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Flow regime alteration in Arctic rivers due to dam operations and climate change

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ABSTRACT

Arctic rivers and water resources currently experience significant hydrological changes due to climate change and global warming. The flow regime alteration in Arctic rivers strongly influences the conservation and sustainability of the native biodiversity of the riverine ecosystem. The change in major characteristics of the daily and monthly flow regime of seven arctic rivers has been assessed in this study. The daily flow (40–120 years) at the outlet of Lena River, Yenisey River, Kolyma River, and Ob' River in Russia; Yukon River in the USA; Mackenzie River in Canada; and Tana River, Norway was used. Except for the Tana River, the rest of these rivers have been regulated. In addition, monthly flow alteration in the headwater of these rivers and below sixteen dams was assessed. In this research, we applied 'Indicator of Hydrologic Alteration' (IHA) and 'River Impact' (RI) methods to estimate daily monthly flow change in the river. Based on the daily analysis, the most significant change was observed for Yenisey and Ob rivers. The Kolyma hydropower shows the lowest impact, while the Shushenskaya Dam on Yenisey shows the highest impact on the flow regime.

1. Introduction

The natural flow regime is essential in the conservation and sustainability of native biodiversity in the river ecosystem. Poff et al. (1997) described flow regime as a term that "describes the variations in the river flow as a response to the flow pulses conveyed through the river network within a watershed". The river's natural flow could be described by observing trends in quantity, timing, and variability of the flow (Poff et al., 1997). The hydrological regime determines the biotic composition, structure, and function of an aquatic, wetland, and riparian (Richter et al., 1997). River regime alteration has been generally categorized into two leading causes: anthropogenic (e.g., river regulation for water supply, transportation, flood control, or land-use changes) and natural due to climate change or climate variability (Gibson et al., 2005).

Global warming and average temperatures in the Arctic region have increased more than twice as fast as the rest of the world for the past 50 years (Ballinger et al., 2020; Gautier et al., 2018; Corell, 2006). Yang and Kane (2021) in their book carefully examined the changes, causes and consequences of Arctic hydrology, ecology and river flow in response to changes in climate. In one of their chapters, they examine variability/trends and possible causes due to climate impact and human effect, of discharge regimes and changes for the Lena and Yukon rivers (Yang et al., 2020). Ge et al. (2013) reported a strong correlation between increased temperatures in April and increased discharge in May in the Yukon River basin. Brabets and Walvoord (2009) reported that the changes in the timing of summer flows in the Yukon River basin were because of climate variability called Pacific Decadal Oscillation (PDO). Observational studies have documented a long-term increase in discharge of Arctic rivers (Holmes et al., 2021; Liu et al., 2022). In addition to this increase, there has been a consistent shift toward earlier peak discharge in the spring (Hiyama et al., 2023; Holmes et al., 2021). For example, future floods were expected to decrease whiles future winter, and autumn floods were anticipated to increase in the Tana River basin. Lotsari et al. (2010) reported future snow cover reduction due to increased temperature and precipitation, leading to a flood timing and

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intensity shift. Moreover, changes were identified in river-ice phenology; river ice melts earlier in spring and freezes later in autumn (Hiyama et al., 2023; Park et al., 2017). Other studies have indicated that increases in winter streamflow are likely associated with a shift in precipitation from snow to rain in late autumn, which consequently increases streamflow in the early winter period (Feng et al., 2021; Makarieva et al., 2019; Wang et al., 2021).

Reservoir regulation can also increase winter low flows and reduces summer high flows (Ranzani et al., 2018; Shiklomanov et al., 2007; Torabi Haghighi et al., 2021). For the Arctic river basins the changes in streamflow from reservoir regulation is relatively small compared with the magnitude of the increase in annual discharge (McClelland et al., 2004). Ye et al. (2003) studied how human activities (dam for hydropower regulation) and natural variations affect the flow regime of the Lena River (one of the largest rivers discharging into the Arctic Ocean). The authors found that climate warming and permafrost degradation caused a runoff increase in winter, spring, and summer seasons and a runoff decrease in the fall season in the upper streams of the Lena river basin, which had no major human impact and no dams. Additionally, the Vilyui Dam for hydropower production significantly altered the monthly flow regime in the lower part (below the dam) of the Lena Basin by increasing winter low flows 30 times and reducing summer high flows by 55%. The results from the data analysis for the Kolymskoye gauging station located at the mouth of the Kolyma River watershed showed a significant increase in low flows and a decrease in high flows after constructing the Kolyma Hydropower Dam. A study on the influence of dams on the Mackenzie River basin by Yang et al. (2015) found that the operation of hydropower plants on the Peace River reduced seasonal flow variation of the Peace River. Yang et al. (2004a) reported that three major dams (Bukhtarminskoe, Shul'binskoe and Novosibirskoe Dam) on Ob' watershed decreased the summer monthly flows and increases the winter low flows. Studies conducted on the flow changes in the Yenisey River basin revealed that the alteration of the river is a result of the combined effect of major hydropower regulated dams in the upper parts of the basin plus increased precipitation from climate change (Stuefer et al., 2011; Yang et al., 2004a).

Owing to the large variations across the arctic regions and their watersheds due to permafrost, climate, hydrology and anthropogenic activities, it is important to understand and examine the underlying flow variations and regime changes. The best way to quantify these changes is to analyze long-term flow data to examine the hydrological regimes and changes due to climatic variation and/or human impacts. Regulation of river runoff by dams leads to fundamental changes in environmental conditions both above and below dams (Carmack et al., 2016). The movement of water masses, thermal regime, chemical composition (Haine et al., 2015), and solid runoff (Bailey et al., 2021), depend on the operation of these dams (Serreze et al., 2006; Timmermans and Marshall, 2020). The diverse consequences of changing river regimes in the Arctic rivers after the construction of dams are currently not fully considered in design or prospective planned developments. At dams there is a big problem associated with reduction of the negative environmental consequences of their creation, as well as resolving conflicts between hydropower and other water users (Liu et al., 2022). The dam forming the reservoir, providing constant water for the time being, changes the natural state of the river flow and is a key factor determining their negative impact on the underlying ecosystems in the Arctic (Feng et al., 2021; Nogovitsyn et al., 2020). In this regard, questions of changing the hydrological regime of the regulated rivers of the Arctic are of practical and scientific interest.

We utilized long-term hydrologic data for seven Arctic rivers to assess the hydrological change and possible influences due to dams. Specifically, the study aims to (1) understanding and quantitatively evaluating the effects of reservoir operation on flow regime alteration (2) testing the performance of daily and monthly regime analysis approach and intercomparison of pre and post dam period. This study forms a starting point for understanding the flow regime of seven Arctic Rivers due to dams.

2. Study area and data

Flow regime alteration in seven arctic rivers, namely: (1) Lena River, Russia (2) Yenisey River, Russia (3) Kolyma River, Russia (4) Ob' River, Russia (5) Yukon River, USA (6) Mackenzie River, Canada and (7) Tana River, Norway was assessed (Fig. 1). These rivers are the main freshwater suppliers for the Arctic Ocean. The main features of the rivers (Brittain et al., 2022; Holmes et al., 2021; Peucker-Ehrenbrink, 2009) and its source about the daily discharge of the seven arctic rivers are shown in Table 1. Most of these rivers have major impoundments for power generation, navigation, irrigation, flood control and human consumption. The information on the major impoundments and the dam's discharge downstream was collected to understand the pre and post-impoundment impacts better. The selection of the Arctic rivers considered in this study were governed by the availability of data both at the river outlet and at the dams considered.

Annual and seasonal flow changes across the arctic rivers must be carefully viewed from the perspective of dams. A comparison of the long-term mean flow in the pre-dam and post-dam periods could demonstrate significant changes, as it heavily influences the flow regime and watershed storage (McClelland et al., 2004). There are more than ten dams in the Yenisey river and only one major large dam in one of Lena's main tributaries, while none across the Tana basin. The majority of the dams constructed across the Arctic rivers considered in this work were in the pre-1975 period. There needs to be a better comprehension of how the Arctic dams affect the annual and seasonal flow characteristics, focusing on the period immediately after dam construction. For this, we selected the dams (based on data availability), as shown in Table 2, located mostly above the river watershed outlet point such that the reservoir regulation could substantially alter the basin streamflow. It should be noted that Table 2 only reports the dam we included in this study and the corresponding monthly discharge from relevant gauges were collected from R-Arcticnet (https://www.r-arcticnet.sr.unh.edu/v4.0/index.html). The data is not uniform and is mostly available between years 1950–2000. There are also other dams (Kureiskoe, Boguchanskoe and Ust'-Khantaiskoe) on Yenisey River and (Whitehorse

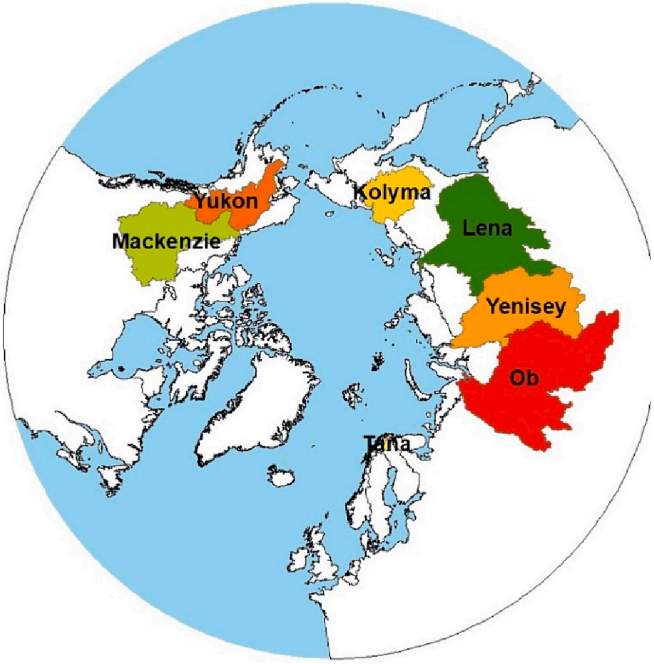

Fig. 1. The geographical location of seven river basins studied in the Arctic region.

hydropower) on headwaters of Yukon River, mentioned in Table 2, but not considered in the study because discharge records are insufficient or unavailable.

