sokolov (1964) provided standard maps of evaporation from open water surface based on observations on all available meteorological stations. For Chukotka aria 27 of meteorological stations were taken into consideration.

2.1.5 Water 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 and in river outflow (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. 3). 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.

Another graduated staff gage for visual water level observations was installed in 100 m downstream of Enmyvaam River from the lake shore. In this point water was in the river channel even before opening and after closing the direct surface outflow due to infiltration of water through porous deposits of the coastal levee. The river level changes were monitored from 14 June to 16 August (Fig. 3) which is longer than period of the surface outflow activity.

2.1.6 The residence time of the water in Lake El'gygytgyn

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).

2.2 Sediment income

Our data are not allow us to estimate the sediment balance of Lake El’gygytgyn but providing important quantitative information about fluvial and aeolian sediment income.

2.2.1 Fluvial sediment supply

Water samples were collected simultaneously with water discharge measurements by so-called integral method (through entire water column). Turbidity was determined after filtration through paper filters (standard so-called “yellow stripe” filters used in Russian hydrometeorological survey) 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. Drying was performed during 6 hours in laboratory oven with 60 °C.

Knowledge about turbidity and water discharge allowed us to calculate sediment discharges.

Below provided the estimation sequence of total seasonal sediment inflow from entire lake watershed area:

$$A_{ij} = Q_{ij} * C_{ij}, \ (6)$$

Where: A_{ij} – sediment discharge of stream -“i” for measurement series -“j” (g s^{-1}); C_{ij} – concentration of suspended particles of stream -“i” for measurement series -“j” (g/m^3).

$$MA_{i_j} = \frac{A_{i_j}}{F_i}, \ (7)$$

Where MA_{ij} – unit area sediment discharge from the watershed area of stream-“i” for measurement series-“j” (g s^{-1} sq. km^{-1}).

$$MA_{m_j} = \frac{1}{n_j} \sum_{i=1}^{n_j} MA_{i_j}, \ (8)$$

Where MAm_j – average unit area sediment discharge for measurement series-“j” (g s^{-1} sq. km^{-1}).

$$A_j = F * \frac{1}{3} \sum_{j=1}^{3} MA_{m_j}, \ (9)$$

Where A_j is sediment discharge from entire lake watershed area (F) for measurement series-“j” (g s^{-1}).

$$A_{in} = T * \frac{1}{3} \sum_{j=1}^{3} A_j, (10)$$

Where A_{in} – total seasonal sediment inflow from entire lake watershed area (g).

Using the same approach water samples were also taken in Enmyvaam River simultaneously with water discharge measurements with subsequent calculation of sediment discharges (Table 1). But this data cannot be used for the sediment outflow estimation (see Sect. 3.2.2).

2.2.2 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. 2.1.2) were melted and filtered through paper filters as described in section 2.2.1.

3 Results and discussion

3.1 Water balance

3.1.1 Water surface inflow and outflow

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. 3).

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. 3). 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.

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.

The Lake El'gygytgyn water balance components for 2003 are summarized in table 2 and figure 4. The total annual water inflow by inlet streams is 0.11 km^3 and outflow 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.

3.1.2 Water supply from the lake ice surface

During spring 2003 (16 May and 23 May) two snow sampling profiles were performed (see Fig. 1), to estimate water supply derived from the lake ice surface. The snow thickness averaged 35.6cm 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}. These data provided a means of estimating the water supply from the snowpack at 0.01km^3 (Table 2).

3.1.3 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, Table 2). 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.

3.1.4 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 (Table 2); i.e. up to 10 % of the total water discharge.

The water level observations in Lake El´gygytgyn and the Enmyvaam River (Fig. 3, Table 2) demonstrate the important role of underground outflow. 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.

Data from table 2 clearly show that underground outflow plays important role in spring as well as in summer and as higher as higher lake level.

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.

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 on Enmyvaam River (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 200m 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 60cm and the pit back-filled; these probes remained active for 7 years and provide a record of local water table and the timing of subsurface thaw and water movement (Figures 2 and 5). In each year, the ground thawed to 60cm 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.

3.1.5 The residence time of the water in Lake El’gygytgyn

All the data provided above allow us to roughly estimate the average hydraulic residence time of the lake at about 100 years (Fig. 4). Obviously the usage of data obtained for one year only causes very significant uncertainty for an average picture. Our estimation of residence time of the water in Lake El’gygytgyn is very approximate but giving the base line for paleoenvironmental interpretations and future balance investigations.

3.2 Sediment income

3.2.1 Fluvial sediment supply

Sediment supply to the lake by inlet streams during spring and summer is estimated at roughly 350 t (Fig. 4).

