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SUMMARY

The aim of this working paper is to provide a description of seasonal and interannual variability of wet zones extent in Western Siberia obtained from radar altimetry data and implication of these and other satellite and historical data for hydrological numerical modelling of the Nadym, Pur and Taz rivers in the Western Siberia. This is a contribution to the Work Package 1.2 "The decadal dynamics of high-latitude lakes and their consequences for GHGs and climate.

MONARCH-A CONSORTIUM

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1 Introduction

The aim of this working paper is to estimate seasonal and interannual variability of wet zones extent over the Western Siberia from radar altimetry and assess their implication for hydrological modelling over the northern part of the Western Siberia (Poluy, Nadym, Pur and Taz watersheds, or PNPT).

Western Siberia is one of the world's largest plains with some unique characteristics that set it apart from neighbouring regions. Largely flat region with abundant precipitation, it is home for some of the most extensive river systems that provide big river input 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 maximal freshwater input among all other seas of the Arctic Ocean. Ob' and Yenisey estuaries represent vast mixing zones for fresh and saline water and influence of fresh water affects places hundreds of kilometres north from estuaries. Ultimately this freshwater input affects hydrology, hydrochemistry and hydrobiology of the Arctic Ocean.

Flat relief of the Western Siberia affects the hydrographical network, creating a multitude of interconnected natural objects - large and small rivers and streams, extensive floodplains, lakes, mires etc. The presence of large flooded areas, lakes and mires in the Western Siberia results in a rate of evaporation higher than for any other large boreal watershed. One of these wetland types - mires - are one of the key players in the global carbon cycle. On one hand they are sequestrating carbon through photosynthesis and accumulation in the peat deposits, acting as a terrestrial sink of atmospheric carbon. On the other hand mires in the permafrost regions of the Western Siberia are a source of methane emission to atmosphere.

2 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 of the ways to estimate presence of water on land is to analyse 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. (2007) have used a multisatellite method, based on 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 (2007a) 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 (Central Siberia, mostly Yenisey watershed) [Bartsch et al, 2007b).

Another source of active microwave data are 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 (Legresy and Remy, 1997) or calm water (mires, small lakes). High radiometric sensitivity and spatial resolution along the satellite track can be successfully used for estimating extent of wet and flooded zones, as well as study lake and river ice.

Here we use radar altimeter data from ENVISAT satellite, in operation since November 2002. Repeat period for ENVISAT is 35 days, and 18 Hz sampling rate provides a 380m along-track resolution. We have identified 21 mid-size watersheds belonging to the Ob' river system, as well as area of inner watershed, and watersheds of Nadym, Pur and Taz rivers, that flow to the Ob' estuary (Figure 1, Table 1). ENVISAT tracks provide a homogeneous coverage of the selected watersheds (Figure 2). For example, for the PNPT region mean number of observations for each of satellite's 35 days-long cycle of 3000 points for Poluy, 9000 for Nadym, 15000 for Pur and 25000 point for Taz.

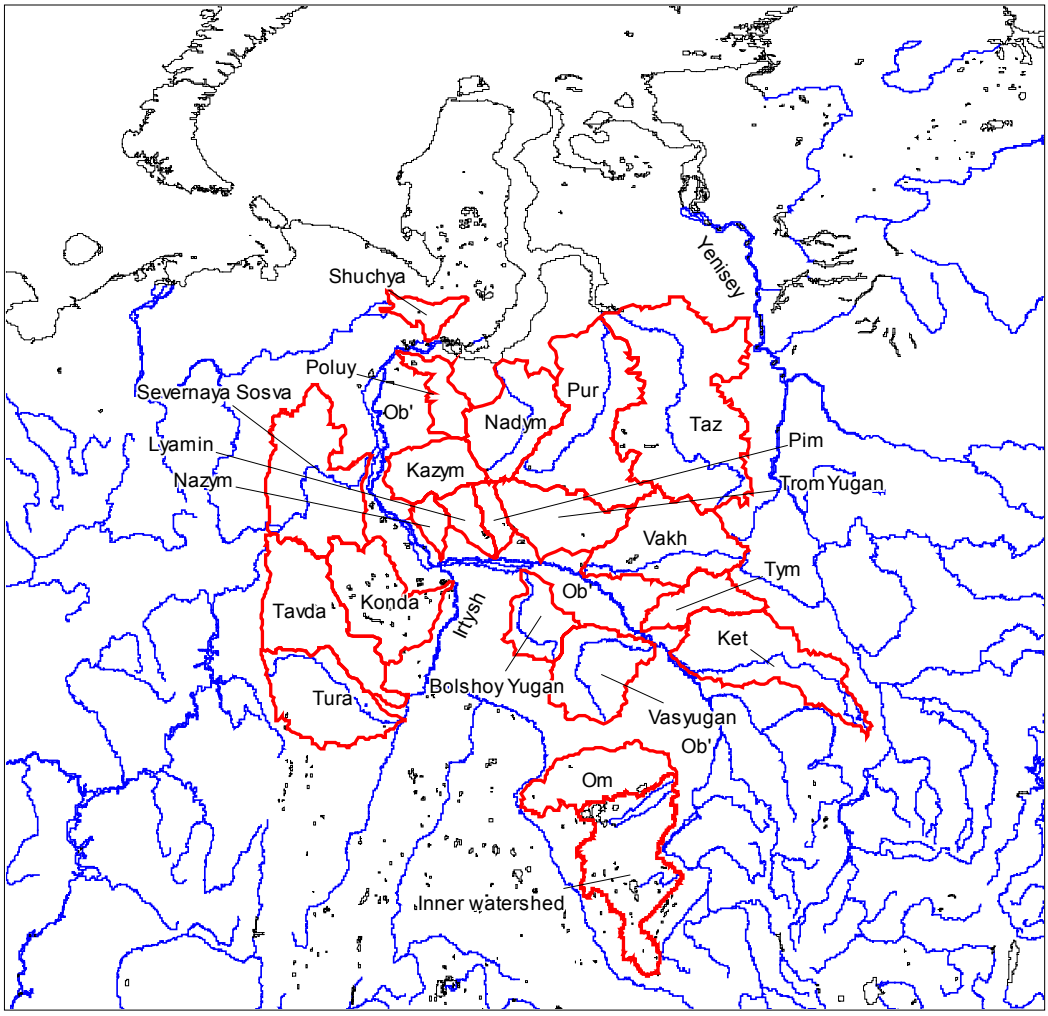

Figure 1. Location of 21 selected watersheds

Table 1. Watershed area of the 21 selected watersheds

No	River name	Watershed area, km^2	No	River name	Watershed area, km2
1	Taz	155666	12	Tym	30902
2	Vakh	76504	13	Ket	94828
3	Pur	103329	14	Vasyugan	63092
4	TromYugan	51820	15	Bolshoy Yugan	33366
5	Nadym	54152	16	Severnaya Sosva	91149
6	Poluy	19557	17	Konda	70592
7	Shuchya	11831	18	Tavda	86629
8	Kazym	34634	19	Tura	78385
9	Nazym	11169	20	Om	62734
10	Lyamin	15528	21	Inner watershed	115524
11	Pim	12055			