Table 1
Period and data source for seven rivers studied.

River	Available data	Drainage area (km^2)	Flow (km^3)	Length (Km)	Data Source
Yukon (YU)	1975–2017	849,000	203.26	3190	US Geological Survey (USGS) and ArcticGRO data
Kolyma (KO)	1978–2017	526,000	102.629	2436	Roshydromet Russia and ArcticGRO data
Mackenzie (MA)	1972–2017	1,780,000	218.499	1740	Environment Canada and ArcticGRO data
Lena (LE)	1936–2017	2,490,000	528.57	4472	Roshydromet Russia and ArcticGRO data
Yenisey (YE)	1936–2017	2,590,000	580.1065	5500	Roshydromet Russia and ArcticGRO data
Ob (OB)	1936–2017	2,530,000	393.954	3650	Roshydromet Russia and ArcticGRO data
Tana (TA)	1911–2017	14,500	5.25	361	Norwegian Water Resources and Energy Directorate (NVE) and ArcticGRO data

3. Methods

This section outlines the research methods utilized to understand the river flow regime alteration due to anthropogenic (dams) or climatic variations. The first part of this section describes the indicator of hydrological alteration (IHA) calculates the values of 33 hydrologic parameters that characterize the intra- and inter-annual variability in water conditions at a daily scale at the river outlet (refers to data mentioned in Table 1). This is followed by a river impact (RI) index approach to understand better the impacts of hydraulic structure using monthly flow data both at the outlet (reported in Table 1) and at the dam locations (refers to monthly data from gauging station near the dams mentioned in Table 2).

3.1. *Indicators of hydrologic alteration*

The indicator of hydrological alteration (IHA) tool was used to analyze the degree of alteration of the discharge at a daily scale based on the Range of Variability Approach (RVA) (Richter et al., 1997; Richter et al., 1996). The IHA tool uses 33 hydrological parameters subdivided into five groups, i.e., the timing, magnitude, frequency, duration, and rate to evaluate the impact of hydrological alteration from anthropogenic natural variation based on RVA. A detailed summary of each of the 33 hydrological parameters and their characteristics can be referred from Richter et al. (1996). Since in this work there was no specific ecological information, the ranges of natural variability are based on the selected percentiles levels or a simple multiple of parameters standard deviation from the natural or pre-impact hydrologic regime, as the analysis does not include from the perspective of ecology due to lack of sufficient data. The hydrological attributes were calculated by splitting data into pre-and post-impact periods according to a) minimum of 20 years of pre- and post-impact data and b) considering the year of

Table 2
Information about major dams in each river basin considered in this study.

River	Country	River Tributary	Dam	Reservoir capacity (km^3)	Reservoir Area (km^2)	Reservoir commissioning year	Dam height (m)	Purposes
Lena	Russia	Vilyui	Vilyui	35.9	2501	1967	75	H
Yenisey	Russia	Yenisey	Krasnoyarsk	73.3	2000	1972	124	H, N
	Russia	Yenisey	Shushenskaya	31.34	621	1990	242	H, N
	Russia	Angara	Irkutsk	46.5	156	1956	44	H
	Russia	Angara	Bratsk	169.27	5470	1967	125	W, H, N
	Russia	Angara	Ust-Ilim	59.4	1873	1974	102	H, N
	Russia	Angara	Boguchanskoe*	59	2326	2012	96	H
	Russia	Kureyka	Kureiskoe*	10	560	1994	81	H
	Russia	Khantayka	Ust'-Khantaiskoe*	24	2120	1975	65	H
Mackenzie	Canada	Peace	WAC Bennett	74.3	1623.9	1968	183	H
	Canada	Peace	Peace Canyon	0.2159	8.4	1980	61	H
Kolyma	Russia	Kolyma	Kolma HPP	15	441	1991	115	H
Ob'	Russia	Ob	Novosibrisk	8.8	1070	1957	33	W, H, N
	Kazakhstan	Irtysh	Kamenogorsk	0.655	37.9	1953	65	I, W, F, H, R, P
	Kazakhstan	Irtysh	Bukhtarma	49.62	5490	1960	90	I, W, F, H, N, R, P
	Kazakhstan	Esil	Sergeer	0.693	116.7	1969	25	I, W, F, R, P
	Kazakhstan	Esil	Astana	0.4109	60.9	1971	29	I, W, F, R, P
	Kazakhstan	Tobyl	Upper Tobol	0.82	87.4	1977	42	I, W, F, R, P
	Kazakhstan	Irtysh	Shulba	2.39	255	1988	36	I, W, F, H, R, P
Yukon	Canada	Yukon headwaters	Whitehorse*	0.013	1100	1957	18	H
Tana	Norway				-na-			

Note: Monthly discharge from relevant gauges near the dams were collected from R-Arcticnet (https://www.r-arcticnet.sr.unh.edu/v4.0/index.html). *These dams were not considered in this study due to insufficient discharge data.

[*] Dam purpose: Irrigation = I, Water Supply = W, Flood Control = F, Hydroelectricity = H, Navigation = N, Recreation = R, Pollution Control = P, Livestock rearing = L.

construction and operation of major dams in each watershed. Then the degree of hydrological alteration (DHA) was calculated based on the computed inter-annual statistics. Three RVA categories were selected by setting 67th percentile (for upper RVA boundary) and 33rd percentile (for lower RVA boundary) while carrying out the non-parametric analysis for all the seven rivers due to the dataset being skewed in nature (Ashraf et al., 2016). The estimation of the degree of hydrological alteration was computed as below.

$$DHA = Absolute\left(\frac{observed\ frequency - expected\ frequency}{expected\ frequency}\right) \tag{1}$$

The expected frequency is the frequency in the pre-impact period, and the observed frequency is the actual observed frequency in the post-impact period. DHA is an absolute value that indicates the magnitude of change. At the same time, hydrologic alteration (HA) could be positive or negative, signifying the decrease or increase of the parameter frequency (Mathews and Richter, 2007). In this work, HA is classified based on the RVA boundary set as low, L (0–0.33), medium, M (0.34–0.67) and high, H (0.68–1).

For Kolyma, Mackenzie, and Yukon rivers data available at river outlet are roughly from 1976 to 2017 (see Table 1), the IHA was utilized considering the pre-impact period (1976–1995) and post-impact period (1996–2015). For Ob, Yenisey, Lena, and Tana rivers data available at river outlet are roughly from 1936 to 2017 (see Table 1), the IHA was utilized considering the pre-impact period (1936–1955) and three post-impact period (1956–1975, 1976–1995, 1996–2017).

3.2. *Annual and intra-annual flow regime Alteration and impact of dams*

To analyze the monthly flow regime, an existing River impact (RI) index methodology from Torabi Haghighi et al. (2014) was used to quantify river regime impacts by combining three major attributes of flow regime (magnitude, timing, and variation in monthly flow) through comparison of intra-annual flow regime pre-and post- dam impact. We also applied the Mann-Kendall test to evaluate the trend in flow. Fig. 2 gives a graphical overview of the RI index methodology. The RI index that gives the measure of river impact factor is given below.

$$RI = MIF^{*}(VIF + TIF) \tag{2}$$

where

- RI is river impact with a value ranging from 0 to 1.
- MIF is a flow magnitude impact factor that is a function of water consumption and quantifies the change in flow magnitude before and after dam development (Fig. 2b).
- TIF is a timing impact factor that considers changes in the timing of maximum, minimum, and median discharge cumulative density function (Fig. 2c),
- and VIF is an intra-annual flow variability impact factor that indicates how a natural flow regime approaches more uniform flow after dam construction (Fig. 2d).

