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PALAEORUNOFF FROM LAKE LADOGA TO THE BALTIC SEA DURING THE HOLOCENE

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Abstract. The article presents the results of the palaeohydrological analysis of the river system reorganization in the North-West of Russia, the Karelian Isthmus. This study aimed at the hydrological calculation of the runoff through the Heinjoki water connection of Lake Ladoga, the Gulf of Finland and PalaeoVuoksa during different periods of the Holocene. The methods of the equation of water balance, hydraulic-morphometric dependencies and the method of geographical analogy were used in this research. The main result of the carried work is the refinement of the existing regional flow model. In particular, the role of the Heinjoki Strait and the Neva River channel in different stages of the Holocene is considered. The authors came to the conclusion that Lake Ladoga always had a runoff to the Baltic Sea. It is shown that most probably in the period of 10,200-3,500 years ago the runoff was carried out through the Heinjoki waterway. The study underlines that the isostatic factor played a significant role in the forming of the water flow. The change in the runoff direction from the Heinjoki waterway to the Neva River is mainly related to the isostatic uplift of the Karelian Isthmus and the northern part of Lake Ladoga. Quantitative parameters of the Heinjoki palaeoflow (flow rate, annual runoff, runoff layer, runoff coefficient) seem

ПАЛЕОСТОК ИЗ ЛАДОЖСКОГО ОЗЕРА В БАЛТИЙСКОЕ МОРЕ В ГОЛОЦЕНЕ

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Аннотация. В статье представлены результаты палеогидрологического анализа реорганизации речной сети Карельского перешейка со времени его дегляциации и спуска Балтийского ледникового озера около 11700 лет назад. Произведен гидрологический расчет стока на основе морфометрических данных по палеоруслам в северной части Карельского перешейка («Хейниокское соединение»), по которым в голоцене осуществлялся сток вод Ладожского озера в Балтику. Для оценки гидрологических параметров палеостока в северной части Карельского перешейка (Хейниокский пролив) использовались зависимости связи расхода воды реки с шириной и глубиной, водно-балансовые соотношения, применены методы палеогеографической аналогии. Основным результатом данной работы является уточнение существующей модели регионального палеостока. В исследовании сделан вывод, что Ладожское озеро всегда имело сток в Балтийское море, а также отмечается роль изостатического фактора в формировании стока через Хейниокский пролив и реку Неву.

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to be roughly equivalent to the modern parameters of the flow of the Neva River.
The article is dedicated to our colleague, a talented geographer and teacher, PhD Oleg Borisovich Averichkin (1979-2010) who first performed the calculations of the paleorunoff of Lake Ladoga.

Ключевые слова: Lake Ladoga; Baltic Sea; palaeohydrology; Karelian Isthmus; Heinjoki waterway; Neva River; Holocene; modeling; palaeoflow parameters

Keywords: Ладожское озеро; Балтийское море; палеогидрология; Карельский перешеек; пролив Хейниоки; река Нева; голоцен; моделирование; параметры палеостока

Introduction

Reconstruction of water runoff in the rivers of the past geological epochs is one of the most important problems of palaeohydrology.

In the area of the Karelian Isthmus, a significant reworking of the water runoff took place after the retreat Scandinavian ice sheet ca 14,000 years before present (further – yr BP) [Subetto et al., 2018]. Crystalline rocks of the Fennoscandian Shield are a powerful factor in influencing the pattern of the river system and rivers often adapt to geological structures. There are no meanders, the channels are straightforward. River intercepts are characteristic, when the river at one of its segments abandons the old channel in favor of the new one in softer rocks. The postglacial isostatic uplift could have a great influence on the work of rivers, for example, by increasing the slopes of rivers, or by changing the slopes to such an extent that they could now have zero or even reverse slope [Makkaveev, 2001].

During 14,000-12,000 yr BP, and prior to the abrupt fall of the Baltic Ice Lake (further – BIL) at ca 11,700 yr BP, Lake Ladoga remained an easternmost extension of the BIL. About 11,700 yr BP, in the area of the Mt. Billingen in the central Sweden, a glacial lobe decayed, which led to the release of the straits, lowering of the runoff threshold and a drop in the level of the BIL from 95 to 20-25 m [Björck, 1995]. Since that time, Lake Ladoga has been isolated from the Baltic, but their contours differed from modern ones [Subetto 2009]. About 14,000 yr BP, the stream bed of the Svir River, was freed from ice, and the Svir River started to flow into the BIL (Lake Ladoga at that time was the eastermost gulf of the BIL). At the same time, reformation of lake-river systems connected to these water bodies began [Kvasov, 1975; Isachenko, 1998; Zobkov et al., 2019] (figure 1).