3.2.1 Enmyvaam River sediment discharge

In 2003 we paced the gauge line in Enmyvaam River for water discharge measurements 100 m downstream from the lake shore. Concentrations of suspended particles during measurements were quit high and calculated sediment discharges are very significant (see table 1). But we are believed that this numbers cannot be used for total sediment outflow estimation because the reason for such significant turbidity is very active riverbed erosion on the way from the lake to the gauge line.

The maximum water discharge down the Enmyvaam River (15.27m^3 s^{-1}), documented during the middle of July, did not coincide with maximum sediment discharge and the peak of lake level or that of the river itself (Fig. 3 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.

This interpretation is supported by the data illustrated in Fig. 6, showing a general drop of the lake/river level coincident with a significant deepening of the riverbed. The maximum sediment discharge (106.02 g s^{-1}) took place in early July, with the initiation of riverbed erosion.

3.2.3 Aeolian sediment input

The average concentration of solids in the snow pack on the lake ice surface was about 0.6 mg per litre of melted water. The values ranged from 0.05mgl^{-1} to 1.32mgl^{-1}. Taking into account the data provided in the section 3.1.2, this allow us to estimate the total sediment income from the lake ice cover to about 6 t, which is less than 2 % of the fluvial sediment supply.

The aeolian sediment supply during summer is unknown. 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 the summer is most likely associated with Lake El’gygytgyn storm events when fine-grained, shoreline material is fed into the lake by strong wind. 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 cannot 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.

From our point of view there are two main reasons for relatively little aeolian supply. 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.

3.2.4 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 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 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.

3.2.5 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 ± 1.0 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 turbidities recognized in lake sediment cores (Juschus et al., 2009, Sauerbrey et al., 2012).

3.3 The main sources of uncertainties

Here we have to highlight the preliminary character of our estimation and mention the following main sources of uncertainties in the calculations:

a) The highest uncertainty is probably related to limitation of our data by one year only (2003). But up to now the water discharge data including both spring flooding and summer period available only for 2003.

b) Our calculation based on only three series of the measurements - one during spring flooding and two - in summer time.

c) We used calculated for measured streams unit area of discharge for with subsequent extrapolation on entire watershed area without taken into consideration the topography of each stream drainage basin.

d) Amount of the liquid precipitation on open water surface have been estimated based on data just one automatic meteorological station installed on southern lake shore. On another hand the distance between regular meteorological stations in Chukotka many times bigger than entire lake basin.

e) Evaporation from the open water surface has been estimated based on standard regional data from 1964. Taken into account the climate change these data more likely does not fully fits into the modern climate situation.

4 Conclusions

1. The first quantitative estimation of the Lake El`gygytgyn water balance and sediment income is provided. All calculations in this work are rough and have a high level of uncertainties due to limited measurements, but even this level of knowledge is extremely important as a basic information for the paleoenvironmental interpretations of the sedimentary record.

2. 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.

3. 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).

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

5. The overwhelming amount of sediment transported into the lake is accomplished by the inlet streams. Aeolian input is not significant and amount only first percents of total input.

6. 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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References

Belyi, V. F.: Impactogenesis and volcanism of the Elgygytgyn depression, Petrology, 6, 86–99, 1998.

Brigham-Grette, J., Melles, M., Minyuk, P., and the El’gygytgyn Scientific Party: Climate variability from the Peak Warmth of the Mid-Pliocene to Early Pleistocene from Lake El’gygytgyn, northeastern Russia, western Beringia, Clim. Past Discuss., in preparation, 2012.

Fedorov, G. B., Schwamborn, G., and Bolshiyanov, D. Y.: Late Quaternary lake level changes at Lake El’gygytgyn, Bulletin of St. Petersburg State University, Series-7, 1, 73–78, 2008 (in Russian).

Glotov, V. Y. and Zuev, S. A.: Hydro-geological features of the El’gygytgyn Lake, Kolyma, 3–4, 18–23, 1995 (in Russian).

Glushkova, O. Y.: Geomorphology and the history of the relief development of the El’gygytgyn lake region, in: The nature of the El’gygytgyn lake basin (problems of study and preservation), NEISRI FEB RAS, Magadan, 26–48, 1993 (in Russian).

Guide to hydrometeorological stations, Edition 6, Part 1, Gidrometizdat, Leningrad, 384 pp., 1978 (in Russian).

Juschus, O., Melles, M., Gebhardt, C., and Niessen, F.: Late Quaternary mass movement events in Lake Elgygytgyn, North-eastern Siberia, Sedimentology, 56, 2155–2174, doi:10.1111/j.1365-3091.2009.01074.x, 2009.

