Chapter 9
River Discharge

Tetsuya Hiyama, Shigemi Hatta, and Hotaek Park

9.1 Introduction

The Arctic Ocean is an important water body that is affected by and has an effect on global climate via changes in its energy and water cycles. It is surrounded by the continents of North America and Eurasia that provide a supply of fluvial freshwater. The pan-Arctic river discharge, which is main topic of this chapter, annually contributes about twice the amount of freshwater as net precipitation (precipitation minus evaporation) over the ocean (Haine et al. 2015), and it acts as a conveyor of substantial quantities of nutrients, carbon, and other elements from its diverse watersheds (Bring et al. 2016). River discharge from the pan-Arctic watershed (or pan-Arctic drainage basin) also influences the salinity and water temperature of the Arctic Ocean, the effects of which can extend to the mid-latitudes constituting a feedback system of the global climate (Prowse et al. 2015a, b). Peterson et al. (2006) reported that changes in freshwater inputs and ocean storage occur in conjunction with amplification of the North Atlantic Oscillation (NAO) and rising air temperatures. Indeed, the long-term effects on the climate system from changing pan-Arctic river discharge are substantial (Rawlins et al. 2010; Haine et al. 2015). Thus, pan-Arctic watershed discharge is considered one of the clearest indicators of the effects of climate change and current global warming.

Recently, Bring et al. (2016) reviewed the principal freshwater processes of terrestrial Arctic drainage with consideration of their function and variation across seven hydrophysiographical regions (i.e., Arctic tundra, boreal plains, shield,

T. Hiyama (✉)
Institute for Space-Earth Environmental Research (ISEE), Nagoya University, Nagoya, Japan
e-mail: hiyama@nagoya-u.jp

S. Hatta
National Institute of Technology, Tomakomai College, Tomakomai, Japan

H. Park
Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokosuka, Japan

T. Ohta et al. (eds.), *Water-Carbon Dynamics in Eastern Siberia*,
Ecological Studies 236, https://doi.org/10.1007/978-981-13-6317-7_9

Fig. 9.1 Map of the pan-Arctic river basins showing catchments and the annual discharge of the six major Eurasian rivers that contribute water to the Arctic Ocean. (Modified from Peterson et al. 2002)

mountains, grasslands, glaciers/ice caps, and wetlands). Their research emphasized the need for coordinated monitoring, modeling, and processing studies at various scales to improve the understanding of change, particularly at the interfaces between hydrology, the atmosphere, ecology, resources, and oceans. Previously, Peterson et al. (2002) reported that average annual discharge of freshwater from the six largest Eurasian rivers (i.e., the Kolyma, Lena, Yenisei (or Yenisey), Ob (or Ob'), Pechora, and Severnaya Dvina rivers; Fig. 9.1 and Table 9.1) to the Arctic Ocean increased by 7% from 1936 to 1999. Shiklomanov and Lammers (2009) showed that annual discharge from the Eurasian pan-Arctic watershed during 1980–2007 demonstrated an unprecedented increase at a rate of 10 km^3 year^{-1}, i.e., almost five times higher than that documented by Peterson et al. (2002) during the period 1936–1999. They also suggested that significant acceleration of the hydrological cycle in the Eurasian pan-Arctic has occurred over the last three decades.

Of all the rivers that flow into the Arctic Ocean, three Siberian rivers (i.e., the Lena, Yenisei, and Ob rivers) are the largest in terms of freshwater discharge (R) (Oshima et al. 2015). Studies on the atmospheric and terrestrial water cycles of these major Siberian rivers have been conducted previously (e.g., Fukutomi et al. 2003; Serreze et al. 2003). Based on a decomposition analysis of atmospheric

Table 9.1 Drainage area and annual discharge data of the six Eurasian rivers indicated in Fig. 9.1 and those of the Mackenzie River in North America

River	Station	Drainage area (km^2)	Discharge (km^3 $year^{-1}$)
Kolyma	Kolymskoye	526,000	102.6
Lena	Kusur	2,430,000	528.5
Yenisei (Yenisey)	Igarka	2,440,000	580.1
Ob (Ob')	Salekhard	2,950,000	394.0
Pechora	Oksino	312,000	138.1
Severnaya Dvina	Ust'Pinega	348,000	105.0
Mackenzie	Norman Wells	1,570,000	266.3

Note that values of annual discharge are slightly different from those indicated in Fig. 9.1 because of the different averaging years (durations)

moisture flux, Oshima et al. (2015) revealed that moisture transport associated with cyclone activity dominates the climatological features of precipitation minus evapotranspiration (P − ET) over the Lena River, whereas moisture transport associated with seasonal mean winds dominates the P − ET features over the Ob River. Conversely, both transport processes have an effect over the Yenisei River (see also Chap. 2). Oshima et al. (2015) also analyzed the R and the P − ET estimated from six atmospheric reanalysis data sets. Although previous studies (e.g., Serreze et al. 2003, 2006) have shown considerable deviations in the variations of P − ET and R, Oshima et al. (2015) found that interannual variations agreed very well with each other when appropriate seasonal time lags were taken into account. Suzuki et al. (2016) found that soil water conditions during the previous fall and winter affect the Lena River runoff and that the time lag between P − ET and R could be attributed partly to snowmelt infiltration into the frozen ground. This means that the terrestrial water storage (TWS) of the Lena River basin in fall is important regarding its discharge the following year.

The Lena River basin in eastern Siberia is one of the largest pan-Arctic river basins of the Eurasian continent (Fig. 9.1 and Table 9.1), contributing about 15% of the total freshwater inflow into the Arctic Ocean (Aagaard and Carmack 1989; Bamber et al. 2012). Yang et al. (2002) used hydrometeorological data (i.e., air temperature, precipitation, flow rate, river ice thickness, and active layer thickness) from the Lena River basin, acquired during 1935–1999, to address the trends of increasing wintertime runoff and increasing early snowmelt. They also claimed that changes in the hydrological processes of the Lena River basin are closely associated with the state of frozen ground (i.e., permafrost), which is affected considerably by climate warming in eastern Siberia. In this context, Brutsaert and Hiyama (2012) proposed methods to relate low river flows (or base flows) of the Lena River during the open water season to the rate of change of the active groundwater layer thickness resulting from permafrost thawing at the scale of the upstream river basin. They suggested that during 1950–2008, the active layer thickness increased at average rates of approximately 0.3–1.0 cm $year^{-1}$ in areas with discontinuous permafrost and at average rates about half as large in colder eastern areas with continuous permafrost.

Warming permafrost changes the hydrological regime, particularly through altered surface and subsurface interactions (Bring et al. 2016). Changes in temperature and precipitation also interact to produce variations in evapotranspiration, runoff, seasonal snow accumulation, and snow season length in permafrost basins. Short-term changes in air temperature, ice cover, and soil moisture do not trigger systematic hydrological shifts in permafrost, although they do provide a "memory" that is manifest during the following warm season, as shown in a recent model–observation study (Park et al. 2013a). Therefore, new research field studies are required to evaluate fully the changing sources, quantity, quality, seasonality, and fate/effect of freshwater in the Arctic regime (Prowse et al. 2015b) and the pan-Arctic watershed, including the Lena River basin.

9.2 Lena River Basin

9.2.1 Geographical Scope

Because the precise geographical features of the Lena River basin have been described in Chap. 1, only those characteristics with importance regarding the drainage basin and the terrestrial water budget are discussed in what follows.

The drainage area of the Lena River basin is 2,430,000 km^2 (Table 9.1), approximately 79% of which is underlain by continuous permafrost (Ye et al., 2009). The Lena River basin consists of three major subbasins: the "Upper Lena" (UL), "Aldan" (AL), and "Vilui" (VI) (Fig. 9.2 and Table 9.2). The Lena River channel is completely covered by snow and ice from November to April; then, spring flooding occurs in May and June (Bennett and Prowse 2010). Because the Lena River basin is underlain by permafrost and because the water storage capacity is low, base flow (low flow) during the winter season (from late November to early May) is the lowest, and peak flow during spring flooding (from late May to early June) is the highest.

As mentioned in the previous section, the large-scale hydroclimatology of the terrestrial drainage system in the pan-Arctic watershed has been examined previously (e.g., Serreze et al. 2003; Oshima et al. 2015). Water-year time series of river discharge (R) and net precipitation ($P - ET$) in the Lena River basin are correlated strongly (Oshima et al. 2015), reflecting the importance of the extensive permafrost in the basin.