Based on the RI index (which varies between a maximum impact of 0 and a minimum impact of 1), the river regime impact can be classified into one of the following five groups, *Low* (RI > 0.8), *Incipient* (0.6 < RI < 0.8), *Moderate* (0.4 < RI < 0.6), *Severe* (0.2 < RI < 0.4), and *Dramatic* (0 < RI < 0.2). For more detailed information about the calculation of these indices, see Torabi Haghighi et al. (2014). The method was carried out to analyze the monthly flow regime alteration trend at the outlet of all the seven arctic rivers to understand the impact of numerous impoundments constructed in the last century across the watersheds (data reported in Table 1). Further, based on the availability of monthly discharge data (reported in Table 2) at the location of dams considered in these arctic rivers, the RI index was calculated again to evaluate the impact of the specific dams on the flow regime. The main features of dams considered for this study are shown in Table 2, located across the different arctic rivers.

4. Results and discussion

The results of the seven arctic rivers are grouped into two groups based on the period of data availability for better understanding. For Group 1 rivers Kolyma, Mackenzie, and Yukon, the available data used in this work are from 1976 to 2017, while in Group 2 rivers (Ob, Yenisey, Lena, and Tana), it is from 1936 to 2017. This section discusses if the flow regime has changed at the outlet of the Arctic rivers. The daily flow regime alteration study was carried out using the daily flow data at the river outlet. While the analysis of the monthly flow regime alteration was carried out using the monthly flow data both at the river outlet and the dams (see Table 2) considered for each river.

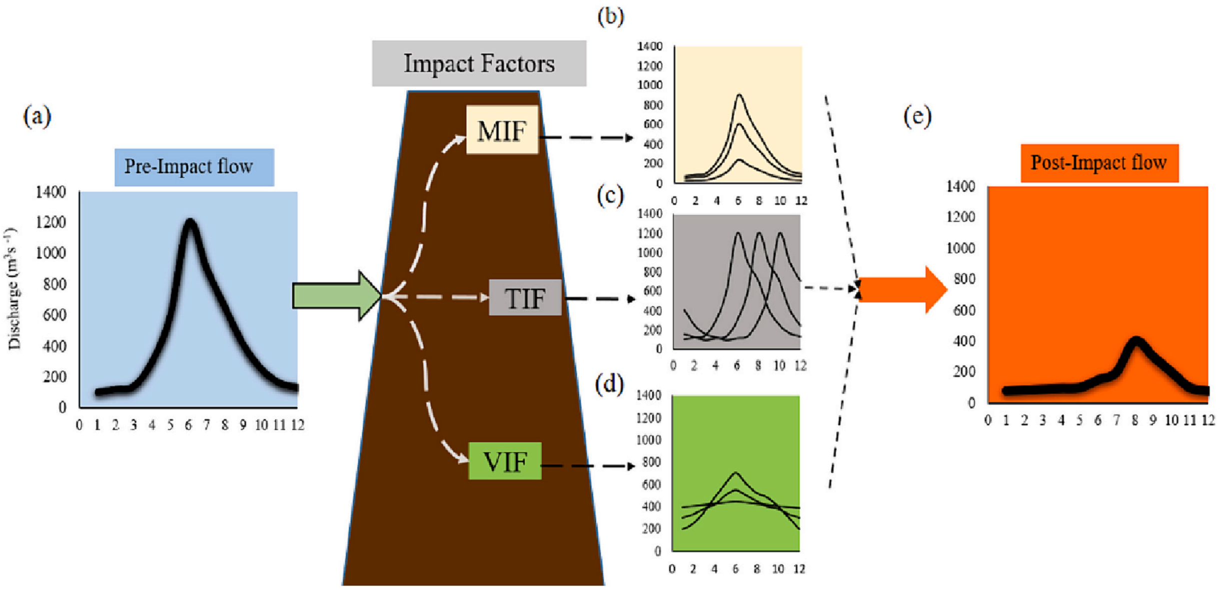

Fig. 2. The graphical concept of river flow impact factors (Torabi Haghighi et al., 2020).

4.1. Analysis of the daily flow regime alteration

We assessed the alteration of the runoff regime using the IHA/RVA approach, which has been widely applied to assess the hydrological alteration (Jumani et al., 2020). This section presents a simplified understanding of the extent of alteration for the rivers considered in this work. Table 3 shows the magnitude of the flow regime metrics for the Group 1 rivers. The pre-and post-impact of **Kolyma's** monthly flow alteration in Fig. 3a shows an increased flow for summer and autumn (June–November, median deviations from +18.03 to +40.88%) with an exception for a reduced flow in August (−3.38%). Even in the winter and spring (December to May), an increased flow was observed. There was not much change in the pre-and post-impact period in July, whereas a decrease in the flow was observed for August. The increased flow in the Kolyma river during the cold season (November–April) was primarily due to the operation of the hydropower plants in the river basin.

The dam's regulation stabilizes almost a slight increase in the flow peak in May, where the flow is highest due to snowmelt season. Majhi and Yang (2008) reported a decreased flow for June in the post-dam era instead of the increased flow. This could be due to the increase and early onset of snowmelt. The operations of the dams have increased the low flow in the Kolyma river, decreasing the low pulse duration and increasing the base flow index but with no change in the high pulses. The decrease in Kolyma river flow in August was consistent with the findings of Majhi and Yang (2008). The operation of the dams resulted in controlling the 7-, 30-, and 90-day maximum flow. The change in the timing of the annual extremes, particularly minimum flows, could have ecological consequences for the river ecosystem. The results confirm flow regime alteration of the Kolyma River by dam regulation and climate change, especially with the low flow magnitudes and timing. The average degree of hydrological alteration in the Kolyma river basin was medium (M, DHA = 41.15%). The degree of alteration on flow regime was classified by RVA analysis as a high level over five metrics (see Table 3): maximum annual flows of 1 day (−72.73%), high pulses per year (+104.5%); rise rate (+84.62%), fall rate (−86.36%) and the number of reversals (−89.77%).

For the **Mackenzie** river, most of the hydrological alteration of the 33 IHA parameters were low (L) except for the rising rate (+67%) and the number of reversals (−88.1%) for which it was high. The average degree of hydrological alteration of the 33 IHA parameters was Low (L, DHA = 31.62). There were significantly decreasing flow trends from June to August and in the 1-,3-, 7-, 30- and 90-day maximum flows (see Fig. 3b). The monthly flow regime alteration of Mackenzie River in Table 3 showed increased flow in the post-impact period for all the months except July and August, while in June, there was no change observed. The increased flow in the winter period (December–February) could be influenced by the large natural and artificial lake, i.e., the Grate Slave lake and the Willistion Reservoir. During summer (June – August), the hydropower operation of filling up the Williston Reservoir on the Peace River reduces the flow reaching the Great Slave Lake (Woo and Thorne, 2003). A reduced flow reaching the Great Slave Lake could reduce the flow out of the Great slave into the Mackenzie River. This is further alleviated due to the early onset of the snow melting season (Yang et al., 2015), which could explain the decrease in the summer period (June–August) since the discharge in the summer period mainly constitutes: snowmelt. Therefore, the anticipation of the melting season before the summer period could reduce the summer flows. The combined effect of early snowmelt from climate change and probably, to a lesser extent, the regulation of hydropower dams in the Peace River could explain the reduced flows in the summer. In contrast, climate change could explain the increased flow in the spring, fall, and winter flow.

It was observed from Fig. 3c and Table 3 that the **Yukon** River had a medium average degree of alteration (DHA = 44.05%). The results of the hydrological impact in Parameter Group #1 were majorly medium (M) to low (L) impact on monthly IHA parameters except for April that showed a high (H) impact. In Parameter Group #2, the results showed a high (H) alteration in 1-, 3-, 7-, and 30-day minimum discharges. The timing of the minimum flow in Parameter Group #3 shows a high (H) hydrologic alteration. In general, the result in this study shows an increased average winter flow in the post-impact period, which is also supported confirms the findings (Brabets and Walvoord, 2009). Based on the finding of (Brabets and Walvoord, 2009), it could be concluded that the high alterations in the April and 1-, 3-, 7-, and 30-day minimum discharges and shift in the timing of minimum flows are due to climate variation. The increased flow in September and October could be due to the precipitation in August and September. The increasing trend in discharge in May could be due to increased temperature from climate change in April (Brabets and Walvoord, 2009; Ge et al., 2013). The decreased discharge trends in June to August could be linked to the temperature increase due to Pacific Decadal Oscillation (PDO) in the Yukon basin (Brabets and Walvoord, 2009). Additionally, PDO could be responsible for shifting the timing of minimum flows in the Yukon River basin. The shift in the timing of minimal flows could negatively impact the ecological processes in aquatic ecosystems (Gibson et al., 2005).