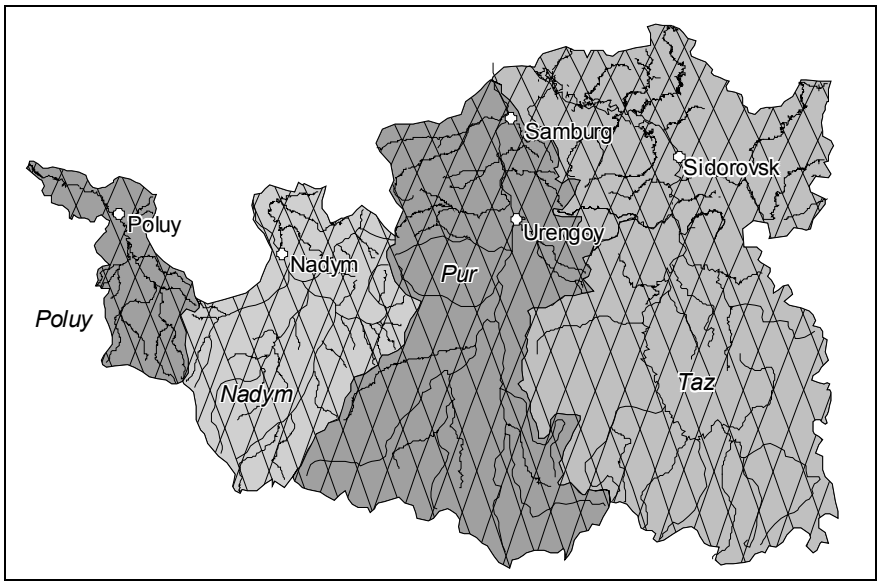

Figure 2. ENVISAT coverage of the PNPT watershed.

As calm water provides much higher return signal than land, a threshold approach was used. Seasonal variability of the radar backscatter signal (Figure 3) indicates significant changes in the return echo strength. 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 ratio of altimetric observations classed as open water to the total number of observations for each cycle and each watershed 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).

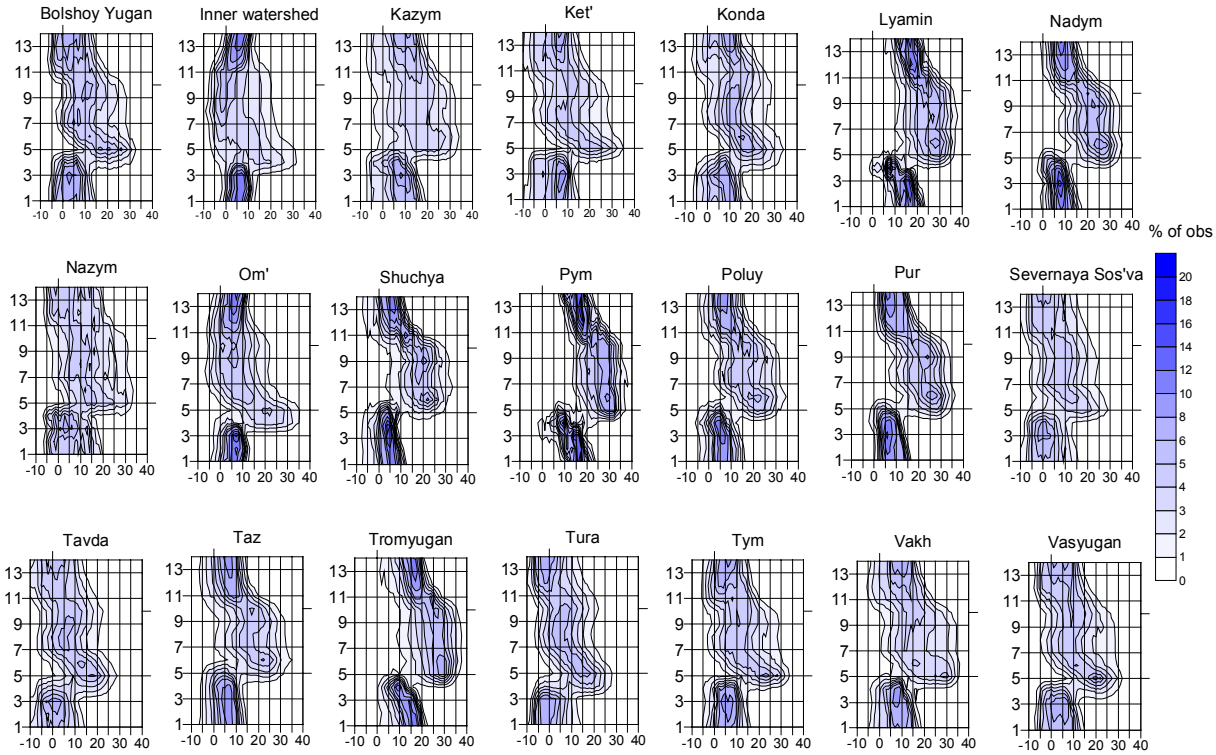

Figure 3. Statistics (in % of the total number of observations) of seasonal variability (Y axis - month number, X axis - backscatter values in Ku band, Ice2 algorithm) for ENVISAT data (cycles 9 to 72).

Analysis of seasonal distribution of wet zones extent allow to classify the selected 21 watershed onto three main groups (Figure 4):

Type 1: Small permanent flooding (one peak) and well pronounced draining

Type 1a: Same as 1 but with two peaks

Type 2: High permanent flooding with insignificant draining

Type 3: Medium permanent flooding with two peaks and well pronounced draining

Figure 5 shows spatial distribution of the identified types, that is illustrating strong dependency of wet zones extent seasonal variability on the watershed location (both zonal and meridional factors). The types change in the general direction from South-West to North-East.

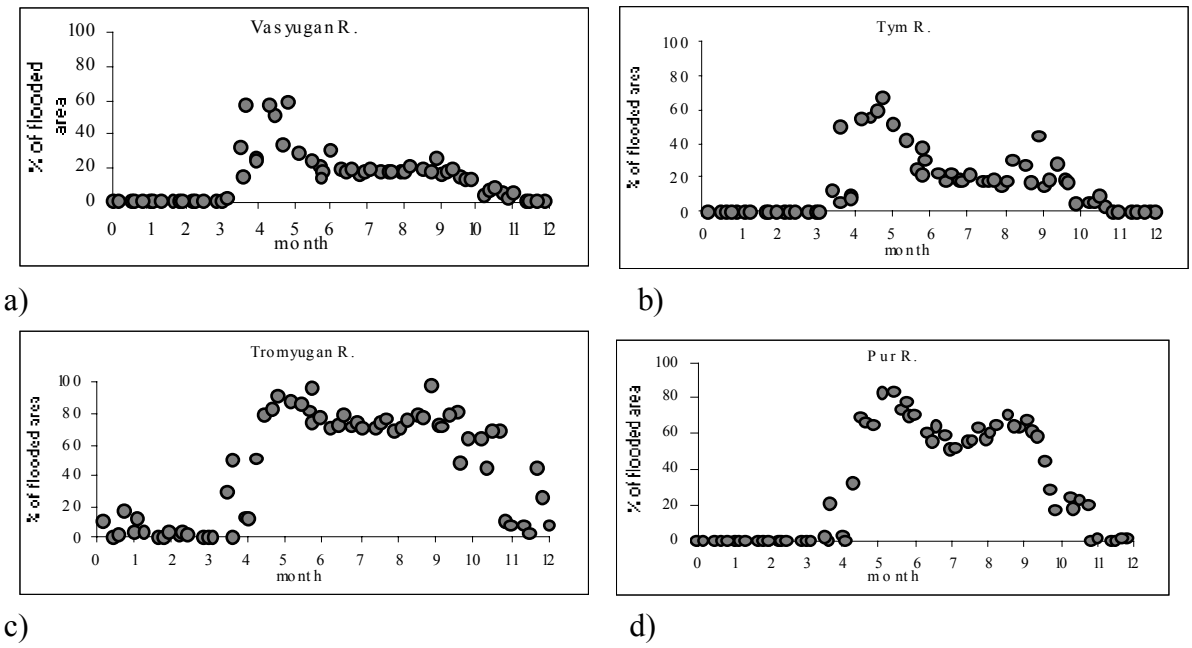

Figure 4. Typical examples of seasonal variability of wet zones extent: Type 1 (a, Vasyugan river), Type 1a (b, Tym river), Type 2 (c, Tromyugan river) and Type 3 (d, Pur river).