Juschus, O., Pavlov, M., Schwamborn, G., Federov, G., and Melles, M.: Lake Quarternary lakelevel changes of Lake El’gygytgyn, NE Siberia, Quarternary Res., 76, 441–451, 2011.

Kohzevnikov, Yu. P.: Vascular plants in the vicinities of the Elgygytgyn Lake, in: The Nature of the El’gygytgyn Lake Hollow, edited by: Bely, V. F. and Chereshnev, I. A., NEISRI FEB RAS Magadan, 62–82, 1993 (in Russian).

Layer, P.: Argon-40/argon-39 age of the El’gygytgyn impact event, Chukotka, Russia, Meteorit. Planet. Sci., 35, 591–599, 2000.

Lozhkin, A. V., Anderson, P. M., Matrosova, T. V., and Minyuk, P. S.: The pollen record from El’gygytgyn Lake: implications for vegetation and climate histories of northern Chukotka since the late middle Pleistocene, J. Paleolimnol., 37, 135–153, doi:10.1007/s10933-006-9018-5, 2006.

Melles, M., Brigham-Grette, J., Minyuk, P., and the El’gygytgyn Scientific Party: Evolution of Quaternary Arctic climate from Lake El’gygytgyn, northeastern Russia, Clim. Past Discuss., in preparation, 2012.

Minyuk, P. S.: Vegetation around Lake El’gygytgyn, in: The expedition El’gygytgyn Lake 2003 (Siberian Arctic), vol. 509, edited by: Melles, M., Minyuk, P. S., Brigham-Grette, J., and Juschus, O., 30–35, 2005.

Mottaghy, D., Schwamborn, G., and Rath, V.: Past climate changes and permafrost depth at the Lake El’gygytgyn site: implications from data and thermal modelling, Clim. Past Discuss., 8, 2607–2644, doi:10.5194/cpd-8-2607-2012, 2012.

Nolan, M.: Analysis of local AWS and NCEP weather data at Lake El’gygytgyn, Siberia, and its implications for maintaining multi-year lake-ice covers, Clim. Past Discuss., accepted, 2012.

Nolan, M. and Brigham-Grette, J.: Basic hydrology, limnology, and meterology of modern Lake El’gygytgyn, Siberia, J. Paleolimnol., 37, 17–35, 2007.

Nolan, M., Liston, G., Prokein, P., Brigham-Grette, J., Sharpton, V., and Huntzinger, R.: Analysis of Lake Ice Dynamics and Morphology on Lake El’gygytgyn, Siberia, using SAR and Landsat, J. Geophys. Res., 108, 8162, doi:10.1029/2001JD000934, 2003.

Sauerbrey, M., Juschus, O., Gebhardt, C., Wennrich, V., Nowaczyk, N., Melles, M.: Mass movement deposits in the 3.6 Ma sediment record of Lake El'gygytgyn, Far East Russian Arctic: classification, distribution and preliminary interpretation, Clim. Past Discuss., in preparation, 2012.

Schwamborn, G., Fedorov, G., Ostanin, N., Schirrmeister, L., Andreev, A., and the El'gygytgyn Scientific Party: Depositional dynamics in the El'gygytgyn Crater margin: implications for the 3.6 Ma old sediment archive, Clim. Past, 8, 1897-1911, doi:10.5194/cp-8-1897-2012, 2012.

Schwamborn, G., Fedorov, G., Schirrmeister, L., Meyer, H., and Hubberten, H.-W.: Periglacial sediment variations controlled by Late Quaternary climate and lake level rise at Elgygytgyn Crater, Arctic Siberia, Boreas, 37, 55–65, 2008.

Sokolov, A. A.: Hydrography of USSR, GIMIZ, Lenigrad, 535 pp., 1964 (in Russian).

Wilkie, K. M. K., Chapligin, B., Meyer, H., Burns, S., Petsch, S., and Brigham-Grette, J.: Modern isotope hydrology and controls on δD of plant leaf waxes at Lake El'gygytgyn, NE Russia, Clim. Past, 9, 335-352, doi:10.5194/cp-9-335-2013, 2013.

Woo, M. Kane, D., Carey, S. and Yang, D.: Progress in Permafrost Hydrology in the New Millennium, Permafrost and Periglacial Process, 19, 237–254, 2008.

Yershov, E. D.: General Geocryology. Studies in Polar Research, Cambridge Univ. Press, English Edition, 1998.

Yurtsev, B. A.: Botanic-geographical zonation and floristic zoning of the tundra in Chukotka, J. Bot., 58, 812–821, 1973 (in Russian).

Zhang, Y., Ohata, T., Kadota, T.: Land-surface hydrological processes in the permafrost region of the eastern Tibetan Plateau, Journal of Hydrology, 283, 41–56, 2003.