The runoff from Lake Ladoga was directed through the system of the Vuoksa river-lake system to the Baltic Sea (modern Vyborg Bay), and the runoff threshold was near settlement Veschevo (Heinjoki). The waterway connecting Lake Ladoga with the Baltic Sea was still in place, consisting of numerous lakes, streams and bays with a labyrinth of islands [Dolukhanov et al., 2009].

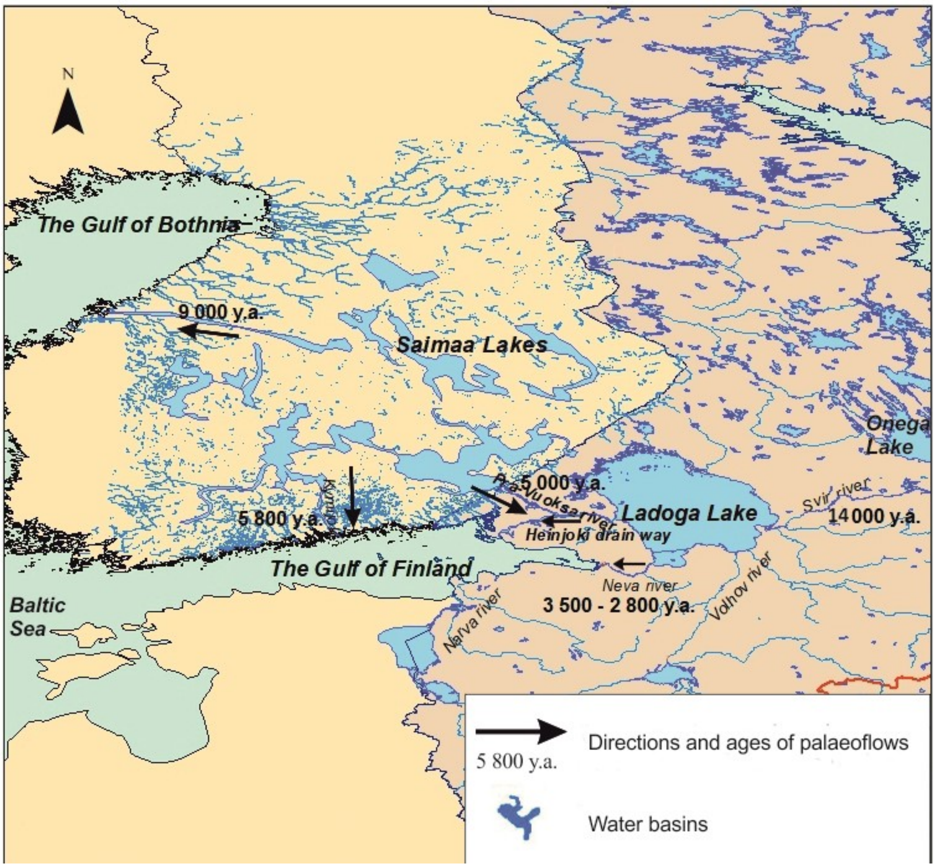

Figure 1. Changes in the hydrographic system of the Ladoga Lake basin
Рисунок 1. Изменения в гидрографической системе бассейна Ладожского озера

Saarnisto [1970, 1995] has demonstrated that Lake Saimaa in southeastern Finland ca 5,900 yr BP started to drain into Lake Ladoga via the Vuoksa River. The resulting influx of fresh water led to the rapid rise of Lake Ladoga and the ensuing Ladoga transgression. Therefore, from the Lake Saimaa' system the flow of water from the north flowed along the old valley of the Heinjoki Strait to Lake Ladoga (NW part) but as the amount of water exceeded the entire volume of the channel, part of the flow went to the Baltic Sea. The northern part of Lake Ladoga situated in the area of a faster uplift of the earth's crust, meanwhile the southern part of the lake submerged. As a result, Lake Ladoga turned into an isolated lake, and overflow began. Lake Ladoga was filling up until its waters flooded the entire valley of the Mga River and approached the narrow isthmus separating the Mga and the Tosna Rivers (Mga-Tosna threshold 18-19 m high). The water level in Lake Ladoga rose above the watershed and the lake's waters run toward to the Baltic Sea, forming the modern Neva River. After that the level of Lake Ladoga fell by 10 m and the Ivanovskie rapids were formed. The River Neva has been formed ca 3,500 yr BP [Alexandrovsky et al., 2009; Dolukhanov et al., 2009; Dolukhanov et al., 2010 and others]. Gradually, the connection between Lake Ladoga and the Baltic Sea through the Heinjoki waterway was stopped. The Vuoksa River began to discharge water directly to Lake Ladoga [Nezhikhovsky, 1973; Saarnisto, 1995; Sevastyanov et al., 2001].