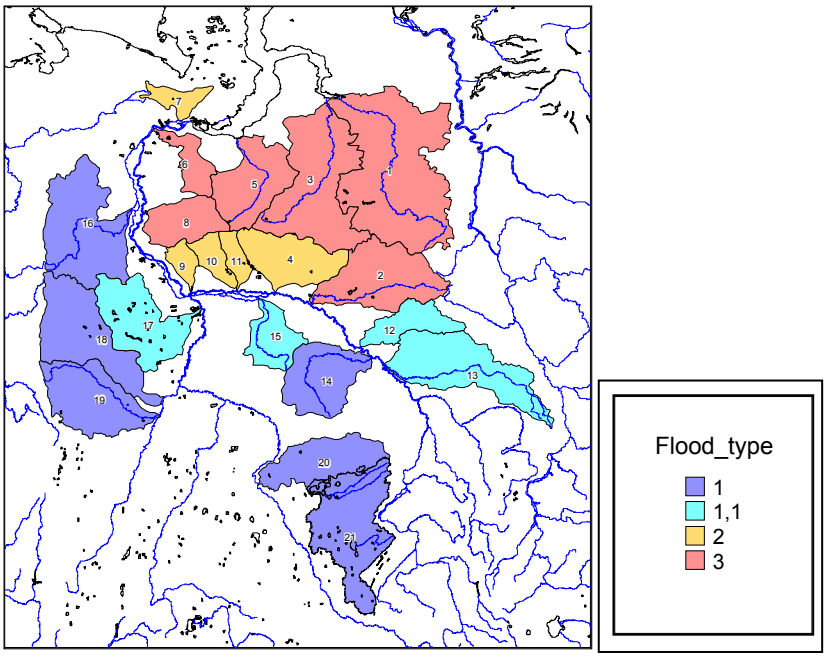

Figure 5. Thematic map of watershed classification according to type of wet zones variability.

The obtained data also make it possible to analyse the timing of the four important dates in the river regime: start of the spring flood, dates of the maximal flood, start of freezing, and date of full freeze-up (Figure 6). The timing is following the general pattern South-West to North-East, reflecting influence of air temperature, snow accumulation and liquid precipitation. However there are some

specificity in the dates for various watersheds, that is related also with heat storage and thermal influence of the Ob' river, and to regional topography (for example influence of the Severniye Uvaly hills, located north of the Middle Ob' region.

Interannual variability of wet zones extent can be illustrated on the example of the two regions - PNPT in the north of Western Siberia (Zakharova et al, 2009), and three rivers located in the southern part - Bolshoy Yugan, Om' and Vasyugan, covering partly the Great Vasyugan Bog, one of the largest bogs on Earth (Figures 7-9).

The ratio of flooded area has two maximas - 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 with spring flood is generally observed in June at the same time or slightly after the peak of discharge for the corresponding river. For PNPT during this period extremely high ratio of flooded areas are observed - average values of 85% for all rivers except Taz, where the average value reaches 66% with maximum of 69% in 2006. This lower ratio for Taz could be related with the relief of its watershed, where Pur-Taz upland and Middle Taz upland provide less place for flooding and development of wetlands. The second maximum related with autumn flood is observed in September, gradually reaching the highest values after the start of discharge increase. Its average values are high: 81% for Nadym (maximum 86% in 2008), 79% for Pur (82% in 2003) and decrease down to 56% for Poluy (with maximum of 66% in 2008) and 52% for Taz (58% in 2004).

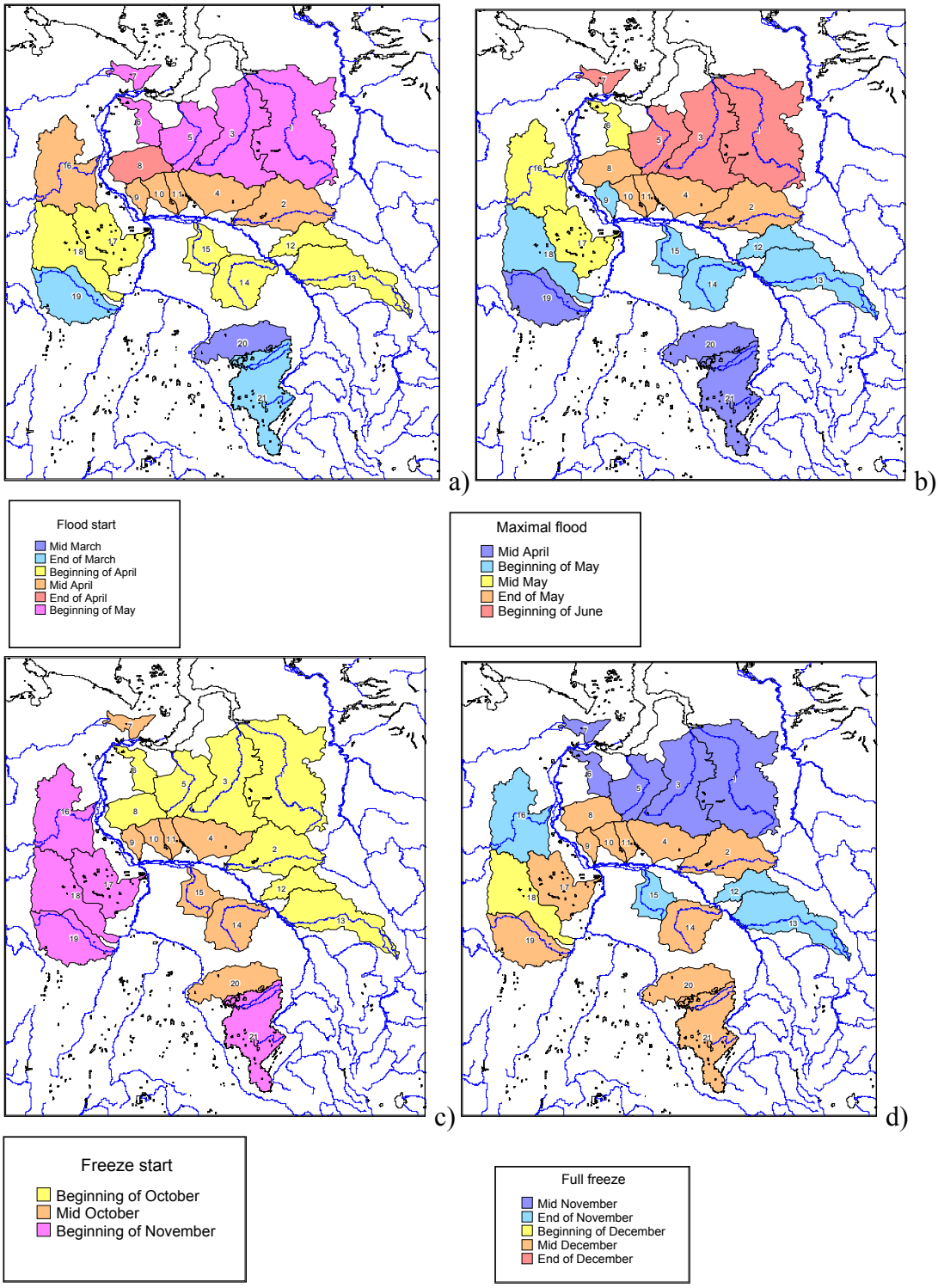

Figure 6. Dates of the: start of the spring flood (a), maximal flood (b), start of freezing (c), and full freeze-up (d)

An important issue is that 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, relation between flooded area and the total amount of water present on the watershed is heavily depending on the phase of the water regime.

