The modern hydrological regime of the northern part of Western Siberia from in situ and satellite observations

E.A. ZAKHAROVA*†‡, A.V. KOURAEV‡†, M.V. KOLMAKOVA‡§, N.M. MOGNARD‡¶, V.A. ZEMTSOV§ AND S.N. KIRPOTIN§

†State Oceanography Institute, St Petersburg Branch, St Petersburg, Russia; ‡Université de Toulouse, UPS (OMP-PCA), LEGOS, Toulouse, France; §Tomsk State University, Tomsk, Russia; ¶CNES; LEGOS, F-31400 Toulouse, France

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We studied the hydrological regime of the rivers Poluy, Nadym, Pur and Taz in the Northern part of Western Siberia. Compared to their large neighbours – Ob' and Yenisey – these four rivers are characterised by more homogeneous natural conditions. This makes them a reliable indicator of climate variability in the Arctic part of Western Siberia. First we present seasonal and interannual variability of river discharge from historical observations. Next we analyse river runoff in the context of climate parameters and assess modern contribution of various sources to the total volume of river water. The volume of meltwater during the spring flood is compared with estimates of snow in situ, and from NCEP and SSM/I. Finally, we estimate the extent and variability of flooded and wet zones from satellite radar altimetry observations.

Keywords: Western Siberia; Arctic rivers; Discharge; Wetlands

1. Introduction

Western Siberia is one of the world’s largest plains with some unique characteristics that set it apart from neighbouring regions. Largely a flat region with abundant precipitation, it is home for some of the most extensive river systems that drain into the Arctic Ocean. Two large (Ob’ and Yenisey) and several smaller rivers bring to the Kara sea an average annual runoff of 1250 km³/year which is the greatest freshwater input among all other seas of the Arctic Ocean. The Ob’ and Yenisey estuaries represent vast mixing zones for fresh and saline water and the influence of freshwater affects places hundreds of kilometres north from estuaries. Ultimately this freshwater input affects the hydrology, hydrochemistry and hydrobiology of the Arctic Ocean.

The flat relief of Western Siberia affects the hydrographical network, creating a multitude of interconnected natural objects – large and small rivers and streams, extensive floodplains,
The presence of large flooded areas, lakes and mires in Western Siberia results in a rate of evaporation higher than for any other large boreal watershed. One of these wetland types – mires – is crucial in the global carbon cycle. Mires sequester carbon through photosynthesis and accumulation in peat deposits, acting as a terrestrial sink of atmospheric carbon. But, in the permafrost regions of Western Siberia, mires are a source of methane emission to the atmosphere.

While Ob' and Yenisey are the most important rivers of the region, in this paper we concentrate on smaller rivers in the Northern part of Western Siberia – Poluy, Nadym, Pur and Taz (referred to here as PNPT) (figure 1). Compared to their large intrazonal neighbours, Ob' and Yenisey, that have complicated river systems and different natural and hydrological regimes, PNPT rivers are characterised by more homogeneous natural conditions. This makes them a reliable and important indicator of climate variability of the Arctic part of the Western Siberia.

Originating at the northern slopes of the Sibirskiye Uvaly hills (altitude ranging from 170–200 m in the west to 230–280 m in the east) PNPT rivers flow northward to the Ob' estuary. While the Nadym river flows to the southern part of the Ob' estuary, the Poluy does not enter it directly but joins the final stretch of the Ob' river near Salekhard just before the Ob' enters its estuary. The Pur and Taz rivers join each other in the Taz estuary, a branch of the Ob' estuary. The Ob' estuary is a large natural object, a result of flooding of the ancient

![Figure 1. Map of North-Western Siberia, showing watersheds and main streams for the Poluy, Nadym, Pur and Taz river systems.](image-url)
river valley. Its length is 760 km, the surface area is 40,800 km² (together with the Taz estuary, 48,550 km²), the average width is 35–80 km and the mean depth 10–12 m [2].

The area drained by the four rivers is about 345,000 km², with watershed size and mean annual discharge increasing west to east (table 1). The Poluy is the smallest river with 18,500 km² of watershed and about 4 km³ of annual flow. The Nadym river has an intermediate position with 64,000 km² of watershed and 12.5–14.6 km³/yr of annual flow. Two times larger than the Nadym are the Pur and Taz rivers. The Taz is slightly bigger than the Pur, with difference in watershed area being more pronounced (112,000 km² for the Pur and 150,000 km² for the Taz) than for river flow (25–28 km³/yr for the Pur and 29–33 km³/yr for the Taz). The PNPT watershed has flat but intensely dissected relief, with slightly bogged interfluvial plains intersected by numerous small rivers valleys [6]. There are many small streams and lakes; large areas are covered by wetlands (mires and seasonally flooded zones).