Zimichev, V. P., Bolshiyanov, D. Y., Mesheryakov, V. G., and Gintz, D.: The features of the hydrological regime of the lake-river systems of the Byrranga Mountains (by example of the Levinson-Lessing Lake), in: Land-Ocean Systems in the Siberian Arctic, Dynamics and History, edited by: Kassens, H., Bauch, H. A., Dmitrenko, I., Eicken, H., Hubberten, H.-W., Melles, M., Thiede, J., and Timokhov, L., Springer-Verlag, Berlin, 353–360, 1999.

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	sediment discharge g/s	date	water discharge m^3/s	sediment discharge g/s	date	water discharge m^3/s	sediment discharge g/s
Enmyvaam River	07/03/03	12.807	106.022	07/17/03	15.271	75.670	08/10/03	9.053	62.527
creek 50	06/12/03	0.580	6.678	n			n		
creek 49	06/12/03	6.094	23.955	07/23/03	0.058	0.138	08/18/03	0.359	0.329
creek 47	06/18/03	0.140	0.351	07/23/03	0.018	0.030	08/18/03	0.018	
creek 44	n			07/23/03	0.020	0.165	n		
creek 45	n			n			08/18/03	0.158	0.164
creek 41	06/18/03	0.220	0.266	07/23/03	0.015	0.190	08/18/03	0.013	0.010
creek 36	n			n			08/18/03	0.034	0.113
creek 35	n			n			08/18/03	0.064	0.260
creek 34	n			07/23/03	0.019	0.021	08/18/03	0.072	0.225
creek 33/1	n			n			08/18/03	0.066	0.062
creek 33	06/18/03	0.170	0.599	07/23/03	0.022		08/18/03	0.073	0.035
creek 32	n			07/23/03	0.052	0.052	08/18/03	0.116	0.133
creek 31	n			n			08/18/03	0.249	0.333
creek 28	n			n			08/18/03	0.048	0.083
creek 27	n			n			08/18/03	0.028	0.026
creek 26	n			07/23/03	0.006	0.583	08/18/03	0.029	0.015
creek 25	n			07/23/03	0.026	0.223	08/18/03	0.055	0.114
creek 23	n			07/23/03	0.516	1.351	08/18/03	0.122	0.023
creek 21	06/19/03	1.720	5.867	07/23/03	0.044	0.083	08/19/03	0.094	
creek 20	n			07/24/03	0.068	0.298	08/19/03	0.105	0.157
creek 19	n			n			08/19/03	0.033	0.025
creek 16	n			07/24/03	0.036	0.160	08/19/03	0.072	0.206
creek 14	06/19/03	1.305	17.879	07/24/03	0.093	0.026	08/19/03	0.152	0.397
creek 12	n			07/24/03	0.010	0.017	08/19/03	0.035	0.046
creek 10	n			07/24/03	0.005	0.014	08/19/03	0.083	0.162
creek 8	n			07/24/03	0.017	1.248	08/19/03	0.014	0.006
creek 7	n			07/24/03	0.012		08/19/03	0.003	0.009
creek 6	n			07/24/03	0.003	0.013	08/19/03	0.005	0.000
creek 5	n			07/24/03	0.002		08/19/03	0.009	0.020
creek 4	n			07/24/03	0.002	0.002	08/19/03	0.003	0.010
creek 3	06/15/03	0.140	1.036	n			n		
creek 2	06/15/03	0.060	0.107	n			n		

n – no measurements.

Table 2. Lake El’gygytgyn water balance components in 2003.

Time period in 2003 (dt)	dV/dt from lake level observa-tions (km^3)	Inflow (Y_1 + Y_2) (km^3)	Pre-cipitations on lake surface (P) (km^3)	surface outflow (Y) (km^3)	Evaporation (E) (km^3)	groundwater inflow (Z_1)	groundwater outflow from balance (Z_2) (km^3)
Period from onset of snowmelt to opening the outflow (June 10 – July 3)	+ 0.02	0.06		0		Unknown	0.04 – E + Z_1 + P
Period from opening the outflow to freezing of active layer (July 3 – October 1)	- 0.03	0.05		0.05		Unknown	0.03 – E + Z_1 + P
2003	0	0.11	0.008 of the rainfall + 0.01 of melted snow	0.05	0.01	Unknown	0.07 km3 + Z_1