For the Great Vasyugan region wet zones extent may reach 55-60% for Vasyugan and Bolshoy Yugan and 60-65% for Om'. Maximal wet zones extent for Vasyugan and Bolshoy Yugan has been observed in 2007, for Om' - in 2003. Low wet zones extent for the first two rivers (25-40%) has been observed in 2004 and 2006. For the Om' only in 2006 low wet zones extent has been observed (40%).

For PNPT region the summer minima for all rivers is observed in August and has the smallest average values of 35% for Poluy, 68% for Nadym, 70% for Pur and 41% for 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 Poluy, 45% for Pur) (Vodogretskiy, 1973) are comparable to these values, though difference in methodologies and definition of "wetlands" are different in both cases.

For the Great Vasyugan Bog region summer minima for Vasyugan (17%) and Bolshoy Yugan (15%) is oberved in July, while for Om' it is one month later - in August (6%). Seasonal variability for 2003-2008 is 12-30% for Vasyugan and Bolshoy Yugan and much higher (35-55%) for Om' river.

The full dataset is presented in the Excel file "Wet zones extent for 21 watersheds.xls" where cycle - Number of ENVISAT cycle, Year Fraction - time expressed as a fraction of the year, and the values for each river are ratios of altimetric observations classed as open water to the total number of observations for each cycle and each watershed (in %).

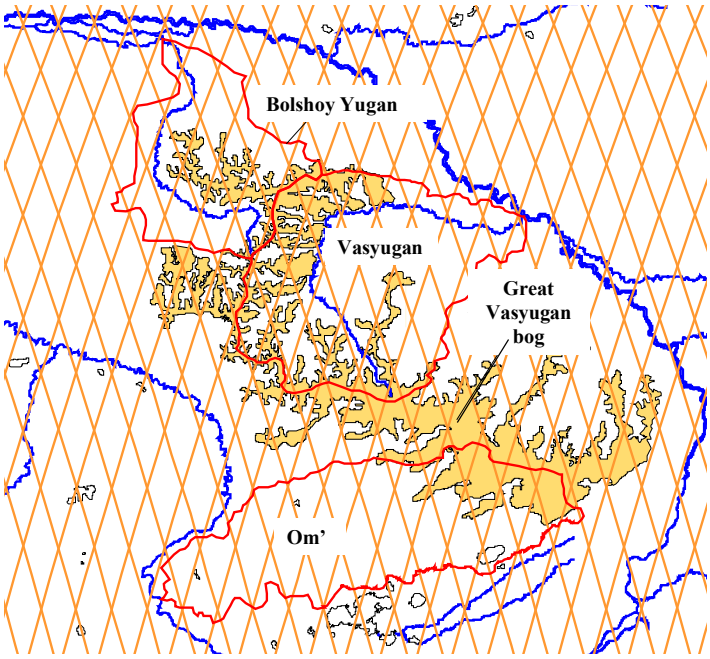

Figure 7. ENVISAT coverage of the three watersheds partly covering the Great Vasyugan bog.

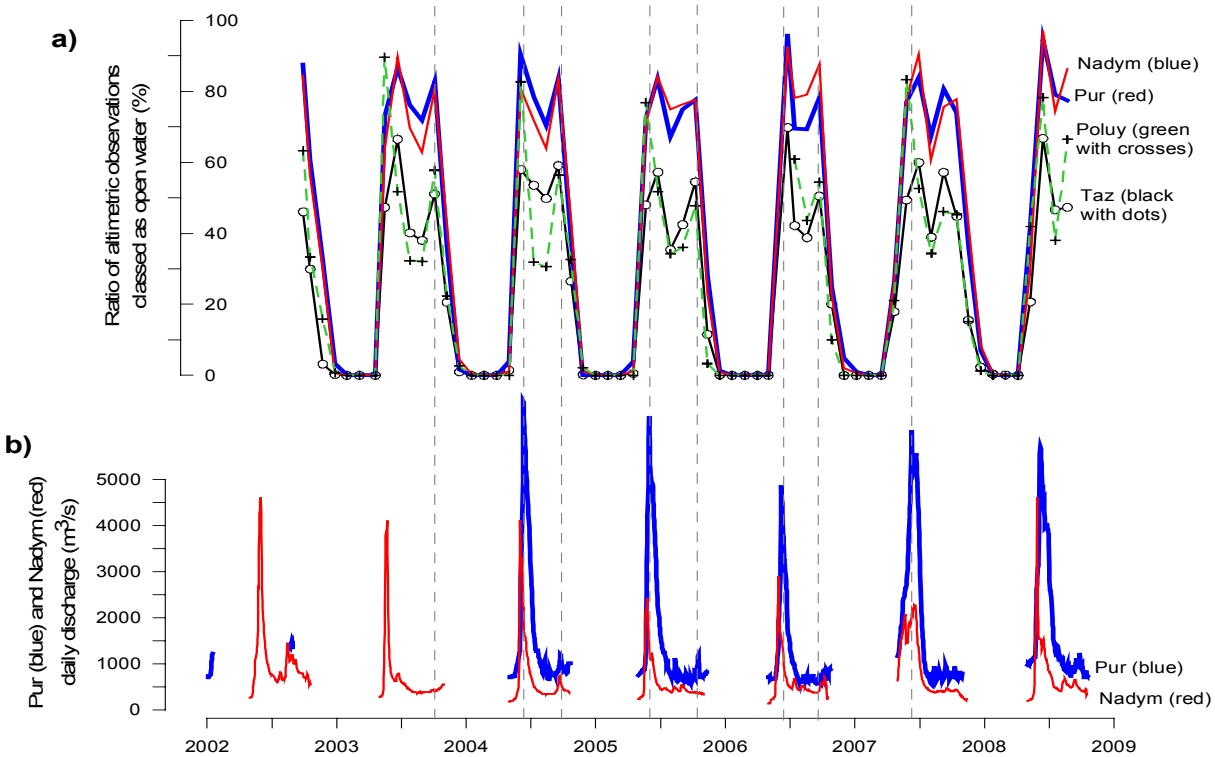

Figure 8. Temporal variability of (a): flooded area / wet zones (% of ENVISAT altimetric observations classed as open water) and (b) daily river discharge for Pur at Samburg and Nadym at Nadym (m3/s). Timing of spring and autumnal maximas of flooded area is shown as grey dashed lines