The PNPT region enjoys a moderate continental climate (except the region of confluence of the Pur and Taz, located in the sub-Arctic climate) with short summers and cold and long winters. The southern part of the watershed is located in the zone of the northern taiga; the central part, in the forest-tundra zone; and purely tundra landscapes appear only in the lower reaches. The mean annual temperature is −9.3°C and average January temperature is −25—28°C [6]. According to [7], the number of days with stable negative air temperature ranges from 200 days in the south to 240 days in the north of the watershed. The total sum of negative degree-days for air temperature (defined as the sum of all negative mean daily temperatures) ranges from 3000 to 4000 and more. During winter precipitation is accumulated as snow, with total annual snowfall decreasing from more than 200 mm for southern parts of the Nadym, Pur and Taz to 100–200 mm for their northern parts and the Poluy. The number of days with snowfall is 200–250. The PNPT rivers are ice-covered for more than seven months every year.

The PNPT rivers are located in the region affected by permafrost (figure 2, table 2). While in the upper reaches it is discontinuous (with 5–10% coverage), the percentage of permafrost and its thickness rapidly increases northward. The lower reaches of the Nadym, Pur and Taz are located in the zone of strong and continuous permafrost, with soil temperatures going down to −7—9°C and thickness up to 300–500 m (see table 2). Only under large rivers such as PNPT and large lakes (with more than 2 m depth) is permafrost absent.

Table 1. Main characteristics of the PNPT rivers.

<table>
<thead>
<tr>
<th>River</th>
<th>Total watershed, km²</th>
<th>Measurement station</th>
<th>Watershed at station, km²</th>
<th>Mean annual runoff, km³ and observation period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poluy</td>
<td>18,410</td>
<td>Poluy</td>
<td>4.03 (1948–68)</td>
<td>3.9 (1953–86)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1953–99)</td>
<td></td>
<td>4.17 (1953–99)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1955–91)</td>
<td></td>
<td>14.46 (1955–91)</td>
</tr>
<tr>
<td>Pur</td>
<td>112,000</td>
<td>Samburg</td>
<td>28 (1939–68)</td>
<td>25.45 (1939–85)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1939–91)</td>
<td></td>
<td>28.25 (1939–91)</td>
</tr>
<tr>
<td>Taz</td>
<td>150,000</td>
<td>Sidorovsk</td>
<td>33.42 (1962–68)</td>
<td>29.68 (1952–65)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1962–96)</td>
<td></td>
<td>32.99 (1962–96)</td>
</tr>
</tbody>
</table>

Notes: [3].

*Russian hydrometeorological database, cited after [4].

*Data from [5].
Under smaller streams, the upper layer of permafrost is located at a depth of several tens of metres [3]. The active layer (depth of seasonal thawing) for tundra landscapes typically ranges from 20–25 cm in the north to 80–90 cm in the south, while for the taiga zone it is up to 2m. Summer thawing of the upper layer leads to the solifluction processes, formation of different polygonal ground cracks as mud-boils (effusion of soft sediments brought to the surface by artesian discharge). Erosion processes are usually not well represented due to extremely short summer.

Figure 2. Map of permafrost types (only types covering the study area are shown) after [8]. For more details on permafrost types see Table 2.

The aim of this article is to assess the modern hydrological state of the Poluy, Nadym, Pur and Taz river watershed using various approaches and to estimate its spatial and temporal variability. In section 2 we present seasonal and interannual variability of PNPT rivers from historical observations. In Section 3 we analyse river runoff in the context of climate parameters, assess the modern contribution of various sources to the total runoff and compare them with historical observations. We also compare the volume of meltwater during the spring flood with various

Table 2. Permafrost types after [8] covering the PNPT watershed.

