Ove Tobias Gudmestad has since September 2008 been a full-time professor of marine technology at the University of Stavanger, Norway. From 1994 to 2008, he was an adjunct professor at the university, teaching courses on marine technology and offshore field development. He has a PhD in wave force analysis and experience from engineering, field development studies, oil and gas development projects, and research in Statoil from 1975 to 2008. When he left Statoil, he was the company’s advisor for Marine and Arctic technology.

Gudmestad has published papers on the actions from waves and earthquakes, on the risk involved in marine operations, and on Arctic field development challenges. He has filed several patent applications related to offshore technology. From 2005 to 2013, he has also been working with the Norwegian University of Technology and Science in Trondheim, Norway, as adjunct professor of Arctic offshore civil engineering and from 2013 as adjunct professor of Cold Climate Technology at University of Tromsø, Norway. He has been awarded honorary doctoral degrees from the Gubkin State University of Oil and Gas in Moscow in 2002 and from Murmansk State Technical University in 2008.
2.1 Introduction

This chapter on “Cold Region Hydrology” puts emphasis on the main theme of the book: engineering hydrology. The chapter is intended to serve as a checklist for engineers and scientists. The objective is to ensure that important aspects of hydrology be covered properly by those working with engineering and scientific aspects related to the cold regions of the world. The chapter is not aiming to reproduce important aspects on hydrology presented elsewhere in the book; however, the cold climate poses additional challenges that have to be solved by the humans working and living in this region. A systematic description of engineering challenges related to hydrology in cold climate is, as far as the author is aware of, not produced elsewhere. It is, furthermore, believed that the book will serve as inspiration for scientists studying specific aspects of cold region engineering hydrology.

It is, however, to be emphasized that wildlife and vegetation serve as “thermometers” on the soundness of the environment. The necessity to ensure that the land is clean and habitable is a key driver for the author’s efforts to prepare the chapter. In this respect, traditional knowledge should be consulted and preserved. No one but those living in the cold climate really knows the promises, the challenges, and the limitations of living there.

The hydrology in cold regions is governed by the cold climate and the presence of permafrost that may be continuous to large depths. During wintertime, the ground is continually frozen from the surface down to the permafrost, and rivers and freshwater lakes are covered by ice, which at some locations can be several meters thick. Shallow freshwater ponds are frozen to the bottom, whereby no water is accessible from these ponds for the communities. The frozen rivers and lakes are used to transport goods to cold climate areas (on ice roads), to transport raw materials, and for the preparation of construction works. For calculation of the bearing capacity of the ice, see [11].

During the summer season, which may start from mid- to late June and continue to mid- to late August, the upper layer of the permafrost melts, resulting in the ground becoming nonaccessible by vehicles, and pollution might easily be carried with the water flow. Shallow tundra ponds become accessible during this season. The melting of glaciers is dependent upon the temperature, and the sum of the product of the average hourly temperature multiplied by the number of hours with this temperature will determine the melting rate. A tendency of increased flooding will be seen with an increase in the “melting degrees hours.” On the other hand, whether the glaciers will be growing or shrinking will...
depend upon the net mass flux: snowfall minus melting. Where the glaciers are shrinking, there is a danger of imbalance in the future hydrology budget.

The upper soil under all roads, permanent access areas, and other civil engineering works/buildings must be cleared, and all construction activities must build on hard ground, that is, must be anchored down to the permafrost. In doing so, it is very important that heat transfer bridges are not created that will cause local melting of the permafrost. Civil engineering works must, therefore, be insulated from the permafrost. Typically, buildings are built above ground, and recently new materials, such as fiber clothing, are used for roads. Piles are being used to anchor civil engineering works, and where the annual precipitation is low, wooden piles having low heat transfer capacity can be used. It is also very important to map water flow paths to avoid buildings, roadways, etc., being flooded during the snow-melt and thaw period.