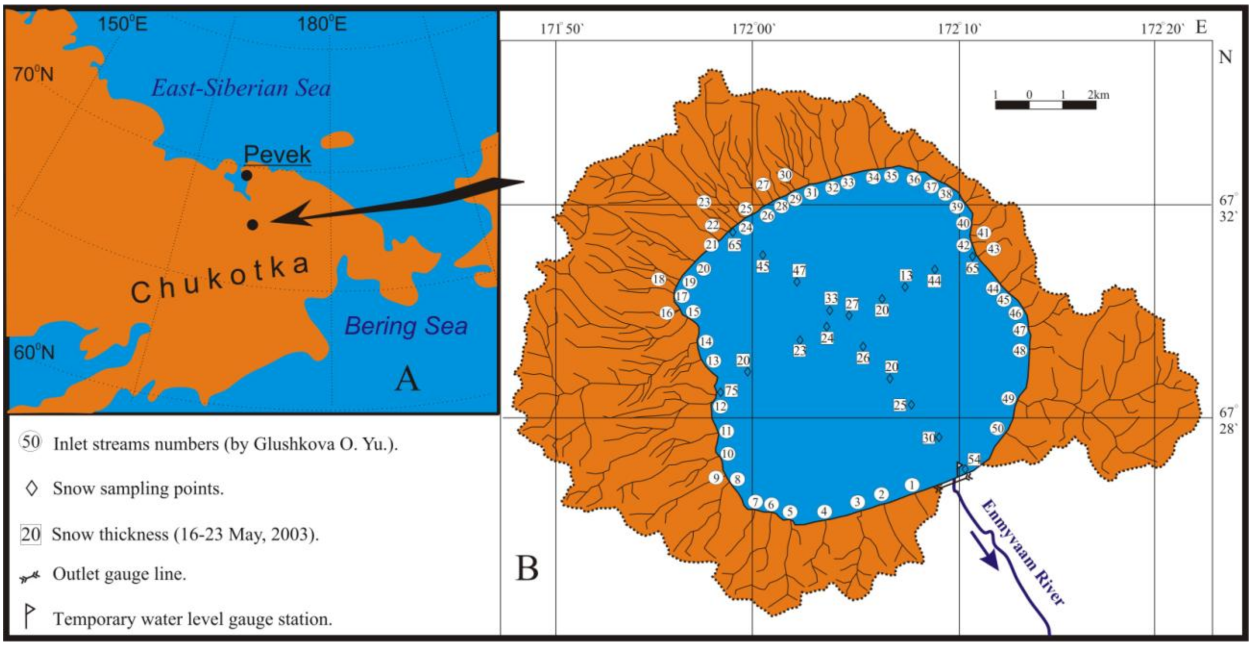

Figure 1. Location (a) and scheme (b) of the Lake El`gygytgyn drainage basin.