<table>
<thead>
<tr>
<th>Type</th>
<th>Percent of coverage, %</th>
<th>Average temperature, °C</th>
<th>Depth of permafrost, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>100</td>
<td>−7 to −9</td>
<td>300–500 m</td>
</tr>
<tr>
<td>9</td>
<td>100</td>
<td>−1 to −3</td>
<td>100–300 m</td>
</tr>
</tbody>
</table>

Continuous permafrost

<table>
<thead>
<tr>
<th>Type</th>
<th>Percent of coverage, %</th>
<th>Average temperature, °C</th>
<th>Depth of permafrost, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>70–80</td>
<td>0 to −2, thaw soils - +1 to 0</td>
<td>up to 100 m, rarely 200–300 m</td>
</tr>
<tr>
<td>11</td>
<td>40–60</td>
<td>0 to −1, thaw soils - +2 to 0</td>
<td>50–70 m, rarely 100–200 m</td>
</tr>
<tr>
<td>12</td>
<td>5–10</td>
<td>0 to −0.5, thaw soils +2 to 0</td>
<td>15-20 m, rarely up to 50 m</td>
</tr>
</tbody>
</table>

Discontinuous permafrost
estimates of snow during the preceding winter. In Section 4 we consider the extent and temporal and spatial variability of flooded and wet zones from satellite radar altimetry observations.

2. Hydrological regime and climate of the PNPT rivers

2.1. Seasonal variability of river discharge

The Poluy, Nadym, Pur and Taz have many common features in the seasonal distribution of discharge. There are three main periods: spring flood, summer-autumn rain flood and winter low level period (figure 3). The spring flood starts in general in the beginning or middle of May and the peak discharge is observed in the beginning of June. Peak discharge largely varies between years of high and low flow. For the Pur and Taz peak discharges can differ 1.5 times – 6390–9430 m$^3$/s for the Pur, and 4010–7070 m$^3$/s for the Taz, while for the Nadym and Poluy they can double – 2430–5480 m$^3$/s for the Nadym and 610–1090 m$^3$/s for the Poluy.

Seasonal variability of water level can reach 2.8 m for the Nadym, 4.3 m for the Pur and 5.1 m for the Taz, leading to inundation of vast areas. Spring floods in Western Siberia often cut off entire villages and cities for several days or weeks. When propagation of the flood wave is complicated by ice jams, this lead to an even larger increase of water level. In Western Siberia in some cases, heavy artillery is used to break the ice and thus decrease the flooded area.

During spring, flood discharge is also associated with highest seasonal sediment load. The water turbidity for the Pur and Taz is very low – 25 g/m$^3$ for the Pur and 20 g/m$^3$ for the Taz and the maximal part of suspended matter comes to the Kara sea during the spring flood. The total suspended sediment load for the Pur at Samburg is 620,000 t/yr and for the Taz at Sidorovsk 580,000 t/yr (at the Taz delta – 910,000 t/yr) [2].

The end of the spring flood has a longitudinal character – it finishes first on the Poluy river (in the beginning–middle of July), then on the Nadym (beginning of July) and Pur (end of July), and in August on the Taz river.

Figure 3. Seasonal variability of PNTS rivers discharge for typical years with extremely high (a) and low (b) discharge. Data are from [5].
Autumnal floods related with rain events can result in one or several peaks of discharge, but with much lower amplitude than for the spring flood. These floods usually raise water level by 0.2–0.7 m. The winter low level period is long – it starts in the beginning of October and lasts about 200 days. Formation of ice cover starts at Pur and Taz deltas on average by 11 October, at Samburg by 15 October. In mid-April river ice thickness is 120 cm at Samburg and 96 m at Sidorovsk [2]. The ice period for the Pur and Taz is about 240 days and the last ice near their deltas can still be observed by 10 June.

2.2. Interannual variability of river discharge

The available mean daily and monthly data for PNPT rivers [5] have different time lengths; many gaps are observed, especially during months where rivers are ice-covered. Figure 4 shows temporal variability of river runoff. In general extremely high- (such as 1975, 1978 and 2002) and low-discharge (1977 and 2000) years are manifested for all rivers. Although data gaps do not allow calculation of reliable temporal trends, several tendencies are evident. For the Nadym the runoff does not show discernible tendencies and for the Taz there are no data in recent years to draw any conclusions. For the Poluy we observe a general decrease of runoff in late 1980s and 1990s. For the Pur there is also a tendency for decrease in runoff, evident both in the 1990s (with low interannual amplitude) and 2000s (with high oscillations).