The history of transformations of river valleys can be reconstructed from the tracks left by the stream bed. Therefore, it becomes possible to calculate the flow rate through the Heinjoki using the morphometric data of the palaeochannel. The purpose of this study is the hydrological calculation of the runoff through the Heinjoki water connection of Lake Ladoga and the Baltic Sea and compare obtained data with modern runoff through the River Neva. The purposes of this research are as follows:

(1) To obtain the morphometric data of the palaeochannels of the Karelian Isthmus region;
(2) To perform the hydrological calculations of the palaeoflow based on morphometric data.

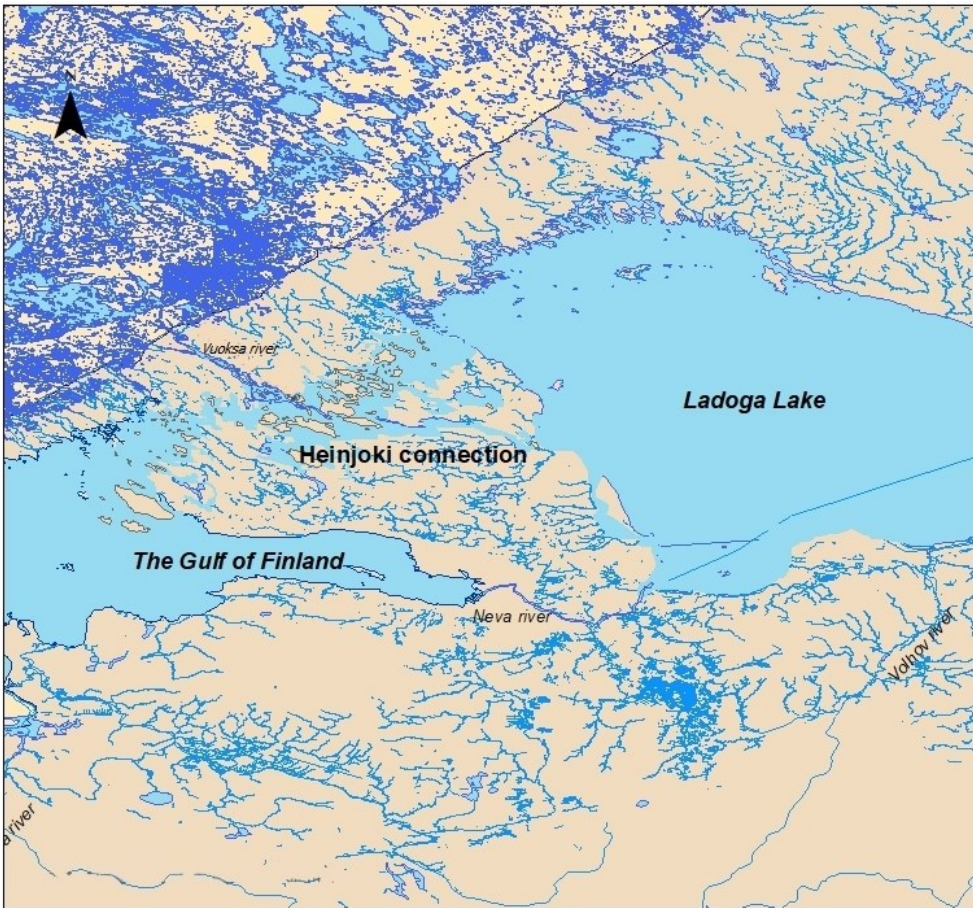

Figure 2. Reconstruction of the Lake Ladoga transgression ca 5,000 – 3,000 yr BP [Ailio, 1915]
Рисунок 2. Реконструкция трансгрессии Ладожского озера ок. 5000 - 3000 л.н. [Ailio, 1915]

Materials and methods

In palaeohydrological reconstructions, the following methods were used [Subetto, Averichkin, Kuznetsov, 2009]:

- water balance equation;
- hydraulic-morphometric dependencies;
- method of geographical analogy.