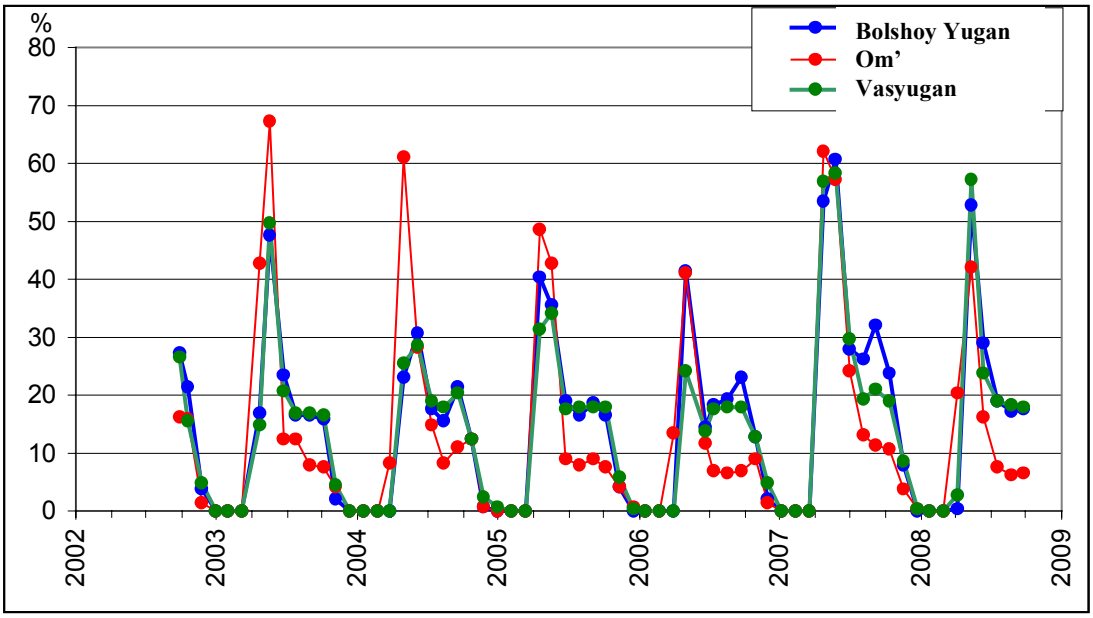

Figure 9. Same as 8a, but for rivers Bolshoy Yugan, Om' and Vasyugan

3 Hydrological modelling of the Poluy, Nadym, Pur and Taz rivers (PNPT) region

3.1 PNPT region description.

While Ob' and Yenisey are the most important rivers of the Western Siberia, in this work we concentrate on smaller rivers in the Northern part of Western Siberia - Poluy, Nadym, Pur and Taz (referred to as PNPT) (Figure 10). Comparing to the their large intrazonal neighbours - Ob' and Yenisey, that have complicated river system and different natural and hydrological regime of its various parts, 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 Nadym river flows to the southern part of the Ob' estuary, Poluy do not enter it directly but join the final stretch of the Ob' river near Salekhard just before Ob’ enters its estuary. Pur and Taz rivers join each other in the Taz estuary, a branch of the Ob' estuary. Ob' estuary is a large natural object, a result of flooding of the ancient river valley. Its length is 760 km, surface is 40800 km^2 (together with Taz estuary– 48550 km^2), average width is 35-80 km and mean depths 10-12 m.

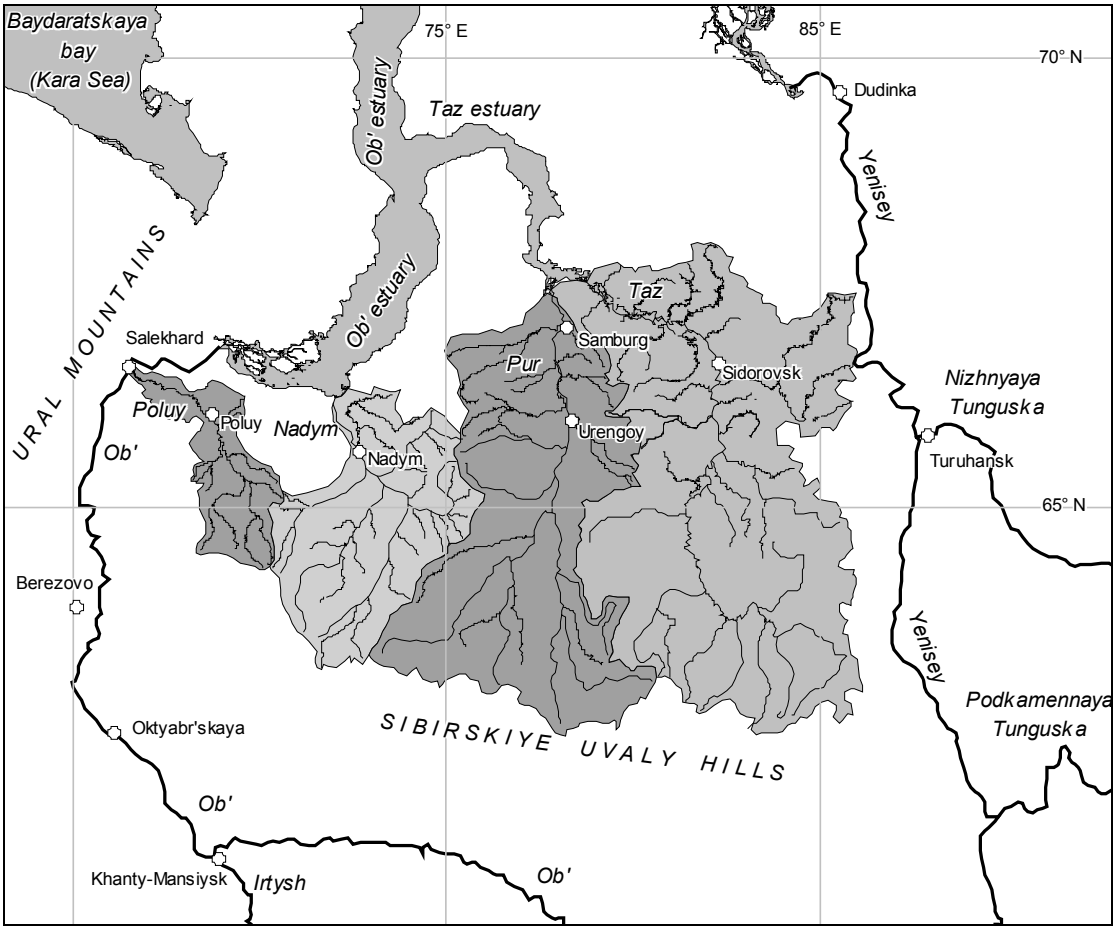

Figure 10. Overview map of the Northern Western Siberia, showing watersheds and main streams for the Poluy, Nadym, Pur and Taz river systems.

The area is drained by the four rivers is about 345000 km^2, with watershed size and mean annual discharge increasing west to east (Table 2). Poluy is the smallest river with 18500 km^2 of watershed and about 4 km^3 of annual flow. Nadym river has an intermediate position with 64000 km^2 of watershed and 12.5-14.6 km^3/yr of annual flow. Two times larger than Nadym are Pur and Taz rivers. Taz is slightly bigger than Pur, with difference in watershed area more pronounced (112 000 km2 for Pur and 150 000 km^2 for Taz) than for river flow (25-28 km^3/yr for Pur and 29-33 km^3/yr for Taz). The PNPT watershed has flat but intensely dissected relief, with slightly bogged interfluvial plains intersected by numerous small rivers valleys (Ershov, 1989). There are many small streams and lakes; large areas are covered by wetlands (mires and seasonally flooded zones).