3. River discharge and its relation with climate parameters

3.1. River runoff its relation with air temperature and precipitation

To evaluate river discharge variability in the context of climate changes, we have used data on air temperature and precipitation from two hydrometeorological stations located west...
(Berezovo) and east (Turukhansk) of the study area (figure 5). These data were complemented by data from NCEP, ERA-40 and University of Delaware (UDel) reanalysis [5]. Reanalysis data originally provided for the Nadym, Pur and Taz watersheds have been averaged. All reanalysis data correspond well to the in situ observations but do not provide some additional information and therefore are not shown (with the exception of data from UDel that extends back in time Turukhansk data).

Air temperature data (figure 5a) show high interannual variability with large amplitude oscillations every 2–3 years. Turukhansk and UDel data for the NPT watersheds reveal the presence of long-term cyclic variability – between 1940s and mid-1970s mean annual air temperatures have steadily decreased from -4°C to -9°C. Since then a warming trend has

![Figure 5. Mean annual temperature (a) and precipitation (b) for Berezovo (black line) and Turukhansk (dashed black line) hydrometeorological stations, and reanalysis data from University of Delaware (UDel, thick grey line, data from [5] averaged over watersheds of Nadym, Pur and Taz).](image-url)
been observed until 1995 (−3.7°C). From 1995, a rapid decrease has been observed until 1998 and since then air temperatures have been on the rise until the end of available observations (2005). For Berezovo air temperature data show similar variability, though amplitude of long-term cycles is less pronounced. In general, the actual situation shows a warming tendency for annual air temperature since the mid-1970s.

Precipitation from in situ and UDel data shows high temporal variability, which is in many cases (but not always) similar for the three time series. Absolute values of precipitation are well within the range of the mean climatic values (540 mm for the Poluy, 605 mm for the Pur and 590 mm for the Taz) [3]. For all the three time series we observe a steady rising trend in precipitation since the very beginning of available observations. This trend increases west to east – it is less pronounced for Berezovo, higher for NPT rivers (UDel data) and is the highest for Turukhansk.

General increase of precipitation for the whole period of available observations and constant or decreasing runoff during the last two decades stress the need to assess better the relation between river runoff and precipitation. One approach is to estimate various constituents of the river discharge.

3.2. Quantifying input of various sources to the river runoff

At the annual scale, a river is fed by three main sources: meltwater, rains and groundwater, and in order to understand better the hydrological processes for each watershed we need to quantify the input of each of these sources for each of the four rivers.

To do this, a method of graphical hydrograph separation can be used [9,10]. In regard to the boreal rivers this technique helps to determine the volume of waters contributed from underground (basic) and overland flows and divide the last one into snow and rain components (figure 5). The method of graphical hydrograph separation is subjective and there exist more advanced techniques, such as the ones based on isotope component analysis [11], though hardly applicable in the case of remote arctic rivers. One of the main benefits of the graphical hydrograph separation is that no additional repetitive – and often costly – field surveys and research are necessary, especially for large and remote boreal regions.

Three main sources of waters were evaluated: a) melting waters during the spring flood, b) basic flow and c) interflow and overland flow caused by the summer and autumnal rains (figure 6).

The spring flood related to snow melting is very pronounced for Arctic rivers and is characterised by rapid rise of discharge and high peak. Depletion of spring flood is often complicated by rains. We suggest that depletion of spring flood follows an exponential law (figure 6, line A–B) and small perturbations in the hydrograph on the falling limb are connected with rains. While making the hydrograph separation these small peaks were cut out. During the most part of spring flood the soil is still frozen, so we consider that there are no losses of snow water for groundwater recharge. At the end of the flood in June–July the soil thaws, and in the river channel waters of interflow (ground and soil horizon) appear.

Water from deep aquifers forms the basic flow. It has a quasi-constant discharge throughout the year and can be estimated during the drought (or ice-covered) periods by an interpolation between the lowest discharge values at the autumn or winter [9,10] (figure 6, line C–D).

We consider as the third source of water a combination of a) the overland flow originated from rain, b) the interflow and c) the flow from the first ground horizon. The last one (if it exists at all) is intimately related to atmospheric precipitation and normally is frozen in the
winter, so we refer it to the seasonally changing source of water contributing between the end of spring flood until the winter.

Sensitivity study of hydrograph separation has been done by varying slightly different approaches. We estimate that the difference in the results obtained does not exceed 5% for separating the deep basic and overland flow, and about 10% for separation of flood and interand overland flow. By processing initial daily discharge data for PNPT rivers [5] we have estimated volumes of flood, interflow and overland, and basic flow (table 3) for each year and for each river.