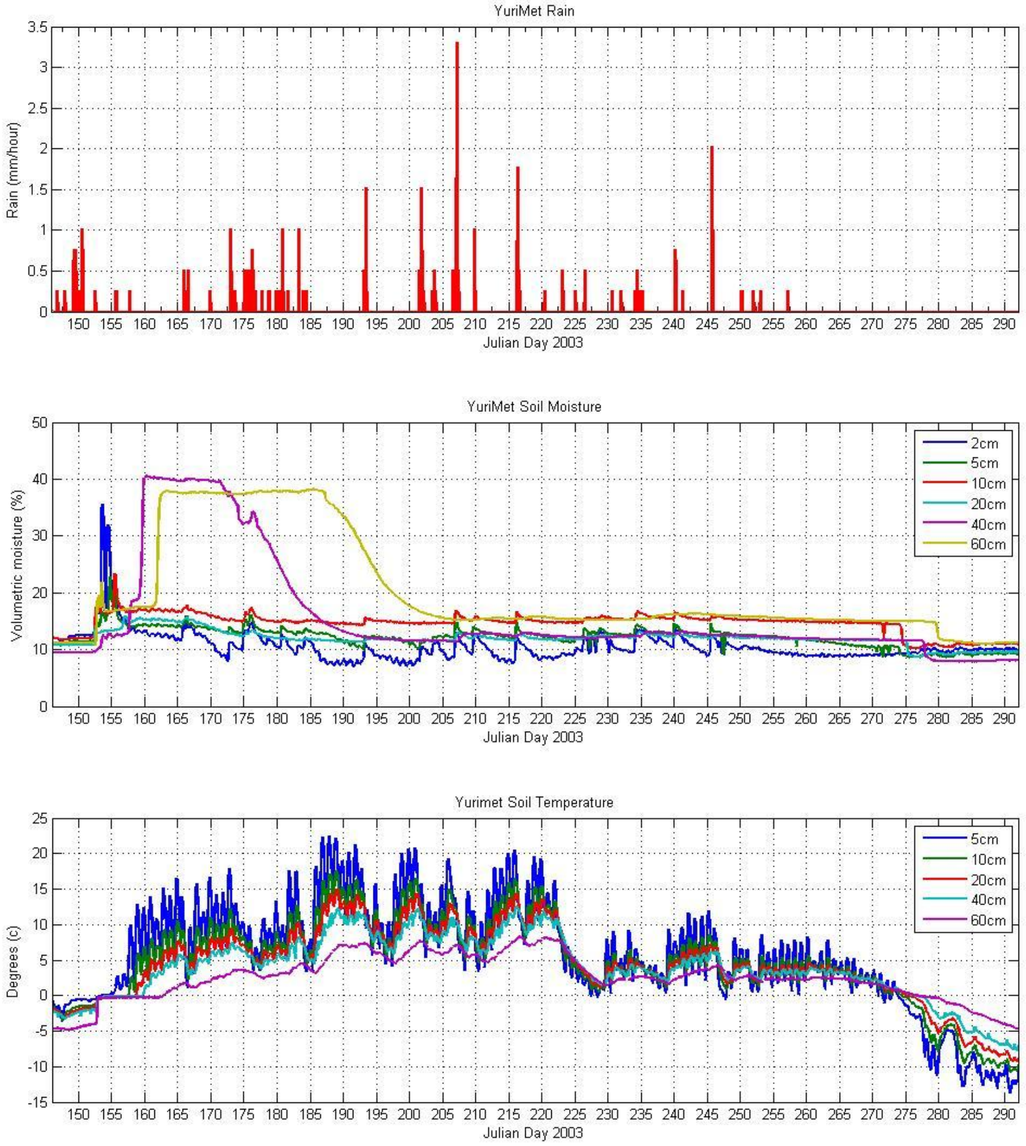

Figure 2. Rain, soil moisture and soil temperature for 2003. Surface soils thaw between day 150-155 (end of May), with energy from the sun, snow melt, and rain. Within a week the deeper soils thaw. The surface soils begin drying out quickly once thawed, but a water table persists for several weeks between 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).

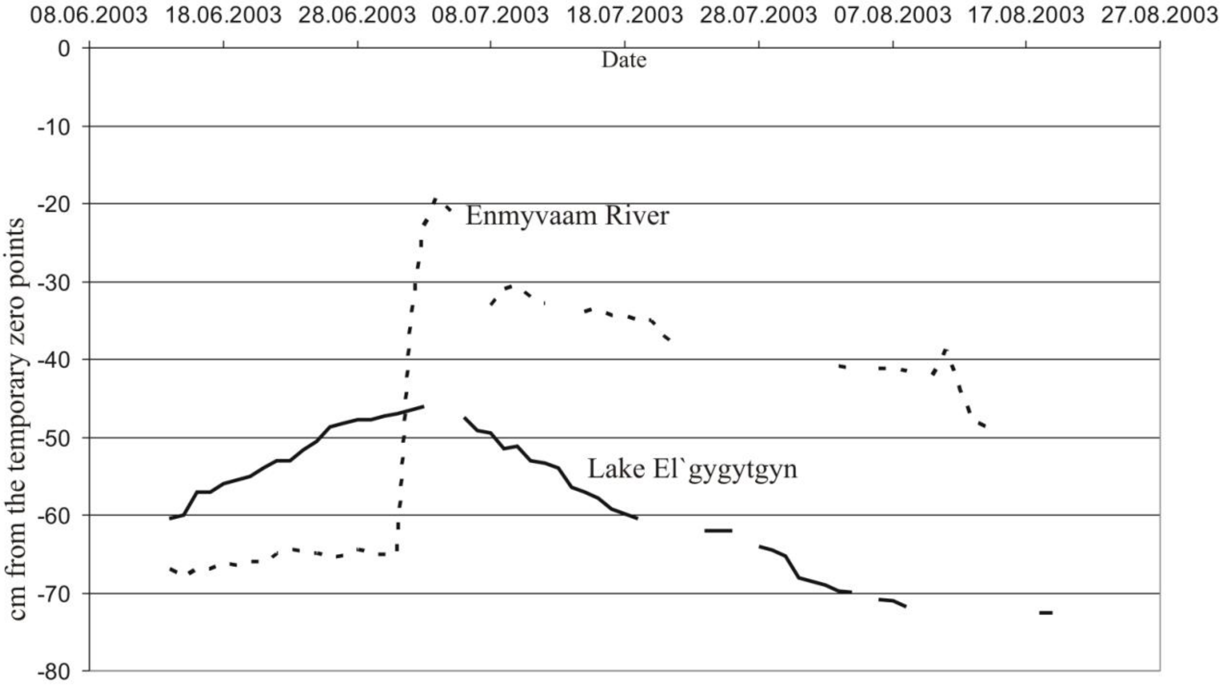

Figure 3. Water level changes in Lake El´gygytgyn (solid line) and Enmyvaam River (dashed line) during summer 2003. Lake and river level measurements had two different temporary zero points.