PNPT region is located in the moderate continental climate (except the region of confluence of Pur and Taz, located in the sub-Arctic climate) with short summers and cold and long winters. Southern part of the watershed is located in the zone of northern taiga, central one - in the forest-tundra zone, while purely tundra landscapes appear only in the lower reaches. Mean annual temperature is -9.3 ºC and average January temperature is -25 -28ºC (Ershov, 1989). According to ("Atlas...), the climatic number of days with stable negative air temperature ranges from 200 days in the south to 240 days in the north of the watershed. Total sum of negative degree-days for air temperature

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 Nadym, Pur and Taz to 100-200 mm for their northern parts and Poluy. The number of days with snowfall is 200-250. PNPT rivers are ice-covered for more than 7 months every year.

Table 2. Main characteristics of the PNPT rivers.

River	Total watershed, km^2	Measurement station	Watershed at station, km^2	Distance from mouth, km	Mean annual runoff, km^3 and observation period		
					Source 1[a]	Source 2[b]	Source 3[c]
Poluy	18410	Poluy	15100	189	4.03 (1948-68)	3.9 (1953-1986)	4.17 (1953-1999)
Nadym	64000	Nadym	48000	110	14.38 (1955-57)	12.57 (1955-1985)	14.46 (1955-1991)
Pur	112000	Samburg	95100	86	28 (1939-68)	25.45 (1939-1985)	28.25 (1939-1991)
Pur	112000	Urengoy	80400	245	23.8 (1962,65,67)		23.99 (1961-1999)
Taz	150000	Sidorovsk	89100	357	33.42(1962-68)	29.68 (1952-1965)	32.99 (1962-1996)

[a] (Vodogretskiy, 1973)

[b] Russian hydrometeorological database, cited after (Akimenko et al., 2001)

[c] data from (Artic RIMS)

The PNPT rivers are located in the region affected by permafrost (Figure 11, Table 3). While in the upper reaches it is discontinuous (with 5-10% coverage), percentage of permafrost and its thickness rapidly increases northward. Lower reaches of 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. Only under large rivers such as PNPT and large lakes (with more than 2 m depth) permafrost is absent. Under smaller streams upper layer of permafrost is located at depth of several tens of meters (Vodogretskiy, 1973). 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 taiga zone it is up to 2m. Summer thawing of the upper layer lead 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.

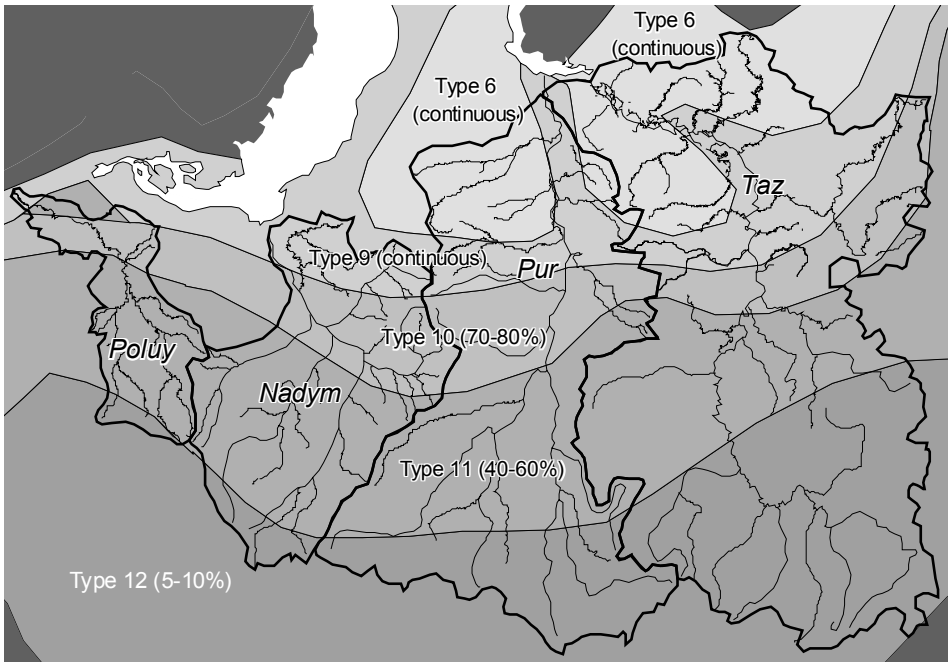

Figure 11. Map of permafrost types (only types covering the study area are shown) after (Kondratyev and Kudryavtsev, 1981).

Table 3. Permafrost types after (Kondratyev and Kudryavtsev, 1981) covering the PNPT watershed

Type	Percent of coverage, %	Average temperature, °C	Depth of permafrost, m
Continuous permafrost			
6	100	-7 to -9	300-500 m
9	100	-1 to -3	100-300 m
Discontinuous permafrost			
10	70-80	0 to -2, thaw soils - +1 to 0	up to 100 m, rarely 200-300 m
11	40-60	0 to -1, thaw soils - +2 to 0	50-70 m, rarely 100-200 m
12	5-10	0 to -0.5, thaw soils +2 to 0	15-20 m, rarely up to 50 m

3.2 Numerical modelling of the hydrological regime of the PNPT rivers.

Using only in situ data it is difficult to have a homogeneous dataset to provide a sound assessment of changes in hydrological regime under constraint of climate changes. Numerical simulation is especially helpful as it may provide discharge values when in situ data are not available - it is often the case with the winter months, as well as for the large periods when for some reasons several years of data are absent. To reconstruct the discharge time series we have applied a distributed hydrological model WATFLOOD (Kouwen, 1988) for the three main rivers of the PNPT watershed - Nadym, Pur and Taz. WATFLOOD is a combination of a physically - based routing model and a conceptual hydrological simulation model of a watershed. The processes modelled include interception, infiltration, evaporation, snow accumulation and ablation, interflow, recharge, baseflow, overland and channel routing, and wetland routing. The model uses Grouped Response Unite method to group hydrologically similar response units. All model parameters have physical interpretation. They can be taken from literature and applied to the watersheds with similar natural conditions. Twelve model parameters are associated with land classes, three with river type and three with wetland routing (Bingeman et al., 2006).

Using digitised historical maps of soil type (1: 2 500000), vegetation type (1 : 1500 000) and landscape classes (1: 1 000000) (Figure 12) we have identified four watershed classes : a) sparse forest on sandy soils, b) bogs on loam soils, c) flooded area fens and d) lake area e) forest on glay soils (Figure 14) and one river class. As the bog and lake area representation is not accurate on the historical maps we used satellite products for adjustment. The average lake fraction for each grid cell was calculated using ASAR lakes of DUE Permafrost product ["DUE Permafrost...", 2011]. Actually only the Nadym river watershed is completely covered by product, so lake fraction was corrected only for this watershed.

Use of radar altimetry data on wet zones extent (Section 2) provide basin-wide information that is impossible to obtain using in situ measurements and presents an opportunity to successfully assimilate them in numerical model. Model parameter of bogs fraction was thus calculated as difference between a) ENVISAT wet zones extent [Zakharova et al., 2009, see also Section 2], and b) ASAR lake fraction ["DUE Permafrost...", 2011] and c) flooded fens fraction (historical maps). The flow directions for each modelling grid cell were calculated basing on GTOPO30 DTM and corrected using topographical maps of 1:200000 scale. Modelling cell size is 0.25° x 0.25°, and time step is 1 day.