Detailed results for the group 2 rivers could be found in Appendix A (Table A1, A2, A3 and A4). The annual flow regime alteration for the **Ob' River** for pre-and post-impact due to the seven dams shows increased flows from 40 to 100% exceedance probability and a slight increase in flow between 15 and 40% exceedance probability at the river outlet. The flow between 0 and 15% exceedance probability had an almost perfect match between pre-and post-impact annual flow duration curves. The average alteration caused by the seven dams in the Ob River catchment was medium (DHA = 45.84%). This study's hydrological alteration of the first three major dams was medium with DHA = 54.46%. The monthly flow alteration of the Ob River due to the impact of the seven dams showed increased post-impact median flow from November–August. It decreased post-impact median flow in September and October. Trend analysis for the period before any of the major dams was constructed showed a significant increasing trend on April 1-, 3-, 7-, 30- and 90-day minimum flows. The increased winter (December–February) flow see Fig. 4a, at the mouth of the Ob' River was due to the releases from hydropower plants that operate in the winter (Yang et al., 2004b). The summer flows (June–August) were expected to reduce due to the filling up of the cascaded reservoirs on the Ob' River basin. However, surprisingly the flow increased during the summer period. This could be attributed to an increase in summer precipitation and higher water abstraction for hydropower and irrigation. The significant trend inflow increases in April and 1-, 3-, 7-, 30- and 90-day minimum flows are partly due to reservoir operation and climatic variations. Nevertheless, these climate change claims are not easy to confirm only with streamflow data. Some extra analysis on the precipitation and temperature or glacier study would be needed to confirm climate change occurs in the basin. The decrease in the hydrological alteration from 54.46% (medium) for the first three dams to 45.84% (medium) for all dams considered in the study confirms the claim that the operation of dams and climate change significantly revises the natural flow regime of rivers.

In **Yenisey River** basin the five major dams considered were constructed in different years (Irkutsk 1956, Bratsk 1964, Krasnoyarsk 1972, Ust-llim 1977, and Sayano-Shushenskaya 1990). The degree of alteration on flow regime at the river outlet, classified by RVA analysis as a high level for most of the metrics. When one dam was operating, the average flow regime of the period was medium (M, DHA = 49.30%), whiles the hydrological alteration after all five dams went operation increased, but in the same category (M, DHA = 66.98%). The mean flow in summer and the annual maximum flow significantly decreased in the post-dam period (see Fig. 4b). Over the last decade, the increase in dam operations led to reduced low pulse duration and the number of reversals significantly in the different post-dam periods. Since the primary purpose of the dams on Yenisey River is hydropower production, which leads to a decrease in the average rise rate (see appendix A). Also, a high

Table 3

Indicators of hydrologic alteration (IHA) for the pre-impact period (1976–1995) and post-impact period (1996–2015) as well as the range of variability approach (RVA) for Yukon, Kolyma, and Mackenzie river. H-High, M-Medium, and L-low levels of alteration via RVA analyses.

Parameter	Yukon					Kolyma					Mackenzie				
	Pre-Impact	Post impact				Pre-Impact	Post impact				Pre-Impact	Post impact			
	IHA-means			RVA		IHA-means			RVA		IHA-means			RVA	
	Magnitude	Magnitude	Deviation magnitude (%)	Deviation from Target Range (%)	Impact Classification	Magnitude	Magnitude	Deviation magnitude (%)	Deviation from Target Range (%)	Impact Classification	Magnitude	Magnitude	Deviation magnitude (%)	Deviation from Target Range (%)	Impact Classification
Parameter Group #1															
October	6938.00	7730.00	11.42	8.08	L	1445.00	1879.00	30.03	−31.82	L	9310.00	9930.00	6.66	−20.63	L
November	3398.00	3682.00	8.36	54.41	M	410.50	578.30	40.88	−45.45	M	4105.00	5020.00	22.29	19.05	L
December	2124.00	2209.00	4.00	8.08	L	338.00	379.60	12.31	−6.49	L	3850.00	3990.00	3.64	32.28	L
January	1699.00	1812.00	6.65	23.53	L	265.50	290.50	9.42	50.00	M	3950.00	4660.00	17.97	−64.29	M
February	1557.00	1543.00	−0.90	−38.24	M	180.00	253.80	41.00	−18.18	L	3515.00	4060.00	15.50	−20.63	L
March	1416.00	1373.00	−3.04	−55.08	M	184.50	226.50	22.76	63.64	M	3330.00	3790.00	13.81	−40.48	M
April	1303.00	1303.00	0.00	76.47	H	144.30	224.50	55.58	63.64	M	3340.00	3705.00	10.93	7.14	L
May	5097.00	9628.00	88.90	41.18	M	146.00	274.00	87.67	36.36	M	12,500.00	14,200.00	13.60	−7.41	L
June	16,110.00	14,330.00	−11.05	−47.06	M	12,200.00	14,400.00	18.03	−45.45	M	20,600.00	20,600.00	0.00	−33.86	M
July	12,660.00	11,360.00	−10.27	−47.06	M	6155.00	6265.00	1.79	63.64	M	16,500.00	16,400.00	−0.61	58.73	M
August	11,020.00	10,900.00	−1.09	−53.68	M	5470.00	5285.00	−3.38	−31.82	M	13,500.00	13,000.00	−3.70	32.28	L
September	10,020.00	10,390.00	3.69	58.82	M	4738.00	5730.00	20.94	−18.18	M	11,150.00	12,350.00	10.76	−47.09	M
Parameter Group #2															
1-day minimum	1274.00	1303.00	2.28	111.8	H	118.00	177.50	50.42	−4.55	L	2610.00	2760.00	5.75	42.86	M
3-day minimum	1274.00	1303.00	2.28	111.8	H	119.20	181.00	51.85	−18.18	L	2610.00	2790.00	6.90	58.73	M
7-day minimum	1274.00	1303.00	2.28	111.8	H	120.60	191.70	58.96	−18.18	L	2610.00	2891.00	10.77	19.05	L
30-day minimum	1302.00	1308.00	0.46	76.47	H	128.10	205.10	60.11	36.36	M	2947.00	3405.00	15.54	−7.41	L
90-day minimum	1377.00	1416.00	2.83	−11.76	L	159.70	232.40	45.52	36.36	M	3440.00	3941.00	14.56	−20.63	L
1-day maximum	18,920.00	18,550.00	−1.96	−29.41	L	21,950.00	24,900.00	13.44	−72.73	H	28,600.00	27,700.00	−3.15	−33.86	M
3-day maximum	18,880.00	18,520.00	−1.91	−29.41	L	20,850.00	23,870.00	14.48	−59.09	M	28,230.00	27,230.00	−3.54	−28.57	L
7-day maximum	18,280.00	18,240.00	−0.22	−47.06	M	19,360.00	22,710.00	17.30	−45.45	M	26,700.00	25,990.00	−2.66	−20.63	L
30-day maximum	16,450.00	17,040.00	3.59	41.18	M	14,060.00	15,130.00	7.61	−31.82	M	22,870.00	22,460.00	−1.79	32.28	L
90-day maximum	13,970.00	13,990.00	0.14	5.88	l	8454.00	9420.00	11.43	9.09	L	18,390.00	18,990.00	3.26	−7.41	L
Number of zero days	0.00	0.00	0.00	0.00	L	0.00	0.00	0.00	0.00	L	0.00	0.00	0.00	0.00	L
Base flow index	0.20	0.21	2.75	5.88	L	0.04	0.06	70.12	9.09	L	0.29	0.31	5.05	−7.41	L
Parameter Group #3															
Date of minimum	100.00	99.00	−1.00	69.85	H	126.00	75.50	−40.08	−31.82	M	334.00	341.00	2.10	−47.09	M

(*continued on next page*)

Table 3 (*continued*)

Parameter	Yukon					Kolyma					Mackenzie				
	Pre-Impact	Post impact				Pre-Impact	Post impact				Pre-Impact	Post impact			
	IHA-means			RVA		IHA-means			RVA		IHA-means			RVA	
	Magnitude	Magnitude	Deviation magnitude (%)	Deviation from Target Range (%)	Impact Classification	Magnitude	Magnitude	Deviation magnitude (%)	Deviation from Target Range (%)	Impact Classification	Magnitude	Magnitude	Deviation magnitude (%)	Deviation from Target Range (%)	Impact Classification
Date of maximum	152.00	155.00	1.97	23.53	L	157.50	155.50	−1.27	−59.09	M	152.00	149.00	−1.97	−28.57	L
Parameter Group #4															
Low pulse count	1.00	1.00	0.00	−7.35	L	1.00	1.50	50.00	−47.93	M	2.00	2.00	0.00	−9.30	L
Low pulse duration	74.50	82.00	10.07	−7.35	L	75.00	17.25	−77.00	−34.55	M	46.50	26.25	−43.55	−64.29	M
High pulse count	1.00	2.00	100.00	−5.53	L	2.00	2.00	0.00	−3.74	L	1.00	2.00	100.00	−14.97	L
High pulse duration	59.00	63.00	6.78	−29.41	L	43.25	50.50	16.76	104.50	H	53.25	48.50	−8.92	19.05	L
Parameter Group #5															
Rise rate	169.50	152.00	−10.32	41.18	M	22.75	22.00	−3.30	84.62	H	100.00	100.00	0.00	67.00	H
Fall rate	−142.00	−85.00	−40.14	−75.29	H	−19.00	−40.25	111.84	−86.36	H	−100.00	−100.00	0.00	42.86	M
Number of reversals	12.00	17.00	41.67	−100.00	H	29.00	71.00	144.83	−89.77	H	28.00	37.00	32.14	−88.10	H