The part of melting water dominates over the basic flow and overland/interflow for the Poluy, Pur and Taz rivers. The basic flow contribution is about the same as for overland/interflow (21–29%). Within the range of accuracy, these values correspond well to the contribution made using data before 1970s [3].

For the Nadym, the results of hydrograph separation show low impact of melt water (29%) and high impact of overland/interflow (45%). These values differ both from other rivers and from historical data for the Nadym for 1955–1966 – 54% for melt water and 13% for overland/interflow [3]. Several possible explanations can be suggested. One is that our calculations are corrupted because the data on provisional discharge from Arctic RIMS website cover only the ice-free period (between the beginning of spring flood and October–November). Not having the reliable recent data we have used an average value for basic flow for 1978–1988 (3.9 km$^3$/yr). If we estimate the basic flow by interpolation between the minimum available discharge of each year (before the flood start) and the minimum available discharge of the next year, the results could be double than those for 1978–1988. But assuming this, results will lead to an even stranger ratio (19% for meltwater, 53% for basic flow and 29% for overland/interflow) and apparently this will not help to explain the difference observed for the Nadym.

Another potential explanation is that the general precipitation and temperature regime have changed. But this is doubtful as we do not observe significant changes for the neighbouring watersheds. In this case it is reasonable to suggest that the watershed properties have been changed as a result of intense human impact related to gas exploration that started in the

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Figure 6. Example of hydrograph separation for Pur at Urengoy in 1992.
3.3. Relation of spring flood and winter precipitation

For the four rivers, the time series of the volume of spring flood have been calculated, and were compared to three datasets of estimates of snow precipitation in the preceding winters: a) \textit{in situ} data, b) solid precipitation from NCEP reanalysis and c) snow water equivalent (SWE) from SSM/I passive radiometer.

\textit{In situ} data for Oktyabr’skaya station [12] is based on snow depth and SWE measures at the transects located in the forest. Comparison of years with big and small amount of snow cover (figure 7) for this station shows that the first snow appears at the beginning of October...
and thereafter its depth and SWE increase rapidly. By January about 65–70% of the total winter snowfall is already accumulated on the watersheds. Strong correlation ($r = 0.91$) has been found between SWE observed in the February and maximal winter SWE, which is normally reached in April. This could be explained by the fact that despite negative temperatures in March–April solar radiation already leads to snow evaporation, and new snow precipitation during these months could be outbalanced by evaporation. As a result in the second part of winter snow depth does not change significantly.

*In situ* data on snow depth and SWE have been complemented by reanalysis data from NCEP. The initial daily data on precipitation from NCEP reanalysis was used to estimate the winter snow accumulation on the river watersheds of the Poluy, Pur and Taz rivers. All precipitation falling when mean daily temperature was negative has been considered as snow and then summed. Another source of information was SWE from SSM/I derived by an advanced snow algorithm [13,14] (figure 8).

The analysis is done only for the Poluy, Pur and Taz rivers, as available discharge time series for Nadym do not correspond to the time limits of the three datasets. The relation between snow depth/SWE estimates among the three datasets is low. Each of the datasets has its positive and negative sides. *In situ* data are the most real, but they do not take into account spatial distribution of snow cover at the regional scale. NCEP data are spatially variable but...
do not take into account snow transformation. SSM/I data have good spatial coverage and account for snow transformation (crystal size) but their quality deteriorate over the ice-covered ground (lakes and bogs).

We did not find a reliable relation between melting water volumes for the Poluy, Pur and Taz rivers from one side and in situ and NCEP snow datasets from the other side. A good relation \((r = 0.95)\) has been found between melting water volume and SWE from SSM/I for the Poluy but not for the other two rivers. It could be related to the fact that among four PNPT rivers the Poluy has the least swamped watershed (wetlands fraction is estimated to be 10%) [3]. Apparently, the lack of relation between accumulated snow and melting water volume is explained by the regulating role of the bogs and lakes widely present at the Pur and Taz watersheds. During snow melting, a large part of the meltwater is retained in

Figure 8. Interannual variability of (a) mean February SWE from SSM/I, (b) NCEP winter precipitation, (c) maximal winter SWE (mm) from forest transects at station Oktyabr'skaya and (d) flood flow (mm) for rivers Poluy, Nadym, Pur and Taz.
wetlands and then is gradually drained out during summer and autumn, thus increasing the part of overland/interflow. The more the watershed is swamped, the bigger is the part of the thus transformed water volume. This stresses the necessity to evaluate the role of water regulation through studies of wetlands regime.