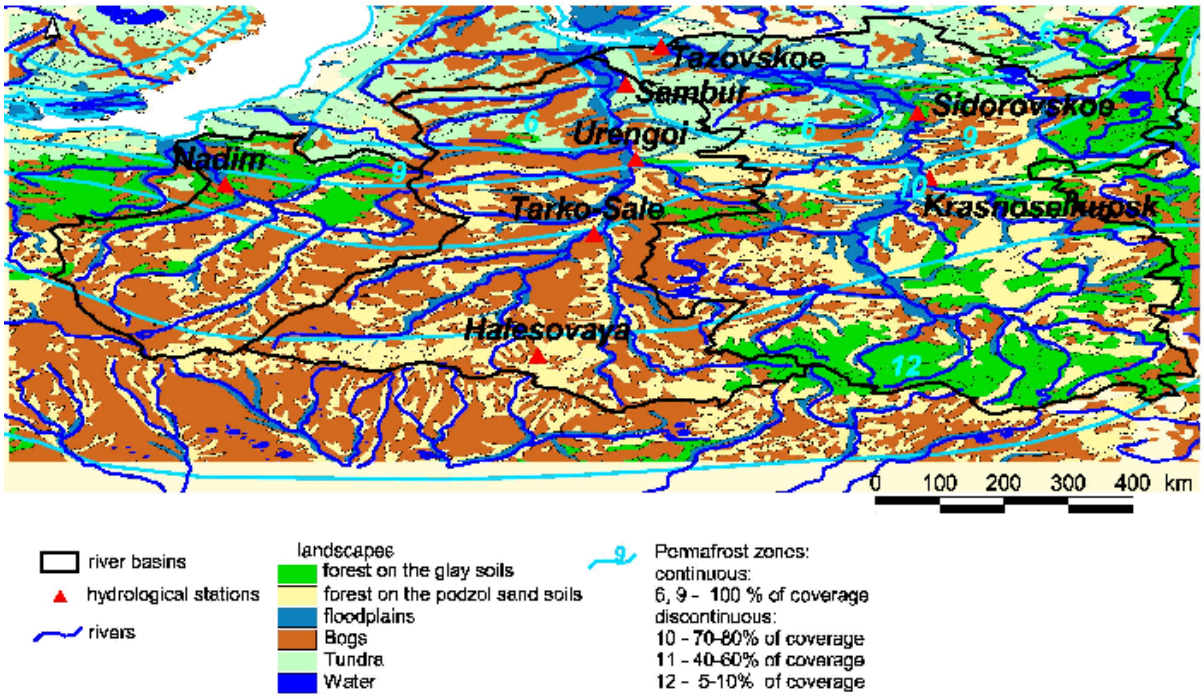

Figure 12. Landscape classes for modelling region

As an external forcing we have used ERA-40 meteorological data (Figure 13). Comparison of WMO meteorological stations with corresponding ERA-40 grid points shows extremely good correlation for air temperature and somewhat lesser but satisfactory correlation for precipitation (Table 3).

As the bogs cover important part of the watersheds in this region the wetland routing module was activated. It significantly improved the discharge simulations. As recommended in Bingeman et al. (2006), first a sensitivity test was performed and then the principal parameters were manually calibrated on the Nadym watershed (in the limits given in that article). As the natural conditions are similar for the Nadym, Pur and Taz rivers , this set of the parameters was applied also for the Pur and Taz rivers. Preliminary results of comparison of numerical simulations of daily discharge values with in situ observations show promising results (Figure 15, Table 5).

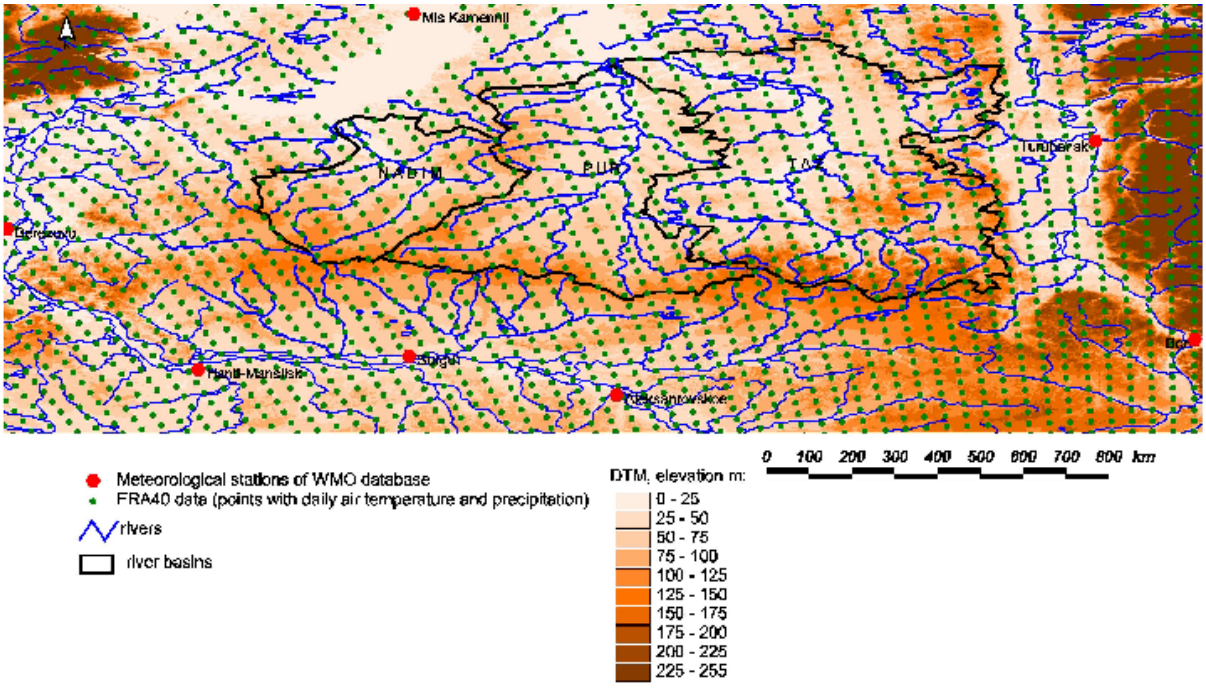

Figure 13. Digital terrain model and meteorological data (ERA-40 and WMO stations)

Table 4. Correlation coefficient between data of WMO stations and ERA40 reanalysis for the same location as well as bias (WMO-ERA40) for period 1979 –2002.