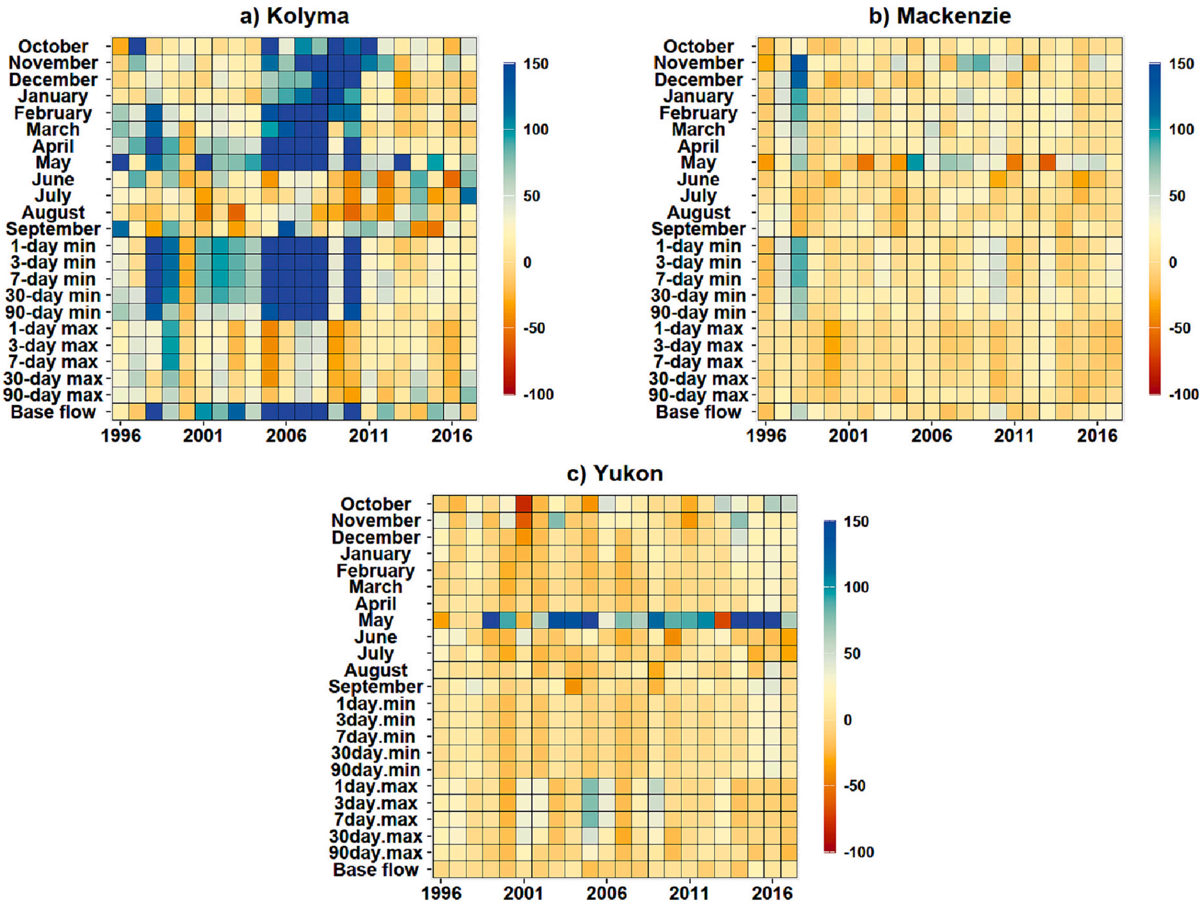

Fig. 3. Heat map quantifying the alteration of the flow regime metrics along the a) Kolyma, b) Mackenzie, and c) Yukon rivers according to relative annual discrepancies between pre-and post-impact/dam periods. The legend shows the color key corresponding to variation in the magnitude of the flow regime metrics.

degree of alteration for the magnitude of low flows compared to high flow was observed in parameter group 2. In addition to the magnitude of low flows, the magnitude of autumn-winter flow, the low pulse count and duration, base flow, the number of reversals and the date of annual minimum flow showed a relatively high degree of alteration. Reservoir operation and climate variation caused a significant decrease in the duration of the low flow pulse. Reservoir operation was the primary factor contributing to the increase in the frequency of flow changes and the decrease in the rising rate of flow at the outlet of the Yenisey River.

The comparison of the flow regime for the period before dam regulation to the period after dam regulation shows the dam operation had significantly increased the low flows and hence significantly altered the flow regime of **Lena River**. The average flow regime of the period before dam operation was low (L) (DHA = 31.67%), whiles the hydrological alteration after dam regulation increased too medium (M). The monthly flow alteration with RVA boundaries for Lena River shows the increased median flow for the post-dam impact period in all the months compared to the pre-dam impact (see Fig. 4c). An increased median flow for 1-, 3-, 7-, 30- and 90-day minimum and a decreased median flow for 1-, 3- and 7-day maximum flows were observed. There was an increased median flow for the 30-, 90-day maximum and baseflow index. The operation of the Vilyui Hydropower Plant is one of the factors responsible for the increased flow in the winter period (December to February) (Berezovskaya et al., 2005). The increased flow in the spring period (March to May) could be due to climate change (Ye et al. (2003)). The filling up of the Vilyui Dams reservoir during the summer period (June – August) reduced the flow peaks in June at the river outlet. The increased flow in July and autumn (September–November) is due to climate change. The increased river hydrological alteration observed before and after dam regulation corroborates the findings from several authors that dam regulation alters the natural flow regime of rivers. The operation of the dams is responsible for the increased low flows and stabilized high flow. However, Ye et al. (2003) suggested that the cause of the increased low flow and stabilized high flows could simultaneously be caused by climate change variation. The increased 1-, 3-, 7-, 30-, 90-day minimum flows and decrease 1-, 7-, and 30-day maximum flows are due to dam operation and climate change. The dam showed the importance of stabilizing the peak flow in June. The significantly increasing trend on June, 1-, 30-, and 90- day maximum flow, and 1-, 3-, and 7-day minimum flows before dam regulation suggest alteration caused by a climatic variation which confirms the finding of Ye et al. (2003).

For **Tana River,** consistent variations between 1956 and 2015 were detected for 85% of the flow metrics (Fig. 4d). The hydrological alteration showed a high (H) alteration mostly for the march and April monthly flows, while a medium (M) to low alteration (L) for the other months as well as other matrix parameters. The average alteration in the 33 IHA parameters of the Tana River basin was medium (DHA = 38.39%). The medium average hydrological alteration and close match between flow duration curve between the pre-and post-impact period in the Tana River IHA analysis confirm the pristine nature of the basin and the absence of any major dam operating in the basin. However, the slight mismatch in the low flow region confirms hydrological alteration in the catchment.

4.2. Analysis of the monthly flow regime alteration

The RI method was applied for inter-annual flow regimes at each river's outlet and at the location of dams.