For the assessment of the palaeorunoff of the Heinjoki waterway system, the relationship between the river flow rate with width, depth and water balance ratios was used. In addition, our palaeogeographical hypotheses is based on the principle of palaeogeographical analogy, that is, the proximity of flow characteristics for modern and ancient river basins with similar contemporary and palaeogeographical conditions [Evstigneev, 1990; Sidorchuk et al., 2000].

Results

The preliminary studies of the Heinjoki paleostraight, conducted earlier near Veschevo village (Heinjoki), allowed to obtain the following information (Table 1). The banks of the channel are composed of Quaternary deposits represented mostly by sands. The banks do not have any floodplains and terraces. The channel alluvium is represented by coarse-grained sand and gravel-pebble deposits, lying on crystalline rocks. The channel had two branches: the width of the first was 400 m, the second was about 300 m. The depth of the both branches was about 6 m (figure 3). The modern water level of Lake Ladoga is ca 5 m. If the modern level of Ladoga would fall 5-6 m below the average, the Neva would flow back and the waters of the Gulf of Finland would enter the lake.

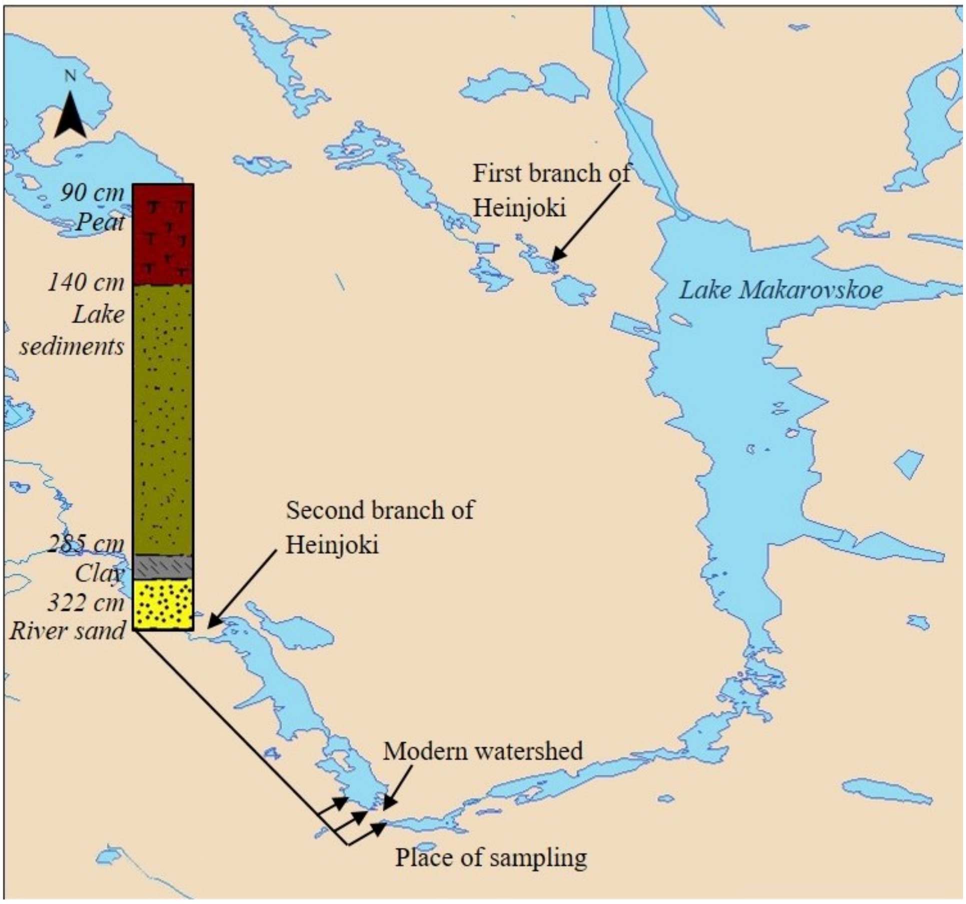

Figure 3. Location of the sediment sampling near the settlement Veschevo (Heinjoki), demonstrated that lake sedimentation began about 3000 years ago, and before that river sedimentation conditions prevailed [Dolukhanov et al., 2009]

Рисунок 3. Расположение отбора проб в районе поселка Вещево (Хейнйоки) показало, что осаждение озера началось около 3000 лет назад, а до этого преобладали условия речного отложения [Dolukhanov et al., 2009]

The level of Lake Ladoga ca 5000 BP in the northern part was ca 21-22 m a.s.l.