Station	P daily, mm	P monthly, mm	bias, mm Pdaily/ Pmonthly	T daily, °C	bias Tdaily, °C
23146_Mys Kamenny	0.50	0.63	-0.56/-17.1	0.99	-1.50
23472_Turukhansk	0.48	0.78	-0.14/-4.1	0.99	-0.25
23631_Berezovo	0.64	0.89	0.00/0.14	0.99	-0.64
23849_Surgut (1979-1984)	0.60	0.84	0.10/3.06	0.99	0.12
23884_Bor	0.5	0.78	-0.12/-3.70	0.99	-0.23
23933_Khanty-Mansiysk	0.63	0.84	-0.00/0.20	0.99	-0.13
23955_Alexandrovskoe	0.51	0.78	-0.17/-5.24	0.99	-0.41

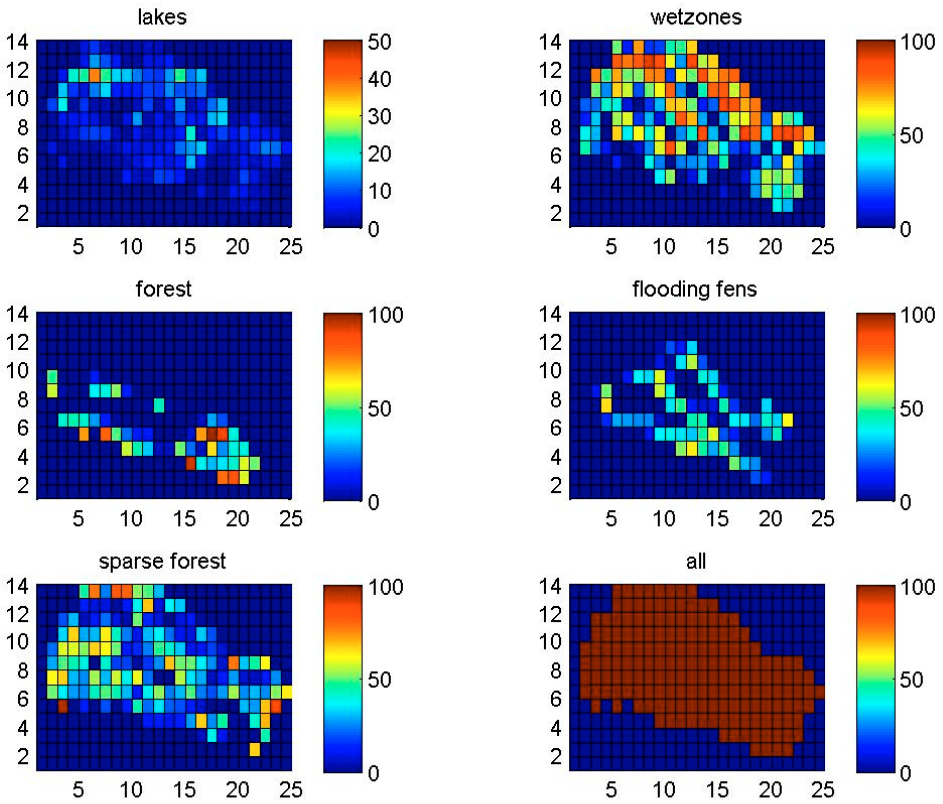

Figure 14. Area percentage for watershed classes for Nadym River.

Additional validation activity will consist in using of water level variability from satellite radar altimetry for calibration of flow routing, especially for Taz river, where in the lower reaches the large plain is inundated during almost the whole summer season. These data will provide unique type of observations for validating and constraining the model over the PNPT region. After the validation, numerical simulation outputs may be used to provide a homogeneous, continuous and reliable estimates of rivers response to external climatic variability.

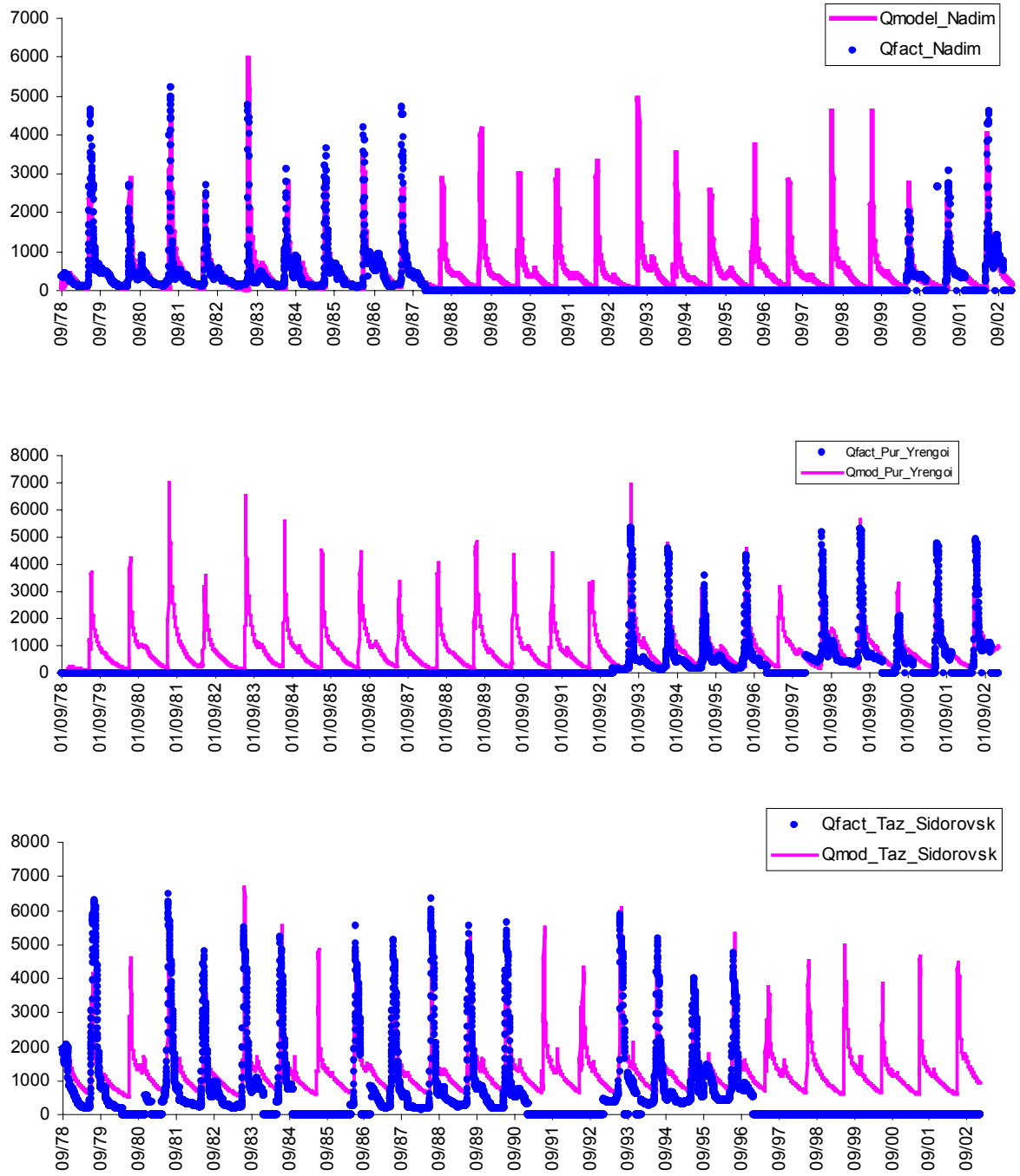

Figure 15. Comparison of the daily modelled discharge (violet line) and in situ discharge measurements for Nadym (upper panel), Pur (middle panel) and Taz (lower panel).

Table 5. Statistical parameters of comparison of discharge values from numerical modelling and in situ data.

River	Period	Nash	R^2	RMS, m3/s	RMS/Qan	Bias
Nadim	09.1978-1987	0.67	0.69	362	0.78	47
Pur_Yrengoi	09.1992-2002	0.68	0.76	544	0.69	260
Taz_Sidorovsk	09.1978-1996	0.66	0.75	775	0.71	271

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