9.2.2 Seasonal Changes in Lena River Discharge

Seasonal changes in Lena River discharge can be divided into the low-flow period (from November to April) and the high-flow period (from May to October). The lowest flow appears in April, and the highest discharge (spring flooding) is in May and June, resulting from the combination of snowmelt water accumulation and ice

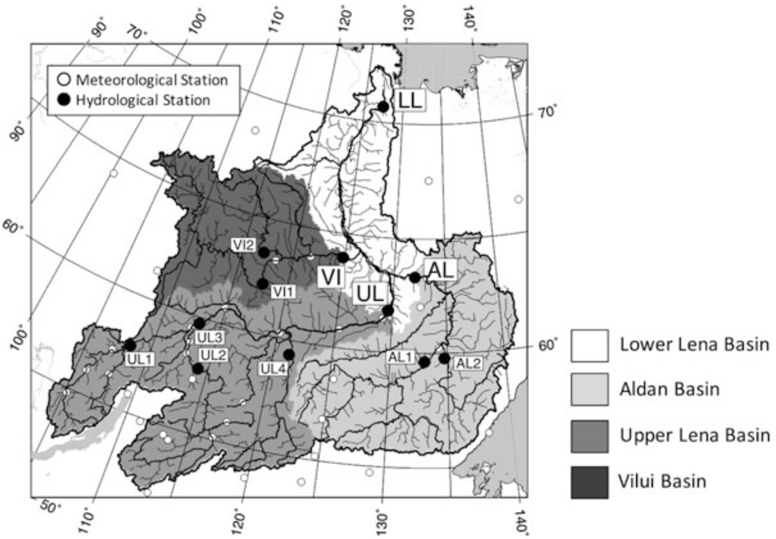

Fig. 9.2 Divisions of the four subbasins of the Lena River, together with locations of hydrological and meteorological stations. Hydrological stations LL, UL, AL, and VI refer to "Lower Lena," "Upper Lena," "Aldan," and "Vilui," respectively

Table 9.2 Station names, drainage areas, and mean annual discharges of the four major subbasins of the Lena River

Station code	Station name	Drainage area ($\times 10^3 km^2$)	Annual discharge ($km^3 year^{-1}$)
LL	Kusur	2430	529
UL	Tabaga	897	221
UL1	Zmeinovo	140	35.4
UL2	Bodaibo	186	49.2
UL3	Krestovski	440	131
UL4	Kudu-Kel	115	32.2
AL	Verhoyanski' Perevoz	696	165
AL1	Ust-Mil	269	86.3
AL2	Chabda	165	36.6
VI	Hatyrik-Homo	452	46.7
VI1	Suntar	202	24.8
VI2	Malyukai	89.6	12.3

Abbreviations are the same as in Fig. 9.2

jam flooding. Figure 9.3 shows the seasonal change in river discharge (i.e., a hydrograph) observed in 1987 at site AL2 (see Fig. 9.2). After the onset of the snowmelt event in the basin, river discharge at site AL2 rose drastically during the middle of May. The highest (annual maximum) flow occurred at the beginning of

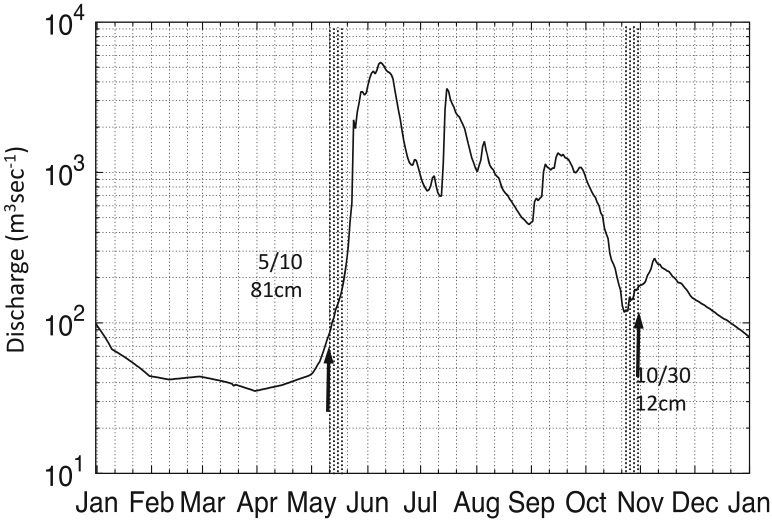

Fig. 9.3 Typical seasonal change in daily river discharge (i.e., hydrograph) observed at site AL2 (Fig. 9.2) in 1987. This hydrograph was reconstructed from the relationship between river discharge and river water level measured at site UL (Fig. 9.2) during 2000–2008. The two arrows in the figure indicate the dates of final (10 May) and first (30 October) appearance of river ice in 1987. River ice thickness on the two dates is also indicated in the figure. Shaded durations are the 10 days after the dates of final disappearance (10 May) and before first appearance (30 October) of river ice

June. Thereafter, several peaks in river flow corresponded to precipitation events. A large drop in river discharge occurred at the end of October. This drop was related to the formation of river ice in the late fall following a period without precipitation (rainfall). The two arrows in the figure indicate the dates of final (10 May) and first (30 October) appearance of river ice in 1987. The ice thickness for both dates is also indicated in the figure. It should be noted that river ice observations were available every 10 days. A sudden increase of river discharge (i.e., a steep slope of the hydrograph) can be seen following the date of ice disappearance. Conversely, a dramatic drop of river discharge can be observed just before the date of the first observation of river ice.

Figure 9.4 shows the seasonal changes of daily river discharge in 2000 observed at stations LL, UL, AL, and VI (see Fig. 9.2). In the three subbasins (UL, AL, and VI), intermittent peaks can be seen following the spring high discharge peaks. These were caused by summer precipitation events in the subbasins. Thus, on the subbasin scale, summer river flooding is not negligible (Gautier et al. 2018). However, at site LL (i.e., the lowest measurement station on the Lena River; Fig. 9.2), the spring discharge had a significantly high peak, and there were no further clear peaks during the summer season. This might be related to the relatively small effects of summertime precipitation events on the river discharge of the entire Lena River basin. Additionally, there are inundation effects in summer in the riverine lowlands between the middle (Hiyama and Takakura 2018) and the

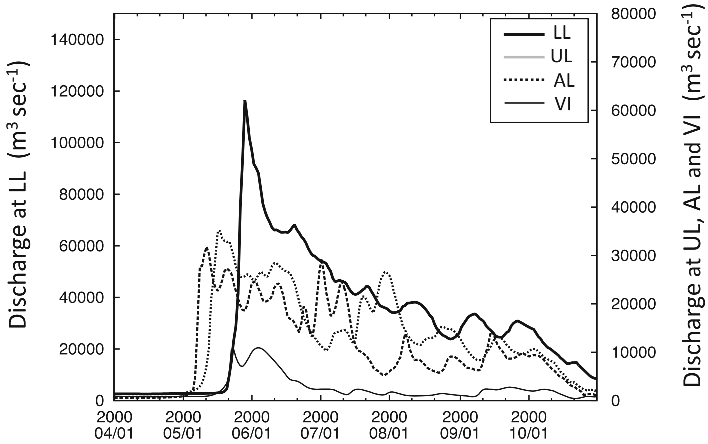

Fig. 9.4 Daily river discharge in 2000 observed at the four hydrological stations (i.e., LL, UL, AL, and VI)

lower reaches of the Lena River. The secondary flood peaks in summer and the inundations of riverine lowlands and/or islands in summer have been increasing in recent years because of the effects of ongoing climate change (Hiyama and Takakura 2018; Gautier et al. 2018).

9.2.3 Long-Term Trend of Lena River Discharge

Long-term records of meteorological–hydrological variables such as air temperature, precipitation, river discharge, river ice thickness, and active layer thickness in Siberian river basins have been previously analyzed intensively (e.g., Yang et al. 2002; Ye et al. 2004; Berezovskaya et al. 2005). Berezovskaya et al. (2004) reported inconsistency in the long-term (1936–1998) changes of basin precipitation and river discharge. For example, they found that Yenisei River runoff increased significantly, while precipitation showed mostly negative trends; the Ob River did not show any significant trend in either precipitation or runoff, and a positive trend in Lena River runoff was accompanied by a weak increase in precipitation. However, it was determined that the precipitation increase in the Lena River basin was not sufficient to support the observed change in runoff. Ye et al. (2003) analyzed long-term (1936–1999) monthly discharge records for the major subbasins within the Lena River basin in order to document significant streamflow hydrology changes induced both by human activities (particularly reservoirs) and by natural variations/changes. They showed that the upper streams of the Lena River basin, relatively free from human impact, experience an increase of runoff in winter, spring, and particularly summer, and a discharge decrease in fall. They also found that reservoir regulation has substantially altered the monthly discharge regimes over the lower reaches of the