To determine the area of the water section, there is universal formula of B.A. Appolov [1974]:

$$F = 2/3\ BH \quad (1),$$

where B is the average channel width,

H is the average depth of the channel.

Kennedy's formula [Kennedy, 1969] is applicable for determining the water velocity, it is used for rectilinear channels and channels with constant water and sediment flow:

$$V_o = 0,84H^{0,64} \quad (2)$$

The water flow is determined by formula:

$$Q = V_o F \quad (3)$$

The average annual flow rate of both branches of the Heinjoki waterway was: Q = 2339 m^3/s (1316 m^3/s – the first branch, 1013 m^3/s – the second branch). The modern annual flow rate of the Neva River is 2530 m^3/s.

The runoff rate of the catchment area can be calculated:

$$M = Q_{av}\ 10^3/F \quad (4)$$

In our research, the River Neva basin was considered as the modern analogue of the palaeolandscape. The runoff rate is equal to 8.28 l/s from km^2. The River Neva runoff rate is 9.25 l/s from km^2.

The annual runoff volume is:

$$W = Q\ T/10^9 \quad (5),$$

where T is the time in seconds per year.

The Heinjoki waterway annual volume of runoff is 73.8 km^3. The annual volume of runoff of the Neva is 79.8 km^3.

The runoff layer is determined by formula:

$$Y = W/F\ 10^3 \quad (6),$$

where F is the catchment area.

The runoff layer is 261.3 mm. The runoff layer of the Neva River is about 284 mm.

Formula for determining the runoff coefficient is:

$$K = Y/X \quad (7),$$

where X is amount of precipitation in the catchment area.

When the amount of precipitation is 700 mm, the runoff coefficient is 0.37; when the amount of precipitation is 500 mm, the runoff coefficient is 0.52. The amount of precipitation in the modern basin of the River Neva is 606 mm, the runoff coefficient is 0.37 accordingly.

The method of analogues provides an opportunity to define the palaeorunoff also for the PalaeoVuoksa. The modern catchment area of the Vuoksa River and the entire system of Lake Saimaa is 69,500 km^2, the volume of the runoff is 20.3 km^3, and runoff layer is 336 mm. The runoff coefficient is 0.48 (precipitation amount of 700 mm) or 0.67 (precipitation amount of 500 mm).

Accordingly, the average annual water flow in the Heinjoki runoff way, before the breakthrough of the Vuoksa water to the Heinjoki way, was 1694 m^3/s, the annual runoff rate 53.4 km^3, the runoff rate 7.9 l/s per km^2, the runoff layer 251 mm, the runoff coefficient at 700 mm – 0.32, at 500 mm – 0.5.

Discussion

A good geographical analogue of the study area (the Neva River basin) is the Great Lakes region in North America. Although these lakes decreased in size after the ice retreating of the Last Glacial time, they were nevertheless preserved, largely due to the Niagara Escarpment, which is a natural step supporting the high water level in Lake Erie. The presence of ridges predetermined the different heights of lake levels, located like a cascade. The most significant difference between the levels of the Lakes Erie and Ontario are predetermined by the cuesta ridges from the Silurian limestones that spawn the famous Niagara Falls. Here the water falls from a height of 50 m. Through the waterfall every second passes 5900 m^3, of which 5600 m^3 belongs to Canadian part. Flow from Lake Ontario occurs through the St. Lawrence River. In the upper current, this river is like a bay of a lake, but then it narrows, the fall becomes large, due to what the river is abundant with rapids. Niagara Falls appeared ca 12,500 yr BP ago. Initially, it drained from a steep ledge, covered with sedimentary rocks which are represented mostly by limestone and dolomite [Larson, Schaetzl, 2001].