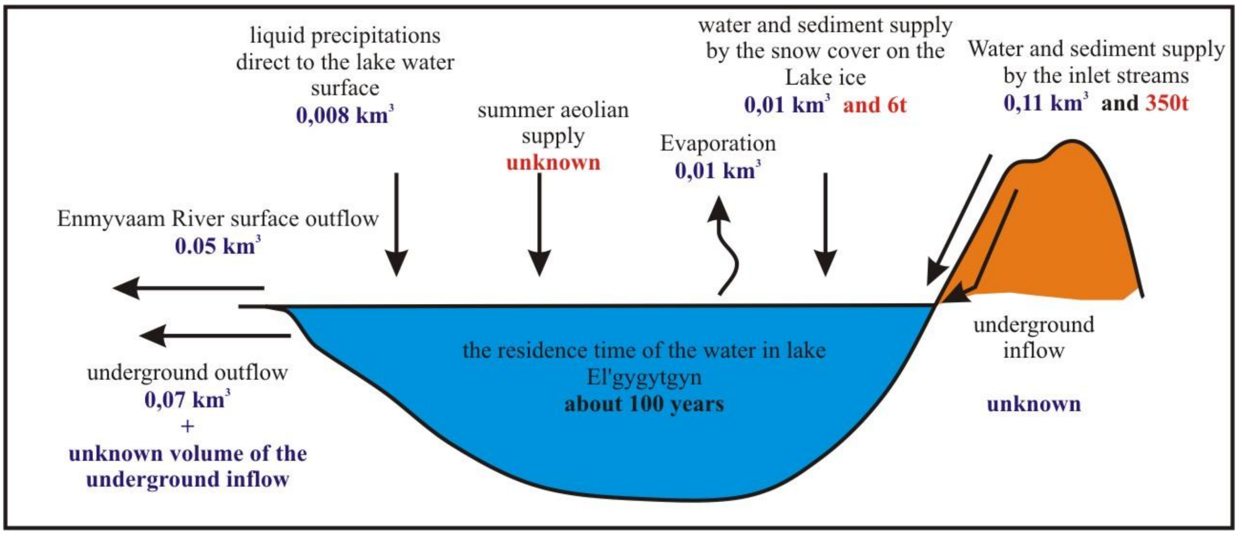

Figure 4. Sketch of Lake El`gygytgyn water balance and sediment income.