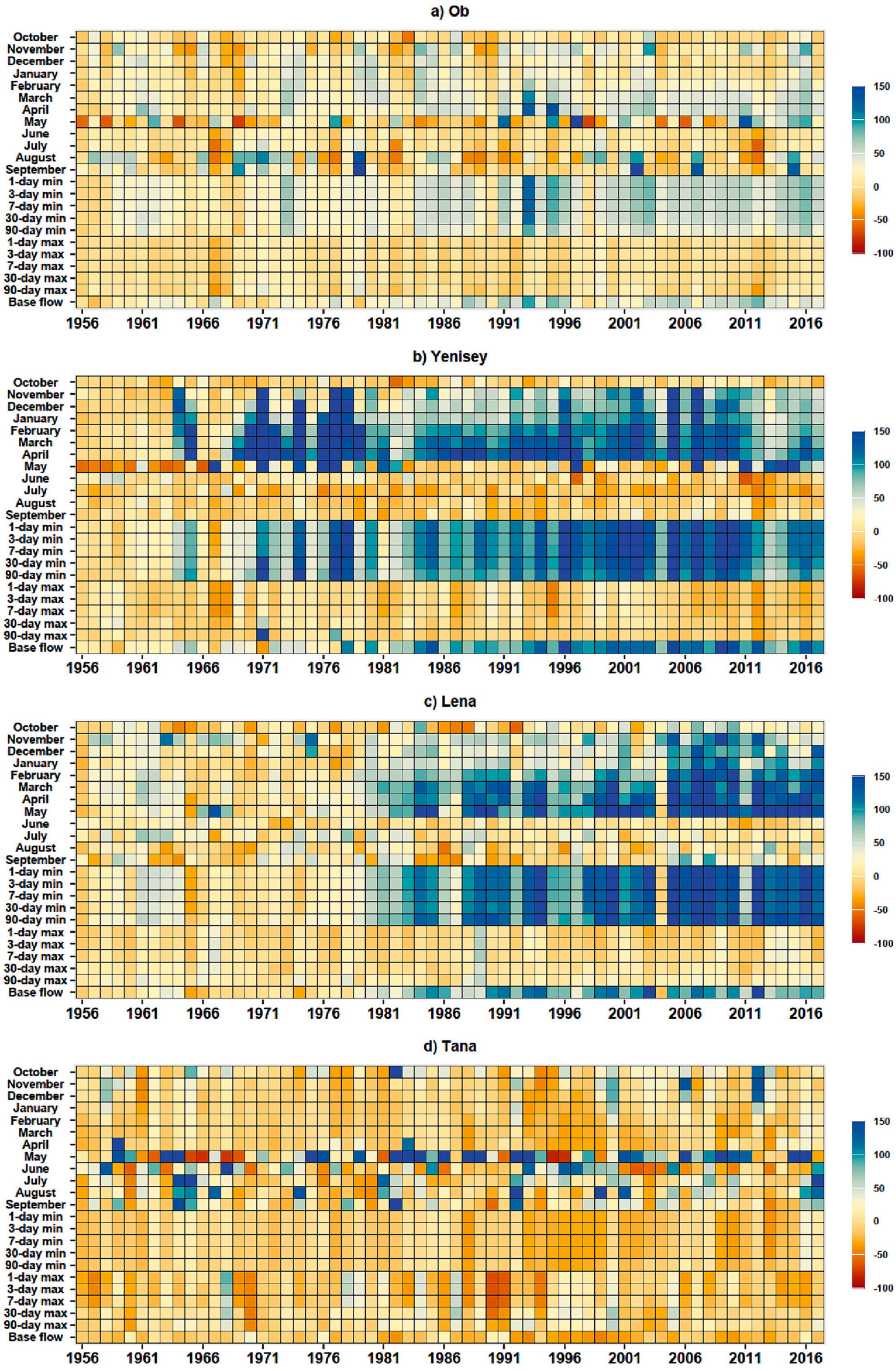

Fig. 4. Heat map quantifying the alteration of the flow regime metrics along the a) Ob, b) Yenisey c) Lena, and d) Tana rivers according to relative annual discrepancies of all three post-impact periods for the pre-impact period (1936–1955). The legend shows the color key corresponding to variation in the magnitude of the flow regime metrics.

4.2.1. Analysis of the monthly flow regime alteration at river's outlet

The analysis of monthly river regime alteration of the Arctic rivers reveals that the impact on monthly mean flow was counterbalanced to some extent, as the months with high mean discharge started to have similar values in both the pre-and post-impact periods. For the Group 1 arctic river, the post-impact period of the seasonality of river regime pattern was reduced compared to the pre-impact period due to the construction of dam structures, as shown in Fig. 5. While for the group 2 rivers, the river outlet shows a strong seasonal pattern in the pre-impact period of 1936–1955 during the spring months (May–June- July), as shown in Fig. 6. While during the different post-impact periods studied in this work, there were no substantial modifications in the monthly regime. However, the minimal alteration seen in Fig. 5 in the three post-impact periods of 1956–1975, 1976–1995, 1996–2015 could be mainly attributed to the various impoundments constructed across the rivers. Except for the Tana river in Group 2, all other rivers showcase a shift in the monthly river regime, particularly in the post-impact period of 1956–1975 and 1976–1975. This is because most of the dams were built in these two periods (Table 2) and therefore exhibits a delay in attaining the spring peaks. Tana river shows the least alteration due to its pristine nature because the Norwegian side of the Tana river is protected against hydropower. Irrespective of the river considered in Group 1 or Group 2, in all the rivers across all post-impact periods, an increase in monthly mean flow is observed for the winter (November–February). This is because due to the increase in usage of the impounded water during the winter months.

Table 4 provides information on the RI index for the rivers in Group 2 for the different post-impact periods concerning the preceding pre-impact period. It groups the different post-impact periods and preceding pre-impact periods to six different scenarios (Sc). For all the seven rivers shown in Figs. 5 and 6, the analysis of the RI index shows that in the post-impact periods, except for the Lena river and Yenisey river all the other five rivers have a low impact on the flow (RI $>$ 0.8, Low impact). For Lena river and Yenisey river, for one of the post-impact periods (1996–2015), an incipient impact on the flow is observed (0.6 $<$ RI $<$ 0.8) compared to the pre-impact period 1936–1955. The impact on the flow regime is due to the magnitude of inflow, reservoir capacity, downstream demand, and reservoir operation. The purpose of the dams also plays a significant role in the impact. We generally see that the RI index was moderately affected at the river outlet across the seven arctic rivers by the dams and their regulatory policies. Also, observing the annual flow for all the seven arctic rivers during data availability, an increasing trend is observed, particularly for the Yenisey, Lena, and Mackenzie with statistically significant levels.

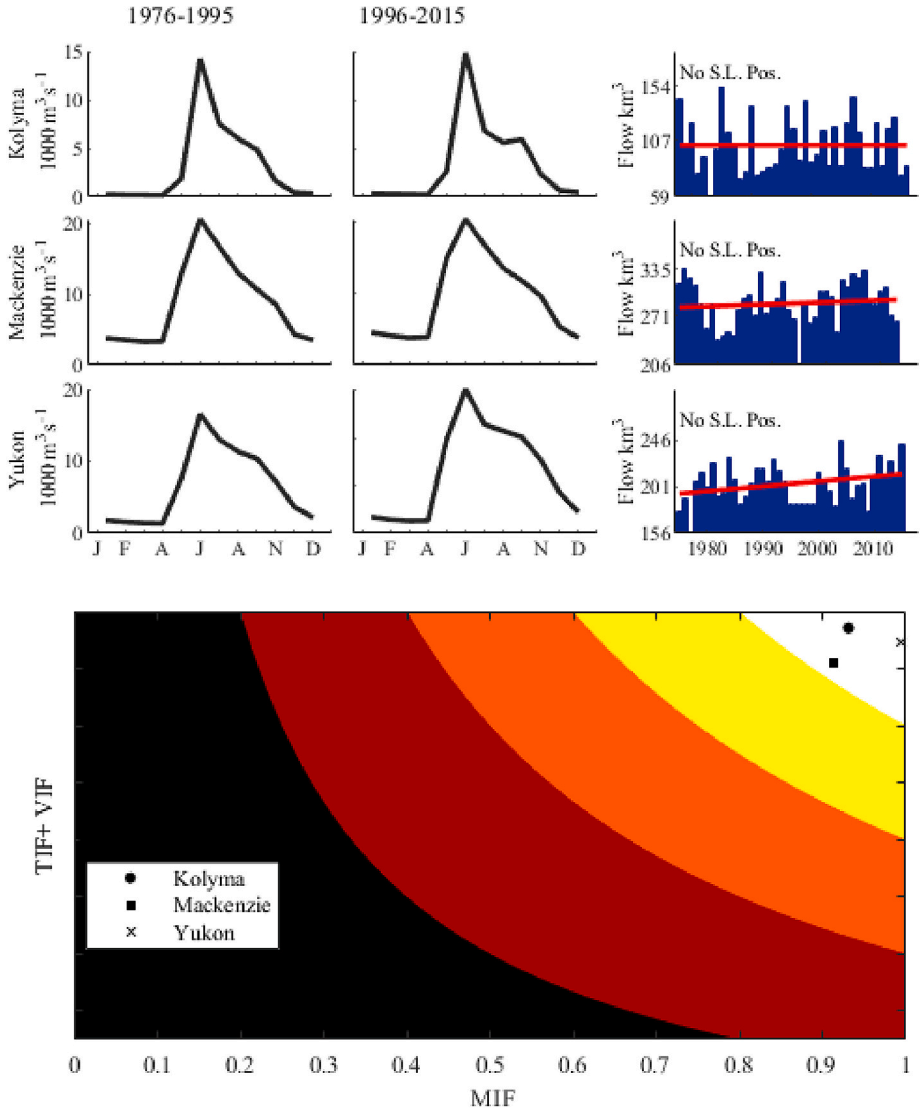

Fig. 5. Monthly flow alteration and river regime impacts in the Kolyma, Mackenzie and Yukon rivers at the river outlet for the Pre-impact period (1976–1995) and Post-impact period (1996–2015). Neg. and Pos. are negative and positive trends. No S.L. and S.L. are not statistically significant and statistically significant.