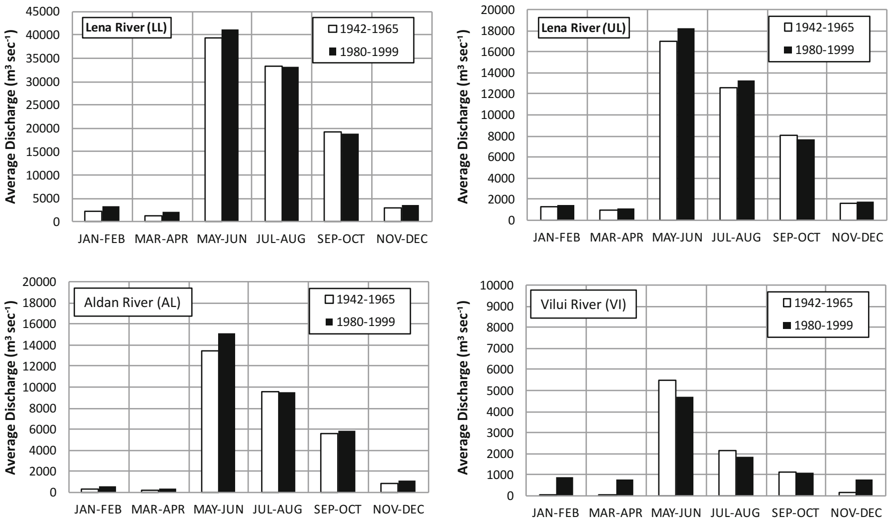

Fig. 9.5 Two-month mean river discharge during 1942–1965 and 1980–1999, as observed at the four hydrological stations (i.e., LL, UL, AL, and VI)

Lena River. Because of a large dam in the west of the Lena River basin (the Vilui subbasin), monthly summertime flows at the Vilui valley outlet (almost 1000 km downstream of the dam) have been reduced by up to 55%, whereas wintertime low flows have increased. Because of the combination and integration of streamflow hydrology changes over the upper and western Lena River basin regions, strong trends of increase (up to 90%) have been observed at the basin outlet during the low-flow (winter) months, and weak trends of increase (<10%) have been found in the high-flow (summer) season. This reservoir regulation affects not only the basin-scale river discharge but also the temperature of the river water (Liu et al. 2005).

Figure 9.5 compares the average discharge every 2 months (January–February, March–April, May–June, July–August, September–October, November–December) observed at LL, UL, AL, and VI (Fig. 9.2) for 1942–1965 and 1980–1999. In order to discard reservoir construction effect on the Vilui discharge, period for 1966–1979 was omitted in the figure. As mentioned above, at the Vilui (VI) River subbasin, discharge in the winter season has increased drastically, while summer discharge has decreased because of the reservoir effect. In contrast, discharge in the Upper Lena (UL) and Aldan (AL) subbasins has increased in both winter and summer. These discharges, which all contribute to the annual flow of the Lena River, as observed at LL, show that the reservoir regulation effect from the Vilui River is relatively small.

Smith et al. (2007) reported rising minimum daily flows in northern Eurasian rivers, and they speculated on the growing influence of groundwater on the high-latitude hydrological cycle. Spring water discharge of mixed water from supra-permafrost and intra-permafrost groundwater (e.g., Hiyama et al. 2013) from taliks (more specifically, perennially unfrozen zones) might contribute to the increase of low river flow.

9.3 Hydrological Modeling for Arctic River Discharge

Observations of meteorological and hydrological variables are less dense in the northern high latitudes, in comparison with lower latitudes, making it difficult to obtain reliable estimates of the water budget components and other surface variables used to assess hydroclimatological variability. Numerical models offer considerable benefits for enlightenment regarding large-scale hydrology in data-sparse regions such as the pan-Arctic watershed. A number of land surface models capable of representing the dynamics of land–atmosphere water and energy exchanges have been developed, and these have been used to evaluate the effects of climate change on hydrological processes at regional to global scales (Slater et al. 2007; Park et al. 2016). The combination of observations and numerical models can capture various aspects of Arctic hydrology and identify those features that contain uncertainties. The Arctic hydrology differs from that of temperate regions in several important ways, primarily related to the unique conditions associated with cold temperatures, which include the dominance of snow cover and spring snowmelt flow, presence of permafrost, and prevalence of lakes and wetlands. In other words, these unique conditions comprise the major elements or characteristics of the Arctic hydrological cycle. Thus, modeling studies have paid attention to parameterization for a wide range of geophysics, particularly with respect to cold processes. Certain models have also been combined with river routing and discharge models in both off-line and coupled modes to simulate channel flows of pan-Arctic rivers (Park et al. 2016).

Coupled hydrological models have been used to explore the spatial and temporal variabilities of pan-Arctic freshwater components. As part of this process, experiments incorporating model comparisons have been conducted to evaluate the capabilities of models to simulate the hydrological processes across the pan-Arctic drainage basin over long time scales. One such representative experiment was the Project for Intercomparison of Land Surface Parameterization Schemes (PILPS) that tested 21 land surface models with respect to their capabilities of representing snow processes, soil freeze/thaw and permafrost, and runoff generation (Bowling et al. 2003). The PILPS intercomparison obtained valuable knowledge regarding the identification of problems in the representations of snow cover, surface runoff, and other physical processes in cold region (Essery and Clark 2003; van den Hurk and Viterbo 2003). Slater et al. (2007) compared the performance of five land surface models with regard to the simulation of pan-Arctic hydrological processes. They found that the models generally simulated the seasonal discharge of large rivers well; however, in comparison with observations, the modeling hydrographs were often out of phase with peak flows that were too high, especially in relation to the Ob and Mackenzie rivers. The overestimations for the Ob and Mackenzie basins have been attributed to the relatively higher snowmelt and runoff inputs in these basins in comparison with other basins (Park et al. 2016). Substantial portions of the Ob (11% of basin area) and Mackenzie (49%) basins are covered by wetlands and lakes that reduce runoff and peak river discharge rates. Therefore, model deficiencies in representing wetland and lake processes could be another possible reason for the overestimation of peak discharges. The Variable Infiltration Capacity (VIC) macro-scale hydrology model, using observed streamflow, snow cover extent, and the dates of lake freeze-up and breakup, has been shown capable of simulating the observed spring peak discharge of the two basins (Su et al. 2005).

Generally, a hydrological model consists of three submodels: a one-dimensional land surface model (LSM), river routing (runoff) model, and river ice model. Several LSMs are reviewed in Chap. 12. Thus, this section focuses only on the modeling of river runoff and river ice processes.

9.3.1 River Runoff Modeling

Ma et al. (2000) developed a distributed hydrological model for application to the river runoff of the Lena River basin. Subsequently, Ma and Fukushima (2002) combined a land surface model with a hydrological model that included river ice processes, demonstrating that it is possible to reproduce daily hydrographs. This pioneering study was important because their modeling showed that the incorporation of the effects of river ice processes enables reconstruction of daily hydrographs for rivers of the pan-Arctic drainage basin, even when observational data are insufficient. Hatta et al. (2009) developed another distributed hydrological model (see Fig. 9.6) for the Lena River basin, capable of estimating daily runoff over long periods (from 1987 to 2003). They showed that daily minimum flows (low flows or base flows) and river ice during winter have considerable effects on the hydrograph.

If contribution of permafrost thaw could be negligible, approximately 60% of the Arctic annual river discharge is attributable to snow-induced water, and the remainder is derived from summer precipitation. Examples of the distributions of net precipitation (P − ET) and thus river discharge (R) during the snowmelt season (end of April to end of May), calculated using the land surface model of Hatta et al. (2009), are shown in Fig. 9.7. Because most of the summer precipitation is accounted for in evapotranspiration (Park et al. 2008), the contribution of summer precipitation to river discharge is relatively low. A considerable proportion of summer discharge is generated from southern mountainous regions (Hatta et al. 2009) where the amount of precipitation is comparatively large. However, the existent meteorological data sets indicate low bias in relation to mountainous precipitation, resulting in underestimation of model-derived summer discharge, which is particularly significant for the rivers of Siberia (Slater et al. 2007; Park et al. 2016). Adam and Lettenmaier (2003) produced a bias-corrected global precipitation data set, which was based on separate average calendar monthly catch ratios for rainfall and snowfall rates for each half-degree grid cell, with adjustment of precipitation rates to allow for the effects of orography. Simulations with the VIC model using forcing data of bias-corrected precipitation were found capable of reproducing the seasonal and interannual variations of discharge of the pan-Arctic rivers (Su et al. 2005), highlighting the large precipitation-related uncertainties in simulations of pan-Arctic river discharge. The increase of satellite monitoring has

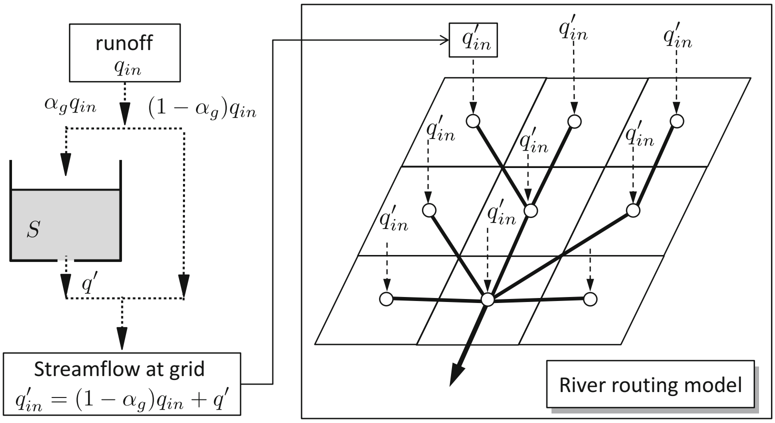

Fig. 9.6 Schematics of tank model (left) and river routing model (right). In the left figure, calculated value of q_{in} (namely, P − ET) from the land surface model is divided into slow groundwater flow component (q') through storage (S) and fast infiltration water component $(1-\alpha_g)\ q_{in}$ in a grid. A parameter α_g is the ratio of the slow groundwater flow component in the target grid. The calculated streamflow q'_{in} in each grid is used in the river routing model of the right figure