In between the summer and winter, there is the freeze-up period and the snowmelt period. In the freeze-up period, the ground freezes gradually and all ponds freeze. At some locations (such as in Barrow, Alaska [11]), precipitation is considerable during this period of the year, with a soaked surface layer as the freezing continues into deeper layers until the upper layers above the permafrost are entirely frozen. During rainfall, the ground becomes almost nonnavigable, and there is a considerable surface water flow.

During the snowmelt period, the runoff is considerable at the surface, but the flow does not penetrate deeply, as the lower layers are still frozen. Considerable flow can occur during this season, depending upon the temperature and the speed of the melting. Water can find new access ways and can cause considerable local damage. Vegetation will insulate the ground layers and be a binding material so the flow will find a route outside of vegetation. Any damage due to the use of heavy equipment can lead to increased surface damage during this period.

The rivers in cold climate areas (and there are huge rivers running north to the Arctic seas [1]) are exposed to enormous changes in the water level from the dry winter, where the surface freezes, and there is limited water transport for the huge amount of water that will be transported in the snowmelt season. In this period, the ice breakup also represents challenges, as the ice may pile up and jam the flow. Huge areas can be flooded, and the broken ice can substantially damage landscape, vegetation, and engineered structures. Furthermore, the rapid flow of water in this period also causes riverbank erosion, extensive sediment transport, and scouring around bridge supports, which can cause bridge collapse.

Last, but not least, the new challenges caused by less sea ice than in the past (an effect of the potential global warming) and, therefore, stronger wave actions cause more erosion of the shoreline than in the past. This influences the hydraulic regime in a way that traditional ponds used for drinking water might be eroded and filled with saltwater, the engineered structures might be undermined by the shrinking shoreline, or saltwater might penetrate deeper into estuaries, causing damage to wildlife and vegetation.

In the following, the specific challenges to the public caused by the hydraulic regime will be reviewed. The challenges and present conceptual solutions will be described, and in some cases, the solutions implemented by communities located in cold climate regions will be referred. The challenges discussed relate to:

- River flow during the snowmelting season
- The specifics during the river ice breakup
- The effect of the shrinking shoreline
- Spreading of pollution
- Drinking water availability
- Sewage transport
- The effect of hydrocarbon production activities
The specifics of cold climate hydrology will be emphasized and will refer to the subjects being discussed in the other chapters. The discussion will be qualitative as the variations are substantial. The chapter will, therefore, serve more as a reminder for persons involved in cold region hydrology challenges. The known can be solved. Those who know they have little knowledge know they need to know more. The dangerous situation is represented by those who do not know that the knowledge is limited and are ignorant about the potential unknown.

Another aspect that will finally be discussed in this introductory section is traditional knowledge. Predictions for the future are based upon sophisticated models, including models where global warming is foreseen. Often, however, information about the past is lacking. Many communities have knowledge about past’s extreme events, and their elders know the legends. It is suggested that the first matter a community developer should consider is the relevance of the traditional knowledge in order to provide a design basis for any engineering project. This will in particular involve information about the hydrology and conditions of the ground and erosion due to actions of water. These data will also involve the behavior of animals, migration of mammals and birds as well as whales, and a consideration related to types of and changes in vegetation.

2.2 Public Challenge: River Flow during the Snowmelting Season

2.2.1 Description

The flow of water in Arctic rivers has a seasonal character (see Figure 2.1) with a low flow during the dry and cold winter where the river freezes, a very high flow during the snowmelt season, and a gradual decrease in the flow during the summer, in particular in areas with little summer precipitation, while the flow increases again before the freeze-up period when some rainfall is normal. Figure 2.1 shows the variation in the water flow in the Mackenzie River, one of the large Arctic rivers.

Some of the largest rivers in the world discharge into the Arctic seas. The major Arctic rivers are as listed in Table 2.1.

![Typical seasonal variation of the flow of water in the Mackenzie River.](From Owens, E. et al., Field guide for oil spill response in Arctic waters, prepared for Arctic Council Emergency, Prevention, Preparedness and Response (EPPR) Working Group, Environment Canada, Yellowknife, Northwest Territories, Canada, p. 348, Figure 6.5, 1988. With permission from Arctic Council.)
2.2.2 Engineering Challenges

The large variation in the flow provides a number of challenges. The primary challenge is the erosion of the riverbank, the damage caused by the flowing ice and flooding (see also Section 2.3). The erosion causes the riverbanks to become unstable, and engineered structures can be undermined. This applies in particular to bridges spanning the river and to port facilities. Flooding causes damage to all engineered structures in large areas along the river.