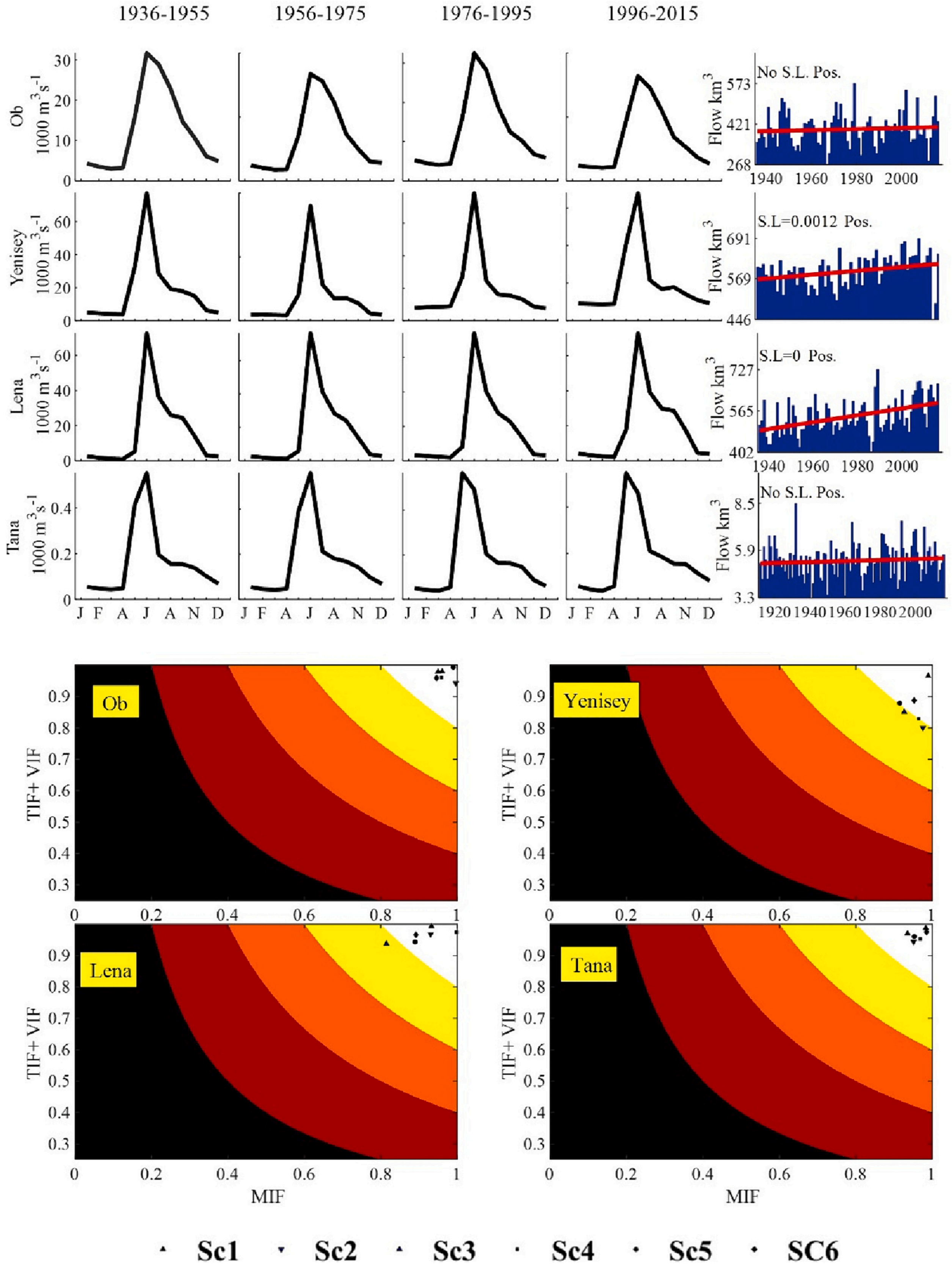

Fig. 6. Monthly flow alteration and river regime impacts in the Ob, Yenisey, Lena, and Tana rivers at the river outlet for the Pre-impact period(1936–1955) and Post-impact periods(1956–1975, 1976–1995, 1996–2015). Neg. and Pos. are negative and positive trends. No S.L. and S.L. are not statistically significant and statistically significant. The RI index is calculated for different scenarios (Sc) which refers to combination of different pre-impact and post impact periods as described in Table 4.

Table 4
River impact index for the Ob, Yenisey, Lena, and Tana rivers in the different post-impact periods (1956–1975, 1976–1995, 1996–2015) for the different pre-impact periods. RI = river impact.

Impact periods			RI index			
Scenario	Pre	Post	Ob	Yenisey	Lena	Tana
Sc1	1936–1955	1956–1975	0.94	0.96	0.93	0.97
Sc2	1936–1955	1976–1995	0.94	0.78	0.90	0.90
Sc3	1936–1955	1996–2015	0.93	0.79	0.76	0.91
Sc4	1956–1975	1976–1995	0.92	0.80	0.97	0.92
Sc5	1956–1975	1996–2015	0.98	0.80	0.84	0.92
Sc6	1976–1995	1996–2015	0.91	0.85	0.86	0.96

4.2.2. *Impact of dams on the flow regime*

Based on the dam construction and operating years for the dams considered in this work shown in Table 2, the pre-and post-impact period was selected. The monthly flow regime alteration due to the operation of such dams was evaluated in Fig. 7 based on the observed discharge obtained from the gauging station located below the dams. Evaluating the impact of 16 dams on the flow regime in the headwaters and river tributaries, the Kolyma hydropower shows the lowest impact (Low impact). The Shushenskaya Dam on Yenisey shows the highest impact (Severe Impact class). The RI index can quantify the effect of different dams on flow; generally, the single-purpose dams built either for flood control or irrigation or navigation or hydropower have negligible impact on flow magnitude. This can be observed in Fig. 7 for dams located on the Kolyma, Lena, and Mackenzie rivers. Since the dams Vilyui (Lena river), WAC Bennett (Mackenzie), and Kolyma (Kolyma river) have an incipient impact on the flow. At the same time, the other dams considered in this work have moderate impacts (0.4 < RI < 0.6), showing the effect of damming on the annual hydrograph. Since most of the dams considered in this work are multi-purpose, the seasonal water usage pattern changes completely, as seen in Fig. 7. Dams used for irrigation store water for usage in dry months, while the ones used for hydropower utilize the stored water as per the electricity demand. There are indirect effects on the downstream ecology and geomorphology, for which the RI index can help us understand the sensitivity of these changes.

4.3. *Discussion*

Climate change affects the timing and magnitude of rivers' flow, essential to ocean circulation, salinity, and sea ice dynamics (Peterson et al., 2002). Global warming and average temperatures in the Arctic region have been increasing more than twice as fast as the rest of the world for the past 50 years (Corell, 2006). The river flow regime determines the biotic composition, structure, and function of an aquatic, wetland, and riparian (Ashraf et al., 2016; Patro et al., 2018; Poff et al., 2010; Watts et al., 2011). The flow regime alteration of a river is the leading cause for impacts in the river ecosystem, which in turn affects the river's ability to support human demands. Reservoir regulation can increase winter low flows and reduces summer high flows in the arctic rivers (Liu et al., 2022; Rawlins et al., 2020; Shrestha et al., 2020). In general, alteration in river flow regime mostly affect river ecosystems and therefore compromises the sustainability of the river to support the organisms that depend on it for survival and existence (Stewart-Koster et al., 2023; Thompson et al., 2021). Global studies have reported that hydrological characteristics of rivers and the risk of ecological changes vary spatially, with regions like South America, Australia and southern Africa with most at risk whereas Boreal regions are least likely to see significant change (Chalise et al., 2023; Krabbenhoft et al., 2022; Thompson et al., 2021). Several authors have reported that climate change, human activities such as the construction of large reservoirs, inter-basin water transfer, water abstraction for urban, industrial and agricultural purposes could change river flow regime in space and time (Bonato et al., 2019; Cherry et al., 2017; Dankers, 2002; Liu et al., 2022; Pollard, 2005; Rasouli et al., 2020; Vörösmarty et al., 1997; Yang et al., 2004b; Yang and Kane, 2021). Anthropogenic interferences (land use/land cover change, river modification) along with climate change, can alter major characteristics of flow regimes for example as shown for