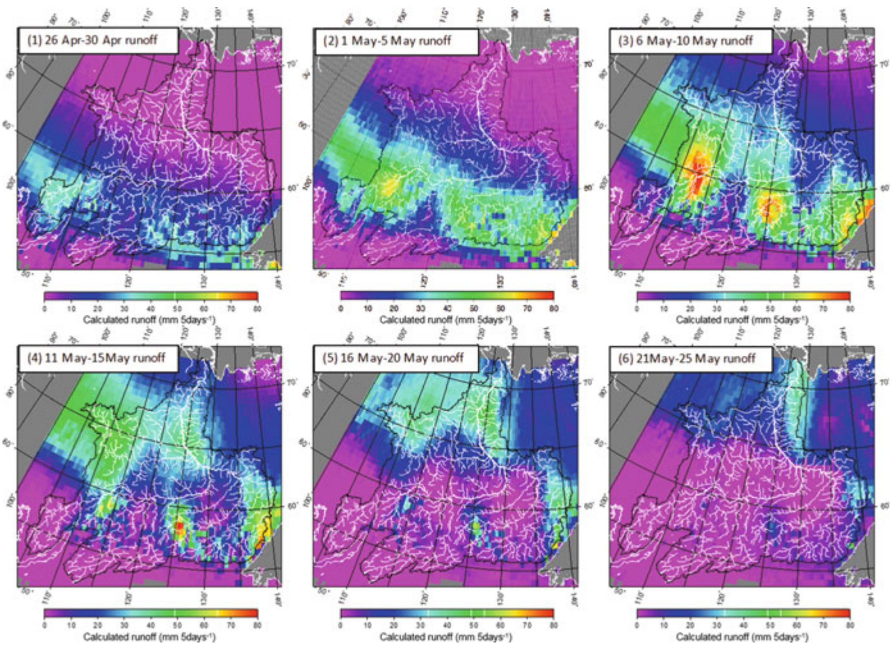

Fig. 9.7 Distributions of river discharge (R) calculated from the land surface model (as mean values of P − ET for the period 1986–2003)

contributed partly to the reduction of such uncertainties; however, satellite observations of the Arctic region have inherent uncertainties related to cloud, snow cover, ice, and permafrost.

In the pan-Arctic watershed, hydrological processes are controlled primarily by the presence or absence of permafrost. Such processes are particularly influenced by both the thickness of the active layer and the total thickness of the underlying permafrost. As permafrost becomes thinner or decreases in areal extent, the interaction between surface runoff and intra-permafrost groundwater becomes more important. The inability of soil moisture to infiltrate to deeper groundwater zones because of ice-rich permafrost could result in very wet surficial soils (White et al. 2007), likely to enhance subsurface runoff and increase discharge. The hydraulic properties of frozen soil have been parameterized as an ice impedance function with a power-law form. A parameter-coupled model simulated significantly higher moisture contents in near-surface soils in permafrost regions, particularly during spring, which brought considerable improvements in comparison with observed hydrographs of large Siberian rivers (Swenson et al. 2012). However, Brutsaert and Hiyama (2012) found that a warming temperature-induced deeper active layer was related positively to increased base flows in areas with discontinuous permafrost in the upper reaches of the Lena River. Similarly, based on observational data from the Lena River basin during 1925–2013, Tananaev et al. (2016) identified that increases in daily minimum flows in the headwaters of the basin were underlain by discontinuous permafrost. An evident fact supported by these results is that warming permafrost contributes to the increase of pan-Arctic river discharge. However, existent models have a consistent problem in representing the presence and physical properties of ground ice within permafrost. Consequently, models cannot account for the mechanism by which warming permafrost-induced water contributes to increasing discharge. One possible way to reduce this deficiency might be to incorporate an isotope process into the model, because it offers the potential for both quantitative assessment and source analysis of the discharge water.

9.3.2 River Ice Modeling

River ice is a major component of the terrestrial cryosphere, and it plays an important role in affecting a range of geophysical systems, e.g., extreme events (or floods) induced by river ice breakup (Bennett and Prowse 2010; Beltaos 2008). However, its entire geographic coverage has not been documented fully. On the continental scale, Bennett and Prowse (2010) analyzed the spatial extent of river networks relative to the location of three 0 °C isotherm periods, recognizing that both the freeze-up and the breakup of river ice are associated closely with the timing of 0 °C air temperatures. On the local scale, Sakai et al. (2015) examined the use of Landsat Thematic Mapper/Enhanced Thematic Mapper Plus (TM/ETM+) imagery to monitor the spatial and temporal extents of spring breakup floods on the Lena River. They suggested that images from Landsat TM/ETM+ sensors could be regarded as data suitable for operational use in flood monitoring of the pan-Arctic rivers, because of their wide geographic coverage, high temporal resolution, and adequate spatial resolution.

As mentioned above, pan-Arctic rivers have distinctive seasonal phenology (freezing in fall and breaking in spring). This seasonality affects seasonal river discharge, with several small rises of water level in the fall and the large spring flood pulse. Runoff induced by river ice breakup has an effect on the timing of peak discharge at a river outlet in spring. Most models that do not include the ice effect tend to produce peaks in simulated hydrographs that are too early relative to observations (Slater et al. 2007). However, some models that do incorporate a river ice scheme can generate adequate simulations for spring peak discharges in various rivers (Ma and Fukushima 2002; Hatta et al. 2009; Park et al. 2016).

The accumulation and melting of river ice can be estimated based on the use of freezing and thawing indices with units of degree days. In order to determine river ice thickness, we can use Stefan's equation, as follows:

$$I_c = \kappa\sqrt{D_f}, \tag{9.1}$$

where I_c is the river ice thickness (cm), D_f is the freezing index (°C day) since the formation of the river ice cover, and κ is a coefficient (cm (°C day)$^{-1/2}$). Theoretically, coefficient κ is 3.48, but it is known that for river ice covered by snow, the appropriate range of values of κ is 1.4–1.7 (Beltaos 1995).

The melting of river ice involves complexities such as thermal and mechanical factors, and it is difficult to account for all these factors in runoff modeling. Using meteorological data, Hatta et al. (2009) set a statistical threshold value for the thawing index based on the maximum river ice thickness. The threshold value for the ice breakup date is given by the following equation:

$$I_{\mathrm{cmax}} = \frac{\sqrt{D_{\mathrm{m0}}}}{\gamma}, \tag{9.2}$$

where I_{cmax} is the maximum ice thickness (cm), D_{m0} is the thawing index on the ice breakup date (°C day), and γ is a coefficient. Hatta et al. (2009) used the mean observed value as γ = 0.037. Because the ice breakup date calculated using Eq. (9.2) does not mean the date when river ice has completely disappeared from the river's surface, Hatta et al. (2009) expressed the gradual decrease of the thickness of river ice (I_c) from the ice breakup date using the following equation:

$$I_c = I_0 e^{-\zeta t_{\mathrm{day}}} \tag{9.3}$$

where I_0 is the ice thickness on the ice breakup date (cm), t_{day} is the number of days after ice breakup (day), and ζ is a coefficient. Because of the lack of a physical method to determine the value of coefficient ζ, it can only be estimated by trial and error based on observed river discharge data.

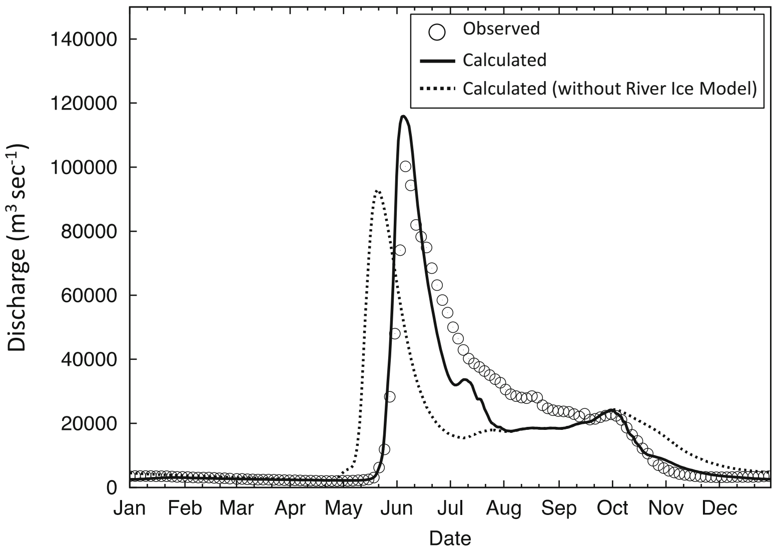

Fig. 9.8 Observed and calculated river discharges of the Lena River (as mean values during 1986–2003). Calculated discharge values were based on simulations with and without river ice modeling

Based on the above methodology, a model experiment (Hatta et al. 2009) was performed that assessed quantitatively that the peak spring discharge simulated by a model that could account for river ice was about 10 days later than a baseline simulation using a model that excluded the impact of river ice (see Fig. 9.8). Similar results were reproduced by a hydrological model for the larger rivers of the pan-Arctic watershed (Park et al. 2016). Frozen river ice grows during winter depending on atmospheric heat fluxes. The winter ice growth reduces river water storage, resulting in reduced low flows in winter. Capturing the correct low flow for pan-Arctic rivers is an ongoing problem for discharge models (Slater et al. 2007). Hatta et al. (2009) emphasized that a greater contribution of permafrost-induced slow groundwater to the winter low flow could account for 30% of the annual discharge.