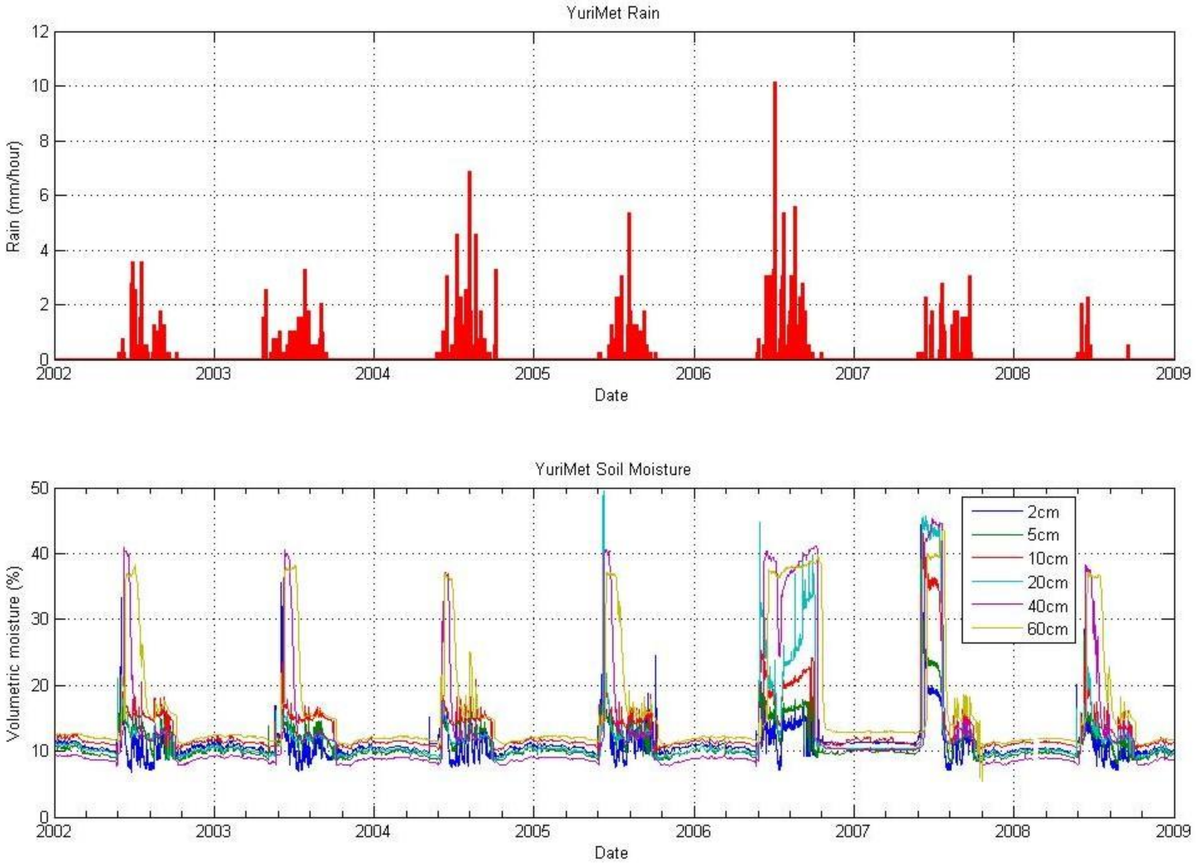

Figure 5. Seven years of rain and soil moisture data from the outwash plain of Lake El'gygytgyn. Rain fall, as measured by a tipping bucket, occurs mainly during the summer months of June, July and August, varying from 70mm, 73mm, 173mm, 106mm, 200mm and 134mm from 2002 to 2007 respectively. The gage apparently malfunctioned in June 2008. Soil moisture 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.

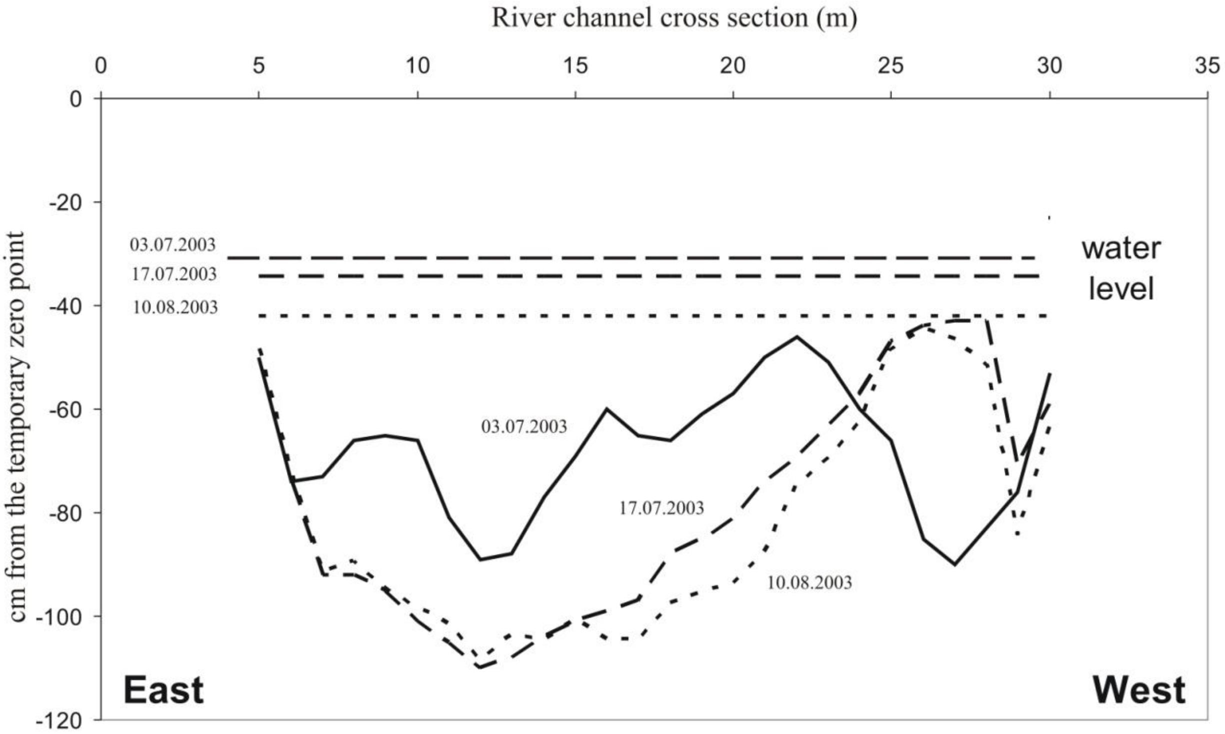

Figure 6. Depth measurements at the head of Enmyvaam River during the summer 2003, compared to the river water levels at the respective times.