The increasing trends in precipitation on the one hand, and decreasing trend (or no trend) in river runoff on the other, are in apparent contradiction. This can be explained by the role of evaporation. According to Serreze [15] and Fukutomi [16] during the four summer months the evapotranspiration on the neighbouring Ob′ watershed is so high that it can exceed precipitation for the same period. This huge loss of the water takes place on the widespread swampy and flooded areas that accumulate waters from snow melting and rains. According to the data for 1950–1970s [3], the maximal evaporation occurs in the June–July (50–60% of total annual evaporation) and reduces in August to 16%. Thus, in spite of increased precipitation, the recent tendency for increasing air temperatures should only have strengthened evaporation and thus further reduced runoff.

Evaporation is one of the constituents of the water budget that is the most difficult to estimate. There are no direct measures of evaporation and it is usually estimated using hydrological or climatic modelling and demands information on many parameters pertaining to atmospheric and soil/water surface conditions (air and soil/water temperature, air humidity, wind speed, wave heights for open water, etc.). In this respect, one of the key parameters that can improve estimates of evaporation over a watershed is the temporal variability of surface occupied by wetlands or flooded areas. This can be done using satellite remote sensing in the active microwave range.

4. Wet zones extent from radar altimetry

Passive and active satellite observations in the microwave range provide reliable, regular and weather-independent data on surface properties. One way to estimate the presence of water on land is to analyse the backscatter coefficient from active microwave instruments. This could be a SAR, scatterometer, radar altimeter, etc. The backscatter coefficient is the ratio between the power reflected from the surface and the incident power emitted by the onboard radar, expressed in decibels (dB).

Side-looking radars and scatterometers have been successfully used for studies of soil wetness and open water identification. Papa et al. [17] have used a multisatellite method, based on a combination of passive microwave data (SSM/I), ERS-1 scatterometer and AVHRR NDVI to estimate pixel fractional coverage of open water at the 0.25° resolution at the equator (773 km² pixel size). They have estimated spatial and temporal variations over the Ob′ river with monthly resolution for 1993–2000. Bartsch et al. [18] have used ENVISAT ASAR in global mode to identify and map boreal peatlands in the Western Siberia. They have also used QuickScat scatterometer data to analyse spatial and temporal variability of spring freeze/thaw cycles for the region of Siberia II project (Central Siberia, mostly Yenisey watershed) [19].

Another source of active microwave data is radar altimeters. Due to nadir-looking capabilities they are much more sensitive to variations in the surface type than the side-looking instruments. Compared to many instruments, the altimetric data are also able to enhance the information content due to their high spatial resolution along the track. While the theoretical footprint of the altimeter data is about 12 km, the main part of the backscatter signal comes from a small area with a diameter of 1–2 km, which occurs in the case of the quasi-specular
signal over ice [20] or calm water (mires, small lakes). High radiometric sensitivity and spatial resolution along the satellite track can be successfully used for estimating the extent of wet and flooded zones, as well as study lake and river ice. Papa et al. [21] have used TOPEX/Poseidon dual-frequency radar altimeter to study inundated wetland dynamics over boreal regions (up to 66°N due to TOPEX/Poseidon orbit limitation). A combination of active and passive data from radar altimeters and passive microwave observations from SMMR-SSM/I has also been used for studies of ice cover phenology of the five largest Eurasian continental water bodies – the Caspian and Aral Seas, the Baikal, Ladoga and Onega lakes [22].

Here we used radar altimeter data from ENVISAT satellite, in operation since November 2002. The repeat period for ENVISAT is 35 days, and 18 Hz sampling rate provides a 380 m along-track resolution. ENVISAT tracks provide a homogeneous coverage of the PNPT watershed (figure 9), with the mean number of observations for each of satellite’s 35 days-long cycle of 3000 points for the Poluy, 9000 for the Nadym, 15,000 for the Pur and 25,000 point for the Taz. As calm water provides a much higher return signal than land, a threshold approach was used. By selecting the 20 dB as the limit value for the Ku band (13.6 GHz) backscatter, we have classed all altimetric observation with more than 20 dB as open water. Then in order to compare watersheds with different size, we calculated the ratio of altimetric observations classed as open water to the total number of observations for each cycle and each watershed (figure 10) to serve as an equivalent of flooded area. Here under ‘flooded areas’ we denote a multitude of objects that are either constant in time (rivers, lakes, wetlands and wet zones) or have seasonal variability (proper flooded areas).