9.3.3 Future Projections

Historically, observations have generally indicated that the discharge of many pan-Arctic rivers has increased (Peterson et al. 2006). However, a trend of decrease has been observed in some North American rivers during the previous few decades, partly due to flow regulation and storage for enhanced hydropower production (Déry et al. 2005, 2016). Thus, the overall increase during the most recent decade has been significant although it may be associated with climate variability (such as the Arctic

Oscillation). For example, the increase in discharge from all observed rivers draining into the Arctic Ocean during 2000–2010 was 300 km^3 greater than during 1980–2000 (Haine et al. 2015). Global climate models have projected that discharges will generally continue to increase over much of the pan-Arctic watershed (Holland et al. 2007). Simulations with hydrological models that adopt inputs from climate models have also shown increased discharges of the order of 10%–50% for most pan-Arctic rivers (Walsh et al. 2005; van Vliet et al. 2013), although regional decreases have been identified in southern interior regions of the pan-Arctic watershed (van Vliet et al. 2013).

Model projections considered atmospheric and oceanic dynamics have provided quantitative values of the changes in discharge of pan-Arctic rivers under future climatic conditions. To understand these changes, address them adequately, and plan for adaptation; however, there is need for more detailed projections and better information regarding uncertainties. In response to these needs, Bring et al. (2017) estimated projected multimodel and multiscenario changes in annual river discharge for 2061–2090 and compared them with model-simulated historical values during 1961–1990. The analyzed results are displayed in Fig. 9.9. It can be seen that significant increases in the projected discharges are concentrated in Siberia, Alaska, and Northern Canada. For regions across Central Canada and both western and central Siberia, the projections indicate significant change, but they disagree on the sign of that change (Fig. 9.9). This finding suggests that existing stations across these regions could form a prioritized set in the monitoring network. Interestingly, the regions where projected changes are significant are consistent with the areas of highest projected increase in snow (Brown and Mote 2009). This highlights the impact of snow associated with increasing precipitation on river discharge in the future. For example, northern Siberia is predicted to experience increasing snow depth under current projections of a warming climate. Park et al. (2013b) reported high statistical correlation between increased terrestrial snow and reduced Arctic sea ice. The decline of Arctic sea ice will become increasingly accelerated under future climatic changes. Global climate models have projected increases in Arctic precipitation during the twenty-first century, which peak in late fall and winter, primarily because of intensified local surface evaporation resulting from retreating winter sea ice (Bintanja and Selten 2014). The increase of the winter precipitation signals the future amplified Arctic hydrological cycle as enhancing permafrost and snow implicated fluxes (Rawlins et al. 2010; Bintanja and Selten 2014).

9.4 River Water Chemistry in the Arctic

9.4.1 Importance of River Water Chemistry in the Arctic

River discharge and the water chemistry (geochemical qualities, geochemical fingerprints) of freshwater influence the physical, chemical, and biological processes of the Arctic Ocean, including stratification and vertical mixing, ocean heat flux,

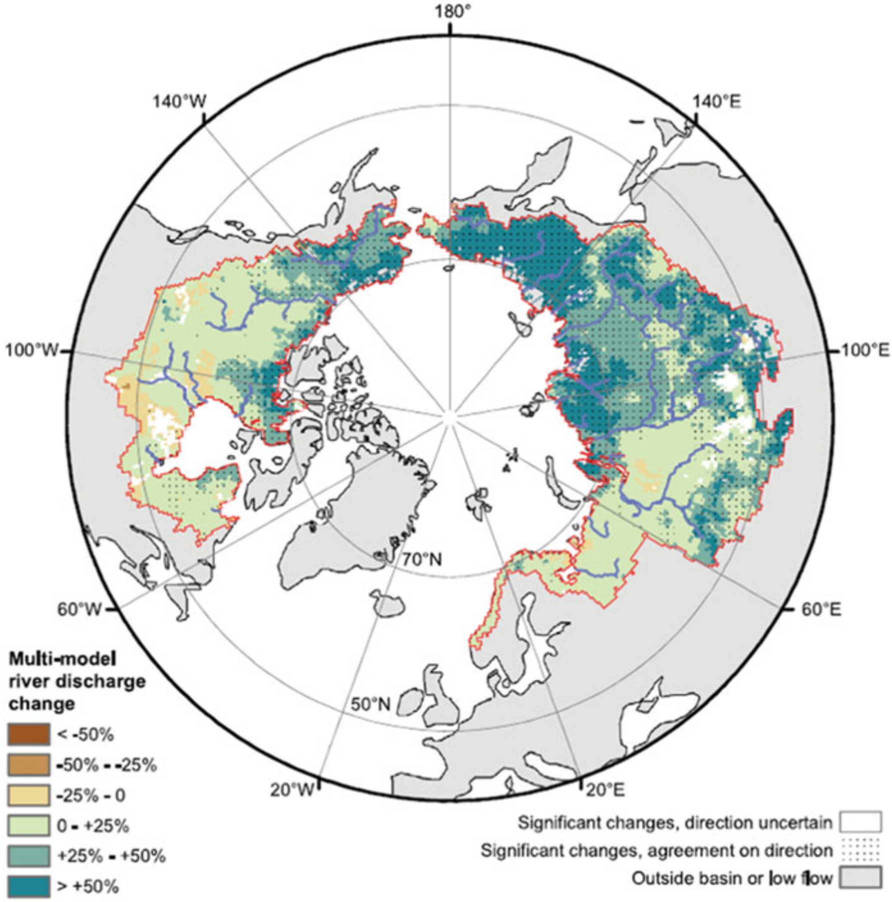

Fig. 9.9 Changes to Arctic river flows. The map shows projected changes in average discharge across the pan-Arctic watershed from 1961–1990 to 2061–2090. White areas, indicating agreement on significant changes but disagreement on sign, show where model agreement (i.e., at least half of the models indicate significant changes ($p < 0.05$) using a two-tailed t-test) is fulfilled. Stippled areas show where model agreement (i.e., as above, and where 80% of the models that show significant change also agree on the sign of change) is fulfilled. Areas that are neither white nor stippled indicate changes with nonsignificant changes. Areas inside the red border on the map but shown in gray are masked because of low average flows (<1 $m^3 s^{-1}$). (Bring et al. 2017)

nutrient supply, primary production, ocean acidification, and biogeochemical cycling. Long-term monitoring of both water discharge and water chemistry in rivers is thus essential for identifying and understanding changes in the Arctic. Important geochemical fingerprints of the Arctic Ocean are dissolved organic carbon (DOC), dissolved inorganic carbon (DIC), dissolved organic nitrogen (DON), dissolved inorganic nitrogen (DIN), and total dissolved phosphorus (TDP), which are known collectively as dissolved organic matter (DOM). Particulate matter such as particulate organic carbon (POC) and particulate nitrogen (PN) are also valuable for investigating the physical, chemical, and biological processes within the Arctic Ocean. It is also interesting to monitor the concentrations and source/composition indicators such as alkalinity, stable water isotopes (HDO and $H_2{}^{18}O$ concentrations, or δD and $\delta^{18}O$ values), nitrate ($NO_3{}^-$), silica (Si), C/N ratio, $\delta^{13}C$, $\Delta^{14}C$, and $\delta^{15}N$ for detecting the permafrost condition and degradation in pan-Arctic river basins.

Frey and McClelland (2009) highlighted linkages between permafrost dynamics and river biogeochemistry in the Arctic, including consideration of the likely impacts that warming-induced changes in permafrost could have on the delivery of organic matter, inorganic nutrients, and major ions to the Arctic Ocean. This is because the Arctic terrestrial freshwater system is likely to undergo transition from a surface water-dominated system to a groundwater-dominated system as the result of permafrost thaw (e.g., Brutsaert and Hiyama 2012). Frey and McClelland (2009) also speculated that there could be important shifts in fluvial transport of organic matter, inorganic nutrients, and major ions, which might in turn have critical implications regarding primary production and carbon cycling in the interior of the Arctic Ocean basin as well as on the shelves. In this context, Carmack et al. (2016) also overviewed the importance of geochemical fingerprints of the Arctic Ocean acquired under the scientific assessment of the Arctic Freshwater Synthesis (AFS) (Prowse et al. 2015a).