2.2.3 Mitigation Measures to Avoid Damage in Strong River Flow

In order to mitigate the effects of the flooding due to snowmelt, several measures must be taken to protect engineered structures.

Like in any harbor, the banks can be protected by breakwaters and rock or concrete block plastering. It is important to calculate the dimensions of the plastering to ensure that it can stand up to the current flow [24]. In addition, the plastering or breakwaters must withstand the actions from the drifting ice during the ice breakup [25]. Recently, the use of textiles has been suggested (Figure 2.2) for plastering [5]; however, the textile must be sufficiently robust to withstand the actions to which they are exposed. Annual replacement of lost bags is required. It is expected that more research work will be conducted in the future to develop suitable materials:

- With a trend of Arctic warming, there will be increased permafrost melting, and the speed of erosion could accelerate. In addition, erosion destroys the vegetation, so erosion is self-reinforcing as vegetation holds the soil in place. It should also be noted that extensive erosion will cause large sediment transport with accumulation of sand or mud banks in the rivers, potentially in the river estuaries, hindering access by vessels. Also, dredging might be necessary to avoid flooding upstream.

- Bridges must be supported in a manner that the riverbank and mid-river supports are not exposed to erosion. This might be achieved by a layer of scour protection around the supports. The scour protection would often consist of rock of sufficient size to avoid being transported with the river current [10].

- Furthermore, the bridge supports must be designed to withstand the actions from ice. Of special interest are the bridge piers designed for the St. Lawrence River crossing to Prince Edward Island, the Confederation Bridge (see Figure 2.3). The piers have coned geometry in the waterline so ice can break up when forced against the bridge pier [7,16].

### Table 2.1 Rivers Discharging into Arctic Seas

<table>
<thead>
<tr>
<th>River</th>
<th>Country</th>
<th>Discharge in Cubic Kilometers per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dvina</td>
<td>Russia</td>
<td>105</td>
</tr>
<tr>
<td>Pechora</td>
<td>Russia</td>
<td>108</td>
</tr>
<tr>
<td>Ob</td>
<td>Russia</td>
<td>402</td>
</tr>
<tr>
<td>Yenisey</td>
<td>Russia</td>
<td>580</td>
</tr>
<tr>
<td>Lena</td>
<td>Russia</td>
<td>525</td>
</tr>
<tr>
<td>Kolyma</td>
<td>Russia</td>
<td>103</td>
</tr>
<tr>
<td>Yukon</td>
<td>United States (Alaska)</td>
<td>203</td>
</tr>
<tr>
<td>Mackenzie</td>
<td>Canada</td>
<td>281</td>
</tr>
</tbody>
</table>

Of particular concern is the height of the bridge deck. In cases where the water flows against the bridge deck, there is a large possibility for loss of the bridge. This calls for data collection of the current speed, maximum water level, and ice conditions. Traditional knowledge regarding past extremes should be consulted to help define the extreme design situation. Like offshore structures for oil and gas, a safety level should be selected to ensure that the probabilities of bridge damage and bridge collapse are within acceptable levels agreed by the society. For offshore structures for the oil and gas industry, these levels are set as annual exceedances of $10^{-2}$ and $10^{-4}$, respectively [11].

- Pipelines for oil and gas produced from onshore fields will often have to cross rivers. They might cross rivers on bridges that should be designed according to the principles defined above, or they might cross rivers on the river bottom. In the last case, the pipelines will be exposed to strong transverse currents and must be designed to be stable on the bottom. Trenching might be required, although...
scouring might undermine the pipeline and cause free span. The erosion of the riverbank might be even more dangerous and cause free spanning pipelines exposed to considerable currents, possibly causing pipeline breakage. For a discussion of the potential pollution effects of damaged and leaking pipelines in the Arctic, see Section 2.8. Utmost care must, therefore, be taken when designing pipeline river crossings to avoid large pollution effects.