The ratio of flooded area has two maxima, one in spring and another in autumn, and a minimum between them. During the winter the region is snow-covered and no altimetric observation is classed as open water, thus 0% ratio. The first maximum related to spring flood is generally observed in June at the same time as the peak of discharge for the corresponding

![Figure 9. ENVISAT coverage of the PNPT watershed.](image-url)
river, or slightly after. For this period an extremely high ratio of flooded areas is observed – average values of 85% for all rivers except the Taz, where the average value reaches 66% with maximum of 69% in 2006. This lower ratio for the Taz could be related to the relief of its watershed, where the Pur-Taz upland and Middle Taz upland provide less place for flooding and development of wetlands.

The second maximum related to autumn flood is observed in September, gradually reaching the highest values after the start of discharge increase. Its average values are high: 81% for the Nadym (maximum 86% in 2008), 79% for the Pur (82% in 2003) and decrease down to 56% for the Poluy (with maximum of 66% in 2008) and 52% for the Taz (58% in 2004). An important issue is that the magnitude of peaks of flooded area ratio is almost the same for spring flood and summer-autumnal rains, though in discharge we observe a dramatic decrease. This is related to the fact that even small level increase leads to relatively large flooding and increase of soil wetness. As a result, the relation between flooded area and the total amount of water present on the watershed is heavily dependent on the phase of the water regime.

The summer minima for all rivers is observed in August and has the smallest average values of 35% for the Poluy, 68% for the Nadym, 70% for the Pur and 41% for the Taz. We suggest that these low summer ratios correspond to the extent of constant wet zones for a given watershed. Historical data for wetland percentage (10% for the Poluy, 45% for the Pur) [3] are comparable to these values, although there are differences in methodologies and definition of ‘wetlands’ in both cases.
Conclusions

Combination of historical in situ observations with satellite remote sensing improves our understanding of the modern hydrological regime of North-Western Siberia and the rivers Poluy, Nadym, Pur and Taz.

Interannual variability of river runoff does not show discernible tendencies for the Nadym, while for the Taz there are no data in recent years to draw any conclusions. For the Poluy we observe a general decrease of runoff since the late 1980s. The same tendency is observed for the Pur, evident both in the 1990s (with low interannual amplitude) and 2000s (with high oscillations). At the same time for the PNPT watershed there is a warming tendency for annual air temperature since the mid-1970s, and a steadily rising trend in precipitation since the very beginning of available observations.

Assessment of modern contribution of various sources (melting water during the spring flood, basic flow and interflow/overland flow caused by the summer and autumnal rains) to the total runoff show that for the Poluy, Pur and Taz the proportion of various sources did not change much compared to the period before the 1970s. But for the Nadym we observe a significant decrease of contribution of melting water, apparently related to anthropogenic impact on the watershed.

Comparison of the volume of meltwater during the spring flood with estimates of snow from the three sources (in situ, NCEP and SSM/I) does not show a convincing relationship. Only for the Poluy has a good relation between accumulated snow and melting water volume been found with the SSM/I-derived snow water equivalent. For the Pur and Taz and for all other snow estimates relations are unstable. We suggest that this is explained by the regulating role of the bogs and lakes, widely present at the Pur and Taz watersheds (and much less on the Poluy watershed). All this emphasizes the need to evaluate the role of water regulation through studies of wetlands regime.

Satellite radar altimetry provides the possibility to estimate the extent and variability of flooded and wet zones for various watersheds. The ratio of wet zones among the total number of observations is related to the relief of the watershed and the total surface of wetlands and flooded zones. The high ratio of flooded areas is typical for both spring flood and (in lesser degree) summer-autumnal floods. The minimal ratio of flooded zones extent observed in summer corresponds to the constant wet zones for a given watershed. Seasonal variability of the flooded area ratio varies by about 20% for the Pur, Nadym and Taz and up to 40% for the Poluy. One part of this volume is drained out as a surface and interflow, while the other part evaporates. Large-scale climate changes and global increase of temperature would only accelerate both these processes.

Based on these interesting results, there is a clear need to continue monitoring of various environmental parameters of Northern Siberia, for practical applications as well as for scientific studies of environmental conditions and climate variability. The most appropriate solution would be the combination of dedicated high-quality in situ observations, various climatic datasets, and satellite observations from radar altimeters and other Earth Observation data.

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