9.4.2 Monitoring of River Water Chemistry in the Arctic

In contrast to river discharge data, long-term data sets on river water chemistry in the Arctic are relatively rare, and we do not yet have sufficient information to assess change on a pan-Arctic scale (McClelland et al. 2015). However, the two types of data are not always collected at the same locations, and decisions regarding whether to continue monitoring river discharge and water chemistry are often made independently (McClelland et al. 2015). Thus, parallel sampling programs on the six largest Arctic rivers (i.e., the Ob, Yenisei, Lena, Kolyma, Yukon, and Mackenzie rivers), which began as the Pan-Arctic River Transport of Nutrients, Organic matter, and Suspended Sediments (PARTNERS) project in 2003 and continued as the Arctic Great Rivers Observatory (Arctic-GRO) in 2008, have been established to improve understanding of the biogeochemical fluxes from the pan-Arctic watershed to the Arctic Ocean (McClelland et al. 2015). Scientists from the United States, Canada, and Russia have participated in both the implementation and the management of this program. The PARTNERS/Arctic-GRO effort has captured wide seasonal and geographical variations in water chemistry that relate to watershed characteristics such as geology, vegetation, permafrost coverage, and active layer thickness. These relationships have provided a framework for tracking future changes in watershed characteristics through river water chemistry (McClelland et al. 2008). Key characteristics of the watersheds drained by the PARTNERS/Arctic-GRO rivers, including catchment area, permafrost coverage, and human population density, have been provided in Holmes et al. (2012). The river chemistry data set includes approximately 50 parameters, and 24 of these parameters were shown in Fig. 1 of McClelland et al. (2008).

The study by Holmes et al. (2012) was the first attempt to focus on the seasonal and annual fluxes of total dissolved nitrogen (TDN), DON, DIN, NO_3^-, TDP, Si, and DOC of the six largest Arctic rivers mentioned above. Tank et al. (2012) examined the magnitudes of riverine DIC fluxes of these same Arctic rivers, and they showed that DIC concentration had considerable and synchronous seasonal variation across the six largest Arctic rivers, estimating the annual DIC flux to be 30 Tg C year^{-1}. They also showed that chemical weathering was dominated by inputs from carbonate rocks in the North American (Yukon and Mackenzie) watersheds, but silicate rocks had a more important role in Siberian (Yenisei and Kolyma) watersheds. Very interestingly, in the coastal ocean, river water-induced decreases in aragonite saturation (i.e., an ocean acidification effect) appeared much more pronounced in the Siberian Arctic than in the North American Arctic and stronger in winter and spring than in the late summer.

Concentrations of uranium, barium, calcium, sulfate, and total alkalinity were much higher in the North American rivers compared with the Eurasian rivers (McClelland et al. 2008). In contrast, the seasonal patterns in chemistry were remarkably similar among the rivers. This seasonality is linked closely to hydrographic variations in all of the rivers. For example, DOC, POC, and PN showed positive correlations with discharge (McClelland et al. 2016), whereas major cations, anions, and DIC had negative correlations (Tank et al. 2012). Interestingly, annual POC yields and exports were consistently smaller than annual DOC yields and exports for the major rivers (see McClelland et al. 2016); however, PN export was found roughly equal to dissolved nitrogen (DN) export. They also found that the seasonal patterns in concentrations and source/composition indicators (C/N ratio, $\delta^{13}C$, $\Delta^{14}C$, and $\delta^{15}N$) were broadly similar among the rivers but with distinct regional differences.

In conjunction with the $\Delta^{14}C$-age of C ($\Delta^{14}C$-DOC and $\Delta^{14}C$-POC), Raymond et al. (2007) first determined the export and $\Delta^{14}C$-age of DOC for the Ob, Yenisei, Lena, Mackenzie, and Yukon rivers for 2004–2005. The total annual DOC flux from these five large rivers was estimated to be around 16 Tg C year^{-1}, and the total annual input of DOC from the pan-Arctic watershed to the Arctic Ocean was estimated as 25–36 Tg C year^{-1}. These fluxes were 2.5 times greater than temperate rivers with similar watershed sizes and water discharges. Based on $\Delta^{14}C$-age estimations, they also predicted that around 50% of DOC exported during the spring thaw was 1–5 years old, 25% was 6–10 years in age, and 15% was 11–20 years old. This implies that a small pool of DOC slightly depleted in $\Delta^{14}C$ is exported with the base flow but the large pool exported with the spring thaw is enriched in $\Delta^{14}C$ (Fig. 9.10). It is interesting to see in Fig. 9.10 that depleted (older) $\Delta^{14}C$-DOC is exported with the base flow in the Ob and Yukon rivers. Conversely, the younger bulk $\Delta^{14}C$-POC ages (non-depleted $\Delta^{14}C$-POC) in the Ob, Yenisei, and Lena rivers suggest that either the organic matter contributions from surface soil layers are proportionally greater or the older organic matter sources such as Yedoma are less influential in the case of particulate matter (McClelland et al. 2016).

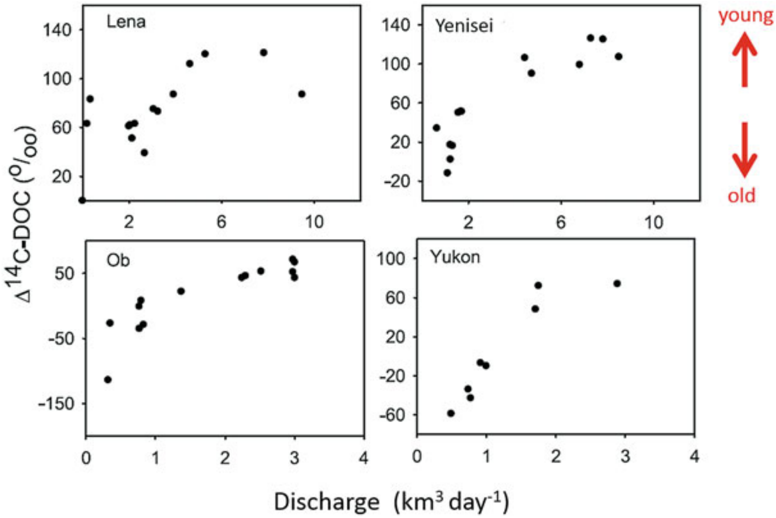

Fig. 9.10 Discharge versus Δ^{14}-DOC plots for all rivers except the Mackenzie River (Modified from Raymond et al. 2007)

9.5 Concluding Remarks

This chapter first provided an overview of the geographical scope of the Lena River basin and the seasonal changes and long-term trends of the Lena River discharge. Then, recent progress in hydrological modeling (i.e., river runoff and river ice modeling) targeting the discharge of the Lena River and other pan-Arctic rivers was described. Additionally, future projections regarding pan-Arctic river discharges were also mentioned. Because underdeveloped infrastructure within the pan-Arctic watershed is susceptible to damage during breakup floods in spring, projections of future discharge and the development of adaptation strategies for mitigating the effects of river floods and/or climate change-induced river disasters will be important regional considerations (e.g., Hiyama and Takakura 2018). In the latter half of this chapter, the importance of both river water chemistry (geochemical fingerprints) and past and ongoing activities regarding the monitoring of river water chemistry in the pan-Arctic rivers was overviewed.

Reductions of ice and snow coverages not only in the Arctic Ocean but also over the pan-Arctic watershed will enhance the regional hydrological cycle. As reviewed by Prowse et al. (2015a, b), there have been and there are projected to be major reductions in the durations of lake and river ice coverage. Such large reductions in ice coverage and the associated enhancement of heating of the water bodies have potential to create a major new flux of moisture to the atmosphere (Vihma et al. 2016). Quantifying the magnitude of moisture loss from freshwater bodies is important, because changes in water budgets/levels and associated alterations in the physical, chemical, and biological conditions contribute to the carbon and/or methane fluxes in the pan-Arctic watershed (Wrona et al. 2016). These changes in hydrological and biogeochemical cycles could also be related to the enhancement of permafrost thaw. Therefore, new field studies are required to evaluate fully the changing sources, quantity, quality, seasonality, and effects of freshwater in the pan-Arctic watershed. To address these issues, continuous measurements of daily river runoff data are essential for producing a data set that can be employed in the future as an input to hydrological models.