2.3 Public Challenge: The Specific Conditions during the Ice Breakup

During the ice breakup in the spring, there are challenges associated with large loading on riverbanks, structures placed in the rivers, and there is a potential for flooding of large areas.

2.3.1 Conditions Caused by the Ice Breakup

Many of the rivers in the Arctic region flow toward the north, and ice begins to melt in the south, while the river is still frozen in the north. This situation creates flooding that may be excessive in the south and also creates huge water and ice pressure on the ice in the north, potentially causing the ice to pile up and jam the river flow, causing even larger flooding.

A series of images demonstrating this phenomenon is shown in Figure 2.4. The images are taken by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA’s Terra satellite, showing the spring flooding in May 2007.

The images were made with both infrared and visible light. Land, burned by wildfire in the past year or two, is marked burn scar. The first image was taken on May 14, 2007, while the river was still frozen [18].

The second image was taken on May 23. The southern extents of the Lena and its surrounding areas are dramatically flooded.

The last image was taken a week later on May 28, and the floods had moved north. Water had, however, spread far beyond the river’s banks. The flood put 12 towns (1,000 houses) under water, damaged or destroyed 41 bridges, and affected more than 14,000 people [18].

Figure 2.5 shows the flooding situation in Yakutsk on May 20, 2010.

2.3.2 Mitigating Measures to Avoid Large Damages

Even if it may not be possible to avoid flooding caused by snowmelt and ice breakup, it is of importance to provide forecasts such that people living in the area where flooding might be expected can take necessary precautions. Evacuation should be properly planned (each household should have a boat available for evacuation), and the most important buildings should be located on higher grounds. In order to plan properly, historical knowledge of the extent of flooding must be consulted in order to provide a suitable design basis for all planning works.

Ice jamming downstream might worsen the flooding situation considerably. Potentially, the use of explosives will help to open the jammed section. Ice jam at a river crossing might damage the bridge and cause large losses, both in terms of money and the time it will take to rebuild the bridge. Figure 2.6 shows how the Kuskokwim River threatens to flood the Western Alaska village of lower Kalskag on May 7, 2012.

2.4 Public Challenge: The Effect on Hydrology of the Shrinking Shoreline

The shrinking shoreline damages the built structures placed on or near the shoreline and causes large problems for water supply organized in the vicinity of shorelines.
2.4.1 Shrinking Shoreline

The shrinking shoreline is an effect of the all-existing erosion of the Arctic shore. With increasing temperatures, the permafrost melts, resulting in increased shoreline erosion. This causes considerable problems for landfall of oil and gas pipelines. The erosion effect is reinforced by less ice offshore; the ice is arriving later and breaks up earlier. The open water area becomes larger as the ice border moves away from shore, providing larger fetch lengths where winds will increase the storm waves, leading to an increased erosion effect. Figure 2.7 shows the projected erosion of the Newtok village shoreline, Alaska [26]. The community of the village of Newtok has voted to relocate its 340 residents to new homes 9 miles away, up the Ninglick River.

In addition to erosion effects, the storm surge can create substantial flooding. Extreme storms combined with high tides can cause extensive flooding of low lands and damage engineering structures and freshwater reservoirs. On July 25, 2010, a large storm surge flooded the Varandey oil treatment terminal in Russia several hundred meters inland [8], causing massive damage to the terminal as the storm surge was combined with large waves. An airport built parallel to the shoreline was virtually destroyed during
the flooding. With less Arctic ice, one can expect that such damaging storms to be more frequent and severe as the longer fetch length can cause the waves to be stronger than were in the past.

2.4.2 Effects on Hydrology

The shrinking shoreline could destroy settlements, and reports from the cold climate areas indicate extensive damage to built structures. Freshwater reservoirs can be destroyed, or flooding can cause
saltwater intrusion in the reservoirs. The hydrological effects can thus be large, and measures should be taken to prepare contingency plans in the event of flooding, and damage to freshwater reservoirs becomes a realistic situation. The damage to the shoreline will also cause changes to wildlife habitats, in particular, to bird nesting locations.