The described situation exists due to the tectonic stability of the region, and therefore the water of Erie did not find another way of flow. That is, the disturbances of the shape of the longitudinal profile and the configuration of the channel in terms of local fluctuations of the earth's crust were smoothed out by the work of the river flow. The area of the Karelian Isthmus and Lake Ladoga was an area of fast deformations when the rate of erosion of the Old Vuoksa and the Heinjoki runoff way turned out to be less than the velocity of the channel shift under the influence of tectonic. In addition, rivers can erode the surface to different depths depending on the nature of rocks. If the river flowed through rocks that could easily be eroded as limestone, for example, it quickly deepened its bed, increased its length, and made it possible for the tributaries to be developed. If the river bed represented by crystalline metamorphic and igneous rocks, e.g. Vuoksa River and the Heinjoki waterway located in the southeastern part of the Fennoscandian Crystalline Shield, then the embedding became difficult and conditions for the development of river valleys worsened. Finally, there was a significant reorganization of the river system. The Neva River and its tributaries, which laid valleys on loose rocks, intercepted the drainage of river basins in areas built up by dense rocks. Something similar happened in Appalachia, where the development of the river beds stopped not as the result from the cessation of erosion, but because erosion became weaker than other factors influencing the relief of the channel, in particular tectonics.

Table 1. Hydrological characteristics of the Neva River and the Heinjoki waterway
Таблица 1. Гидрологические характеристики реки Невы и Хейниокского пролива

Water balance characteristics	**Neva River**	**Heinjoki waterway**	**Heinjoki waterway before influx of the Vuoksa River ca 5,000 yr BP**
Catchment area, km^2	282 000	282 000	212 800
Average annual water flow rate, m^3/s	2530	2339	1694
Runoff volume, km^3/year	79.8	73.8	53.4
Annual runoff layer, mm	284	261	251
Runoff coefficient	0.38	0.37 – 0.52	0.32 – 0.5
Runoff rate l/sec from km^2	9.2	8.3	7.9

Thus, during the uplift of the Karelian Isthmus and north of Lake Ladoga, the parameters of palaeochannels of the Heinjoki straight changed. First of all, there was a decrease in their depths, which led to a decrease in runoff from Lake Ladoga to the Baltic and, accordingly, an increase in the volume of water mass of the lake. The calculations show that if the depth has decreased to 3 meters, then the average annual flow rate would be 1235.7 m^3/s. In this case the runoff rate is equal to 4.37 l/s per km^2, the runoff volume is 38.9 km^3 per year, the runoff layer is 137 mm, the runoff coefficient varies from 0.19 to 0.27.

Reduction of the flow from Lake Ladoga by 27.5 km^3 gives the corresponding increase in the volume of Ladoga's water mass. In about 40 years, the volume of Lake Ladoga should be increased by 1,100 km^3, that is, a second Lake Ladoga could appear, which should create another runoff way. After the formation of the Neva River, the Vuoksa River flowed eastward, and the replacement of the river mouth to modern city Priozersk surroundings took place. Due to the geological processes on the Karelian Isthmus, centurial land uplift led to the final drying out of the western channel of the Vuoksa River in the 17th century, and now only a chain of lakes connected by sections of narrow rapids reminds of it. According to the law of factorial relativity, reaction of the different parts of the hydrological system to the changing conditions is not the same and is non-simultaneous [Makkaveev, 1955; Channel process, 1959]. Therefore, the estuary area of the Vyborg branch of the Vuoksa River had a long-term connection with the Gulf of Finland of the Baltic Sea.

So, we can formulate the following conclusions:

- Lake Ladoga has been connected to the Baltic Sea throughout its history since its deglaciation (first as the easternmost gulf of the Baltic Ice Lake until 11,700 yr BP, later as a part of the Ancylus Lake, and then as an isolated lake with the outflow in the northern part of the Karelian Isthmus with Hejnjoki threshold from 10,200 to 3,500 yr BP).
- The quantitative parameters of the Heinjoki runoff (flow rate, annual runoff, runoff layer, runoff coefficient) roughly correspond to the current flow parameters of the Neva River. However, they are somewhat smaller than the Neva River has, which is associated with different geological and geomorphological conditions for the formation of the Neva River and Heinjoki channels.
- The change in the runoff direction from the Vuoksa to the Neva is mainly related to the tectonic uplift of the Karelian Isthmus and the northern part of Lake Ladoga.

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