References

Aagaard K, Carmack EC (1989) The role of sea ice and other fresh-water in the Arctic circulation. J Geophys Res 94(C10):14485–14498. https://doi.org/10.1029/JC094iC10p14485

Adam JC, Lettenmaier DP (2003) Adjustment of global gridded precipitation for systematic bias. J Geophys Res 108(D9):4257. https://doi.org/10.1029/2002JD002499

Bamber J, van den Broeke M, Ettema J, Lenaerts J, Rignot E (2012) Recent large increases in freshwater fluxes from Greenland into the North Atlantic. Geophys Res Lett 39:L19501. https://doi.org/10.1029/2012GL052552

Beltaos S (ed) (1995) River ice jams. Water Resources Publications, LLC, Colorado, 372p. isbn:978-091833487-9

Beltaos S (ed) (2008) River ice breakup. Water Resources Publications, LLC, Colorado, 462p. isbn:978-188720150-6

Bennett KE, Prowse TD (2010) Northern hemisphere geography of ice-covered rivers. Hydrol Process 24:235–240. https://doi.org/10.1002/hyp.7561

Berezovskaya S, Yang D, Kane DL (2004) Compatibility analysis of precipitation and runoff trends over the large Siberian watersheds. Geophys Res Lett 31:L21502. https://doi.org/10.1029/2004GL021277

Berezovskaya S, Yang D, Hinzman L (2005) Long-term annual water balance analysis of the Lena River. Glob Planet Chang 48:84–95. https://doi.org/10.1016/j.gloplacha.2004.12.006

Bintanja R, Selten FM (2014) Future increases in Arctic precipitation linked to local evaporation and sea-ice retreat. Nature 509:479–482. https://doi.org/10.1038/nature13259

Bowling LC, Lettenmaier DP, Nijssen B, Graham LP, Clark DB, Maayar ME, Essery R, Goers S, Gusev YM, Habets F, van den Hurk B, Jin J, Kahan D, Lohmann D, Ma X, Mahanama S, Mocko D, Nasonova O, Niu G-Y, Samuelsson P, Shmakin AB, Takata K, Verseghy D, Viterbo P, Xia Y, Xue Y, Yang Z-L (2003) Simulation of high-latitude hydrological processes in the Torne-Kalix basin: PILPS phase 2(e) 1: experiment description and summary intercomparisons. Glob Planet Chang 38:1–30. https://doi.org/10.1016/S0921-8181(03)00003-1

Bring A, Fedorova I, Dibike Y, Hinzman L, Mård J, Mernild SH, Prowse T, Semenova O, Stuefer SL, Woo M-K (2016) Arctic terrestrial hydrology: a synthesis of processes, regional effects, and research challenges. J Geophys Res Biogeosci 121:621–649. https://doi.org/10.1002/2015JG003131

Bring A, Shiklomanov A, Lammers RB (2017) Pan-Arctic river discharge: prioritizing monitoring of future climate change hot spots. Earth's Future 5:72–92. https://doi.org/10.1002/2016EF000434

Brown RD, Mote PW (2009) The response of northern hemisphere snow cover to a changing climate. J Clim 22:2124–2145. https://doi.org/10.1175/2008JCLI2665.1

Brutsaert W, Hiyama T (2012) The determination of permafrost thawing trends from long-term streamflow measurements with an application in eastern Siberia. J Geophys Res 117:D22110. https://doi.org/10.1029/2012JD018344

Carmack EC, Yamamoto-Kawai M, Haine TWN, Bacon S, Bluhm BA, Lique C, Melling H, Polyakov IV, Straneo F, Timmermans M-L, Williams WJ (2016) Freshwater and its role in the Arctic marine system: sources, disposition, storage, export, and physical and biogeochemical consequences in the Arctic and global oceans. J Geophys Res Biogeosci 121:675–717. https://doi.org/10.1002/2015JG003140

Déry SJ, Stieglitz M, McKenna EC, Wood EF (2005) Characteristics and trends of river discharge into Hudson, James, and Ungava bays, 1964-2000. J Clim 18:2540–2557. https://doi.org/10.1175/JCLI3440.1

Déry SJ, Stadnyk TA, MacDonald MK, Gauli-Sharma B (2016) Recent trends and variability in river discharge across northern Canada. Hydrol Earth Syst Sci 20:4801–4818. https://doi.org/10.5194/hess-20-4801-2016

Essery R, Clark DB (2003) Developments in the MOSES 2 land-surface model for PILPS 2e. Glob Planet Chang 38:161–164. https://doi.org/10.1016/S0921-8181(03)00026-2

Frey KE, McClelland JW (2009) Impacts of permafrost degradation on arctic river biogeochemistry. Hydrol Process 23:169–182. https://doi.org/10.1002/hyp.7196

Fukutomi Y, Igarashi H, Masuda K, Yasunari T (2003) Interannual variability of summer water balance components in three major river basins of northern Eurasia. J Hydrometeorol 4:283–296. https://doi.org/10.1175/1525-7541(2003)4<283:IVOSWB>2.0.CO;2

Gautier E, Dépret T, Costard F, Virmoux C, Fedorov A, Grancher D, Konstantinov P, Brunstein D (2018) *Going with the flow*: hydrologic response of middle Lena River (Siberia) to the climate variability and change. J Hydrol 557:475–488. https://doi.org/10.1016/j.jhydrol.2017.12.034

Haine TWN, Curry B, Gerdes R, Hansen E, Karcher M, Lee C, Rudels B, Spreen G, de Steur L, Stewart KD, Woodgate R (2015) Arctic freshwater export: status, mechanisms, and prospects. Glob Planet Chang 125:13–35. https://doi.org/10.1016/j.gloplacha.2014.11.013

Hatta S, Hayakawa H, Park H, Yamazaki T, Yamamoto K, Ohta T (2009) Long term runoff analysis of the Lena river basin using a distributed hydrological model. J Jpn Soc Hydrol Water Resour 22:177–187. https://doi.org/10.3178/jjshwr.22.177 (in Japanese with English abstract)

Hiyama T, Takakura H (2018) Global warming and human-nature dimension in Northern Eurasia. Global Environmental Studies (GES)/Springer, Singapore, 224p. isbn:978-981-10-4647-6. https://doi.org/10.1007/978-981-10-4648-3

Hiyama T, Asai K, Kolesnikov AB, Gagarin LA, Shepelev VV (2013) Estimation of the residence time of permafrost groundwater in the middle of the Lena River basin, eastern Siberia. Environ Res Lett 8:035040. https://doi.org/10.1088/1748-9326/8/3/035040

Holland MM, Finnis J, Barret AP, Serreze MC (2007) Projected changes in Arctic Ocean freshwater budgets. J Geophys Res 112(G4):G04S55. https://doi.org/10.1029/2006JG000354

Holmes RM, McClelland JW, Peterson BJ, Tank SE, Bulygina E, Eglinton TI, Gordeev VV, Gurtovaya TY, Raymond PA, Repeta DJ, Staples R, Striegl RG, Zhulidov AV, Zimov SA (2012) Seasonal and annual fluxes of nutrients and organic matter from large rivers to the Arctic Ocean and surrounding seas. Estuar Coasts 35:369–382. https://doi.org/10.1007/s12237-011-9386-6

Liu B, Yang D, Ye B, Berezovskaya S (2005) Long-term open-water season stream temperature variations and changes over Lena River basin in Siberia. Glob Planet Chang 48:96–111. https://doi.org/10.1016/j.gloplacha.2004.12.007

Ma X, Fukushima Y (2002) A numerical model of the river freezing process and its application to the Lena River. Hydrol Process 16:2131–2140. https://doi.org/10.1002/hyp.1146

Ma X, Fukushima Y, Hiyama T, Hashimoto T, Ohata T (2000) A macro-scale hydrological analysis of the Lena River basin. Hydrol Process 14:639–651. https://doi.org/10.1002/(SICI)1099-1085(20000228)14:3<639::AID-HYP959>3.0.CO;2-0

McClelland JW, Holmes RM, Peterson BJ, Amon R, Brabets T, Cooper L, Gibson J, Gordeev VV, Guay C, Milburn D, Staples R, Raymond PA, Shiklomanov I, Striegl R, Zhulidov A, Gurtovaya T, Zimov S (2008) Development of a pan-Arctic database for river chemistry. EOS Trans Am Geophys Union 89(24):217–218. https://doi.org/10.1029/2008EO240001

McClelland JW, Tank SE, Spencer RGM, Shiklomanov AI (2015) Coordination and sustainability of river observing activities in the Arctic. Arctic 68. https://doi.org/10.14430/arctic4448

McClelland JW, Holmes RM, Peterson BJ, Raymond PA, Striegl RG, Zhulidov AV, Zimov SA, Zimov N, Tank SE, Spencer RGM, Staples R, Gurtovaya TY, Griffin CG (2016) Particulate organic carbon and nitrogen export from major Arctic rivers. Glob Biogeochem Cycles 30:629–643. https://doi.org/10.1002/2015GB005351

Oshima K, Tachibana Y, Hiyama T (2015) Climate and year-to-year variability of atmospheric and terrestrial water cycles in the three great Siberian rivers. J Geophys Res Atmos 120:3043–3062. https://doi.org/10.1002/2014JD022489