2.5 Public Challenge: Hydrology and Spreading of Pollution

The flow of water can cause severe spreading of pollution, and it is necessary to plan and implement mitigating measures to avoid such spreading.

2.5.1 Spreading of Pollution with the Water Flow

Noncontrolled flow of water can spread pollution from open dumps and dams holding waste, for example, waste from the mining or oil industries. The flow during the snowmelt season could, in particular, be noncontrollable, and poisoned water can find its way to water reservoirs or to settlement areas.

2.5.2 Mitigating Measures to Limit Spreading of Pollution

To avoid spreading of pollution with flowing water, in particular in cold climate areas where the snowmelting and river ice breakup could cause large flooding, the communities must map the older dumps and make every effort to cover the dumps properly. New dumps and waste areas must be located on higher grounds and properly be secured to avoid spreading of polluted water. However, seepage could still occur, in particular, if the permafrost melts and poisoned water finds its way from covered dumps to the water reservoirs. In the event that such situations are threatening, the dumps will have to be dug up, and the potentially polluting soil must be securely placed. In a worst case, massive pollution could make a settlement inhabitable. For reference, see the discussion of the effects of the large oil pollution in Komi Republic, Russia, in 1994, Section 2.8.

For the extraction of oil from tar sand, substantial amounts of water are being used. This water becomes contaminated and must be stored in large tailing ponds. This both depletes local water reserves and threatens to pollute the environment and nearby communities through leakages and during flooding [9]. For reference, see Figure 2.8.
2.6 Public Challenge: Drinking Water Availability

In the Arctic region, the all-year availability of drinking water represents a large challenge, and there is a need to carefully plan for the provision of clean and nonpolluted drinking water to the communities.

2.6.1 Challenge to Provide Drinking Water

In the Arctic climate, permafrost is hindering natural groundwater from providing drinking water to the public. One is, therefore, during the winter dependent on water from frozen rivers or lakes. Shallow reservoirs, however, freeze, and much of the water is contained by the frozen ice. A primary concern is possible pollution, either from the ground (e.g., from dissolved metals) or from the public, in particular from older dumps that were common and that are leaking. Water treatment is, therefore, necessary to ensure acceptable water.

2.6.2 Example 1 Solution: Drinking Water to Longyearbyen, Svalbard

In winter, drinking water in Longyearbyen, 78°13′ N, 15°38′ E, comes from Isdammen located east of the settlement (Figures 2.9 and 2.10). Isdammen originally consisted of three small lakes and was established during the construction of the road to Mine 5. Today, Isdammen comprises a volume of 2.7 million m³. The depth is on average 1.7 m, with a maximum of 5 m and water intake at 4 m. In winter, the ice thickness is typically less than 1.5 m. A large volume of the water reservoir is frozen to ice. The water source is basically meltwater from glaciers through the Endalen River [14] and possibly from groundwater [13] through an opening, “a talik” in the permafrost. The natural catchment area is 34.4 km², of which 15% is covered by glaciers [23] (Figure 2.11) [4].

The image shown in Figure 2.10 was acquired on July 12, 2003, and the area is located at 78.2° N latitude, 15.6° E longitude.
Before the water reaches the tap in Longyearbyen, it is filtered in three large sand filters and passes through UV radiation. The water treatment plant ensures that the water in Longyearbyen meets public drinking water requirements. The water supply net is 30 km long and covers the Longyearbyen settlement to the airport. The waterline is above ground and is insulated and equipped with heating cables to ensure the water does not freeze [15].
2.6.3 Example 2 Solution: Drinking Water to Barrow, Alaska

Isatkoak (Esatkuat) Lagoon is located centrally in the Barrow settlement (Figure 2.12). The lagoon remains partially unfrozen year round. The lagoon is separated into sections by artificial berms, and the upper lagoon serves as the primary source of drinking water for the city of Barrow, 71°23′ N and 156°28′ W. Water drawn from the lagoon is treated by filtration and distributed to the settlement.