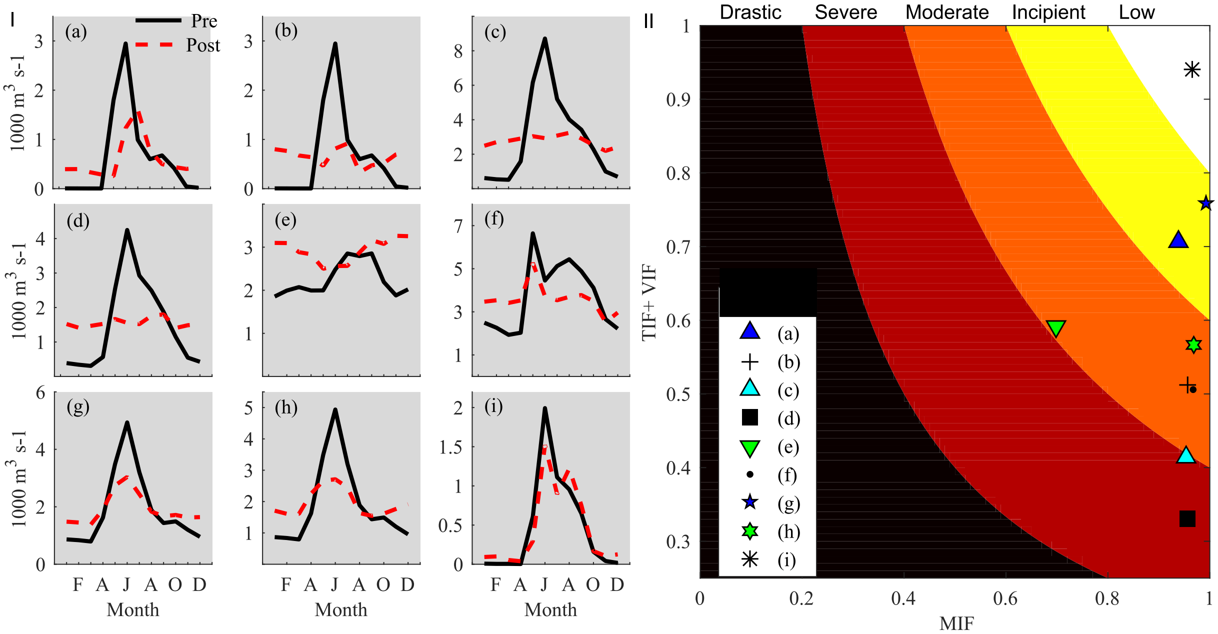

Fig. 7. Monthly flow alteration and river regime impacts at the major dams considered. The flow regime in the pre-impact period is shown in black, while the post-impact period is shown in red. a): Vilyuy HPP on Vilyuy (Lena) Before1968 & (1967–1980), (b): Vilyuy on Vilyuy (Lena) Before1968 & (1979–1995), (c): Krasnoyarsk Dam on Yenisey at Bazaikha Before1970 & (1970–2000), (d): Shushenskaya Dam on Yenisey Before1989 & (1990–2000), (e): Bratsk HPP on Angara (Yenisey) Before1968 & (1969–1990), (f): Below Bratsk and Ust-ilim dam on Angara at Boguchany (Yenisey) Before1956 & (1974–2010), (g): WAC Bennett on Peace (Mackenzie) Before1969 & (1968–1981), (h): WAC Bennett on Peace (Mackenzie) Before1969 & (1981–2010), (i): Kolyma HPP on Kolyma Before1982 & (1981–2000). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

European rivers (Schneider et al., 2013), Ceyhan river basin case in Turkey (Torabi Haghighi et al., 2021), Mediterranean rivers (Sadaoui et al., 2018), Lake Urmia basin (Fazel et al., 2017), Tigris River in Iraq (Torabi Haghighi et al., 2023), Mississippi River basin (Mohammed and Hansen, 2024), Yangtze River basin (Guo et al., 2022; Liu et al., 2024) etc. among others. Based on IHA analysis on the Upper Mississippi River basin low flow conditions have been increasing whereas baseflow has only been increasing in approximately half of the watershed indicating that at watershed scale land use may have a stronger influence than climate (Mohammed and Hansen, 2024). A RVA of 80.26% i.e. significantly alteration in the hydrological regime was reported for the Liujiaping River in Hunan Province, China after the construction of the dam (Fang et al., 2023). The influence of Aslantas, Menzelet and Sir dam on the mid basin of Ceyhan river was severe with the RI value 0.29, whereas RI value at the end of the highly regulated Euphrates river to the immediate east of the Ceyhan basin is below 0.20 i.e. drastic impact (Torabi Haghighi et al., 2021; Torabi Haghighi et al., 2020). The effect of human interventions on rivers, for example, dam operations and water withdrawals are very case study-specific which showcases fragility and spatial heterogeneity of the risks and in some situations could provide solution (modifying river regulation and operation rules) to mitigate the impacts of climate change posed to river ecosystems.

In this work even though the monthly regime alteration due to climate change and dams was not substantial, the study of regime change is important to understand the gravity of the situation at delta/coastal areas. Dams and increasing water abstraction together with climate change will worsen the effect. The study results will provide a baseline for further research to explore the relationship between the river and its ecosystem with the hydrological variation during the pre-and-post river impoundment period. In terms of regulated and unregulated (pristine) rivers, for the regulated arctic rivers, the impact on the natural flow regime from operating large reservoirs can be traced far downstream of the river at the outlet. In this work, the Tana River is completely unregulated, while Yukon is semi-pristine. Total flow alteration (average DHA of 38% for all the 33 IHA parameters) in the pristine Tornionjoki can be almost wholly attributed to climate change and climate variability. A higher daily low flow pattern, particularly in winters, was observed for the regulated Arctic rivers. The extent of the impact on the flow regime at the river outlet was significantly weakened due to the cascading effect of the dams. Even though the reservoirs are located several thousand kilometers upstream of the river outlet, the water level regime is also strongly altered and the impact on the flow regime (Gibson et al., 2006; Peters et al., 2006). The flow in the Arctic rivers is naturally derived from sporadic rainfall, snowmelt in spring, and the melting of ground-ice, snowbanks, and glaciers. Therefore, the river flow was highly seasonal, with a well-defined peak flow due to snowmelt at the beginning of summer. Hence, the findings of this study align with the findings documented in the past. An increase of +7% in mean annual discharge for seven Eurasian arctic rivers was observed from 1369 to 1999 (Peterson et al., 2002). A similar trend was also predicted from some arctic rivers using GCMs (Kattsov et al., 2007; Shiklomanov and Shiklomanov, 2003). The changes observed in this work for the flow in the snowmelt season are in line with the increase in Eurasia river flow as observed by (Troy et al., 2012). The impact of most of the dams considered in this work was relatively small compared to the increase in flow in recent decades. However, it is important to carefully view the changes in flow regime due to the dams since the warming climate proves to have a strong influence on the winter flow regime. One of the reasons for observed alteration in river regime, particularly in the winter season, could be a higher rate of permafrost thawing as observed in various literature (Jacques and Sauchyn, 2009; Walvoord and Striegl, 2007).

A warming climate could also influence the open-water and ice-influence period combined with the decline in snow accumulation which could heavily influence the duration and magnitude of hydrological extremes and events. The winter flow regime of Arctic rivers is strongly dependent on the river ice conditions (Smith et al., 2007). In recent decades anticipation in the river freezing and break-up by up to three weeks has been observed (Lique et al., 2016). These trends are worrisome, which gets further complicated with changes in snow accumulation and snowmelt patterns. The river ice phenology is a complex phenomenon that is not only influenced by flow rates, air and water temperature, snow thickness, and hydraulic conditions of the river but also on the river ice thickness, timing, seasonality and its strength (Beltaos and Prowse, 2009; Das et al., 2015). Due to the lack of long-term observations for river ice formation, the relationship of various variables is not well understood.

5. Conclusion

Arctic climate change is progressing faster than the global average; hence further research is needed to determine possible changes in the seasonal runoff characteristics of Arctic River systems that feed the Arctic Ocean. In this study, a framework for assessing the impact of dam on arctic rivers was carried out by analyzing the daily and monthly flow regime alterations. Analysis of discharge for the seven main largest Arctic-draining rivers indicates that the combined annual discharge from these rivers has increased. This apparent increase in freshwater volume contribution from 2000 onwards may be attributable to accelerated high latitude warming in recent decades. Compared to other seasons, fall exhibited the greatest increase. This may be a result of delayed river ice freeze-up dates or increased late-summer and autumn precipitation. A distinct shift toward earlier melt timing was also indicated by a strong decrease in proportional summer discharge along with a corresponding increase in spring discharge. The seven arctic river discharges studied are not uniform, indicating increased discharges from Eurasian basins and decreased/increased discharges from North American basins. The seasonality associated with each basin flow regime was also investigated. These objectives were achieved by analyzing daily discharge data over the entire available length of record for each river, ranging from 40 to 90 years during 1936–2017. In combination with lower peak magnitudes, longer peak durations, and lower summer proportions, increasing winter and fall discharge proportions suggest a flatter and steadier annual hydrograph with earlier anticipation of peaks. While this obvious shift in seasonality may have significant implications for the Arctic water cycle, it is still unclear how much of this transition is due to regulations by the dam and how much is due to climatic changes. Reduced autumn peak flows could reduce sediment transport, in turn affecting the local aquatic ecosystem. A rise in the winter flow means an increase in the magnitude of low flows, resulting in unfavorable conditions for some aquatic animals' migration and spawning, which can worsen if the annual minimum flow occurs sooner.

Despite the recent window of observation used for the combined flow, many basins have had some flow control in place for prolonged periods. Most large-scale estimates of climate change impacts on flow regimes ignore actual reservoir alterations and are simulated with constant outflows. There is a great need for sharing reservoir regulation information to better understand the water security in the arctic regions. Although the dams in the studied river basins play an important role in the region's economy, future water politics and policies can cause a slew of issues and have a detrimental effect on the river's flow regime.

CRediT authorship contribution statement

Epari Ritesh Patro: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Sahand Ghadimi:** Writing – review & editing, Resources. **Abolfazl Jalali Shahrood:** Writing – review & editing, Visualization. **Nasim Fazel:** Writing – review & editing, Writing – original draft, Visualization, Supervision. **Olga Makarieva:** Writing – review & editing, Supervision, Data curation. **Ali Torabi Haghighi:** Writing – original draft, Visualization, Validation, Supervision, Project

administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloplacha.2024.104442.

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