Park H, Yamazaki T, Yamamoto K, Ohta T (2008) Tempo-spatial characteristics of energy budget and evapotranspiration in the eastern Siberia. Agric For Meteorol 148:1990–2005. https://doi.org/10.1016/j.agrformet.2008.06.018

Park H, Walsh J, Fedorov AN, Sherstiukov AB, Iijima Y, Ohata T (2013a) The influence of climate and hydrological variables on opposite anomaly in active-layer thickness between Eurasian and North American watersheds. Cryosphere 7:631–645. https://doi.org/10.5194/tc-7-631-2013

Park H, Walsh JE, Kim Y, Nakai T, Ohata T (2013b) The role of declining Arctic Sea ice in recent decreasing terrestrial Arctic snow depths. Pol Sci 7:174–187. https://doi.org/10.1016/j.polar.2012.10.002

Park H, Yoshikawa Y, Oshima K, Kim Y, Ngo-Duc T, Kimball JS, Yang D (2016) Quantification of warming climate-induced changes in terrestrial Arctic River ice thickness and phenology. J Clim 29:1733–1754. https://doi.org/10.1175/JCLI-D-15-0569.1

Peterson BJ, Holmes RM, McClelland JW, Vorosmarty CJ, Lammers RB, Shiklomanov AI, Shiklomanov IA, Rahmstorf S (2002) Increasing river discharge to the Arctic Ocean. Science 298:2171–2173. https://doi.org/10.1126/science.1077445

Peterson BJ, McClelland J, Curry R, Holmes RM, Walsh JE, Aagaard K (2006) Trajectory shifts in the Arctic and subarctic freshwater cycle. Science 313:1061–1066. https://doi.org/10.1126/science.1122593

Prowse T, Bring A, Mård J, Carmack E (2015a) Arctic freshwater synthesis: introduction. J Geophys Res Biogeosci 120:2121–2131. https://doi.org/10.1002/2015JG003127

Prowse T, Bring A, Mård J, Carmack E, Holland M, Instanes A, Vihma T, Wrona FJ (2015b) Arctic freshwater synthesis: summary of key emerging issues. J Geophys Res Biogeosci 120:1887–1893. https://doi.org/10.1002/2015JG003128

Rawlins MA, Steele M, Holland MM, Adam JC, Cherry JE, Francis JA, Groisman PY, Hinzman LD, Huntington TG, Kane DL, Kimball JS, Kwok R, Lammers RB, Lee CM, Lettenmaier DP, McDonald KC, Podest E, Pundsack JW, Rudels B, Serreze MC, Shiklomanov A, Skagseth Ø, Troy TJ, Vörösmarty CJ, Wensnahan M, Wood EF, Woodgate R, Yang D, Zhang K, Zhang T (2010) Analysis of the Arctic system for freshwater cycle intensification: observations and expectations. J Clim 23:5715–5737. https://doi.org/10.1175/2010JCLI3421.1

Raymond PA, McClelland JW, Holmes RM, Zhulidov AV, Mull K, Peterson BJ, Striegl RG, Aiken GR, Gurtovaya TY (2007) Flux and age of dissolved organic carbon exported to the Arctic Ocean: a carbon isotopic study of the five largest arctic rivers. Glob Biogeochem Cycle 21: GB4011. https://doi.org/10.1029/2007GB002934

Sakai T, Hatta S, Okumura M, Hiyama T, Yamaguchi Y, Inoue G (2015) Use of Landsat TM/ETM+ to monitor the spatial and temporal extent of spring breakup floods in the Lena River, Siberia. Int J Remote Sens 36:719–733. https://doi.org/10.1080/01431161.2014.995271

Serreze MC, Bromwich DH, Clark MP, Ertringer AJ, Zhang T, Lammers R (2003) Large-scale hydro-climatology of the terrestrial Arctic drainage system. J Geophys Res 108(D2):8160. https://doi.org/10.1029/2001JD000919

Serreze MC, Barrett AP, Slater AG, Woodgate RA, Aagaard K, Lammers RB, Steele M, Moritz R, Meredith M, Lee CM (2006) The large-scale freshwater cycle of the Arctic. J Geophys Res 111: C11010. https://doi.org/10.1029/2005JC003424

Shiklomanov AI, Lammers RB (2009) Record Russian river discharge in 2007 and the limits of analysis. Environ Res Lett 4:045015. https://doi.org/10.1088/1748-9326/4/4/045015

Slater AG, Bohn TJ, McCreight JL, Serreze MC, Lettenmaier DP (2007) A multimodel simulation of pan-Arctic hydrology. J Geophys Res 112(G4):G04S45. https://doi.org/10.1029/2006JG000303

Smith LC, Pavelsky TM, MacDonald GM, Shiklomanov AI, Lammers RB (2007) Rising minimum daily flows in northern Eurasian rivers: a growing influence of groundwater in the high-latitude hydrologic cycle. J Geophys Res 112:G04S47. https://doi.org/10.1029/2006JG000327

Su F, Adam JC, Bowling LC, Lettenmaier DP (2005) Streamflow simulations of the terrestrial Arctic domain. J Geophys Res 110(D8):D08112. https://doi.org/10.1029/2004JD005518

Suzuki K, Matsuo K, Hiyama T (2016) Satellite gravimetry-based analysis of terrestrial water storage and its relationship with run-off from the Lena River in eastern Siberia. Int J Remote Sens 37:2198–2210. https://doi.org/10.1080/01431161.2016.1165890

Swenson SC, Lawrence DM, Lee H (2012) Improved simulation of the terrestrial hydrological cycle in permafrost regions by the community land model. J Adv Model Earth Syst 4:M08002. https://doi.org/10.1029/2012MS000165

Tananaev NI, Makarieva OM, Lebedeva LS (2016) Trends in annual and extreme flows in the Lena River basin, northern Eurasia. Geophys Res Lett 43:10764–10772. https://doi.org/10.1002/2016GL070796

Tank SE, Raymond PA, Striegl RG, McClelland JW, Holmes RM, Fiske GJ, Peterson BJ (2012) A land-to-ocean perspective on the magnitude, source and implication of DIC flux from major Arctic rivers to the Arctic Ocean. Glob Biogeochem Cycle 26:GB4018. https://doi.org/10.1029/2011GB004192

van den Hurk B, Viterbo P (2003) The Torne-Kalix PILPS 2(e) experiment as a test bed for modifications to the ECMWF land surface scheme. Glob Planet Chang 38:165–173. https://doi.org/10.1016/S0921-8181(03)00027-4

van Vliet MTH, Franssen WHP, Yearsley JR, Ludwig F, Haddeland I, Lettenmaier DP, Kabat P (2013) Global river discharge and water temperature under climate change. Glob Environ Chang 23:450–464. https://doi.org/10.1016/j.gloenvcha.2012.11.002

Vihma T, Screen J, Tjernström M, Newton B, Zhang X, Popova V, Deser C, Holland M, Prowse T (2016) The atmospheric role in the Arctic water cycle: a review on processes, past and future changes, and their impacts. J Geophys Res Biogeosci 121:586–620. https://doi.org/10.1002/2015JG003132

Walsh J et al (2005) Cryosphere and hydrology. In: Arctic climate impact assessment. Cambridge University Press, Cambridge, pp 183–242

White D, Hinzman L, Alessa L, Cassano J, Chambers M, Falkner K, Francis J, Gutowski WJ Jr, Holland M, Holmes RM, Huntington H, Kane D, Kliskey A, Lee C, McClelland J, Peterson B, Rupp TS, Straneo F, Steele M, Woodgate R, Yang D, Yoshikawa K, Zhang T (2007) The arctic freshwater system: changes and impacts. J Geophys Res 112(G4):G04S54. https://doi.org/10.1029/2006JG000353

Wrona FJ, Johansson M, Culp JM, Jenkins A, Mård J, Myers-Smith IH, Prowse TD, Vincent WF, Wookey PA (2016) Transitions in Arctic ecosystems: ecological implications of a changing hydrological regime. J Geophys Res Biogeosci 121:650–674. https://doi.org/10.1002/2015JG003133

Yang D, Kane DL, Hinzman L, Zhang X, Zhang T, Ye H (2002) Siberian Lena River hydrologic regime and recent change. J Geophys Res 107(D23):4694. https://doi.org/10.1029/2002JD002542

Ye B, Yang D, Kane DL (2003) Changes in Lena River streamflow hydrology: human impacts versus natural variations. Water Resour Res 39:1200. https://doi.org/10.1029/2003WR001991

Ye H, Yang D, Zhang T, Zhang X, Ladochy S, Ellison M (2004) The impact of climatic conditions on seasonal river discharges in Siberia. J Hydrometeorol 5:286–295. https://doi.org/10.1175/1525-7541(2004)005<0286:TIOCCO>2.0.CO;2

Ye B, Yang D, Zhang Z, Kane DL (2009) Variation of hydrological regime with permafrost coverage over Lena Basin in Siberia. J Geophys Res 114(D17):D07102. https://doi.org/10.1029/2008JD010537