2.7 Public Challenge: Sewer System and the Influence on the Hydrology

The design of a proper sewer system in an Arctic community represents a major challenge that needs to be given high attention. Of particular importance is the challenge to avoid pollution to the environment and to drinking water basins.

2.7.1 Challenge to Hydrology from the Sewer System

All modern societies must have a sewer system. The sewer will be mixed with water and could represent a source of pollution, in particular if the sewer comes in contact with the free flowing water. In areas where flooding occurs, the release of sewer could cause contamination of the freshwater system and a considerably unpleasant smell to the community.
2.7.2 Example Solution: Sewage System for Longyearbyen, Svalbard

Contained in Longyearbyen, there are exposed sewer pipes with swan-necks. These are connected to drain collection basins at each 50 m (see Figure 2.13). At the locations where the drain is being collected, there might be a little smell because the flow is dependent upon gravity and requires ventilation. These basins act as overflow basins if the drain becomes clogged or frozen. The drainage network is 23 km long. The drain is discharged at 50 m depth, 3 km into the Advent Fjord [14].

2.8 Effect from Hydrocarbon Production Activities

During the 1970s, oil production was increased in Russia due to an oil shortage in the world market, and the lack of proper technology (in particular pipeline technology and lack of leak detection technology) caused large pollution levels in some Russian rivers and lakes. In 1975, for example, several large West Siberian rivers that run north through Russia's biggest oil production region and empty into the Arctic Ocean had oil concentrations 21 times the maximum permissible level, according to a government report, “Status of Environmental Pollution in the USSR 1975–1976” [20].

A very large oil spill occurred in August 1994, when old pipelines in the northern Komi Republic began to leak. The oil spill was officially measured at 79,000 ton or 585,000 barrels; however,
independent estimates put it at up to 2 million barrels [24]. The oil was stored in a large dam, as was the state of the art for containing pollution in the former Soviet Union. Two months after the spill began, heavy rains broke the dam, and a large amount of oil was released into rivers and across the tundra near the city of Usinsk [20].

The oil that did not immediately spill into the Arctic Ocean-bound Kolva, Usa, and Pechora rivers spread over 186 km² of marshland and tundra [22]. There it froze during winter months. The following spring, the oil from the frozen tundra washed back into the streams, seeped into the surrounding vegetation or traveled further down the Pechora to the Barents Sea.

2.9 Traditional Knowledge

The value of traditional knowledge should not be underestimated. This knowledge is critical when providing a design basis for any activity. In particular, in cold climates where written knowledge may be scarce, traditional knowledge going back hundreds of years will be extremely important [12]. Regarding hydrological aspects, large situations of flooding, large river ice situations with severe ice breakup, and large storm surge effects are some of the situations where traditional knowledge, even legends, might enlighten and constitute a design basis for engineering projects.

2.10 Summary and Conclusions

With reference to [12], the schematic of the Arctic hydrological cycle in a region of thick ice-rich permafrost can be presented as in Figure 2.14. Snowmelt is the most important event leading to large water flow and considerable challenges to engineered structures. In the event we do not respond properly to these challenges, large damage may occur. In this chapter, some descriptions of the challenges have been provided and pointed to solutions that may be implemented to minimize the damage.

Of particular recommendations in this chapter are measures to avoid environmental damages and consultation with the local society to identify past events that can be seen as dimensioning for future events. This will not, however, lead us to disregard models taking new trends into account, such as planning for a potentially future warmer climate. In a chapter on the hydrology of the cold climate regions, it must also be reminded that all life, vegetation, birds, animals, and humans are dependent upon clean, nonpolluted, and abundant volumes of water resources.
FIGURE 2.14  Schematic of the Arctic hydrological cycle in a region of thick ice-rich permafrost where we have added the interaction with frozen groundwater. We refer also to [28], where groundwater interaction is not considered.

References

8. Gazprom, May 2012, Private information provided by personnel from Gazprom during an Arctic Engineering Seminar arranged at the Gubkin University of Oil and Gas, Moscow, Russia.


