Chapter 8
Water and glaciers

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8.1 Water in glaciers

Water can flow at the surface, within, and at the base of an glacier. Glacier hydrology is of interest since:

- Glacier-fed rivers provide much of the water for agriculture (Canadian prairies, central Asia) and for hydro-electrical power production (Iceland, France, Switzerland, Norway).
- Glacier run-off has unusual features, such as:
  a) large diurnal variations,
  b) maximum flow occurs during summer (when many rivers are dry),
  c) englacial storage of water.
- In the Alps and Norway, sub-glacial tunnels drilled to get water for hydroelectric plants. Need to know water flow at the bed.
- Sudden drainage of glacier-dammed lakes or of water stored within glaciers and associated mudflows are a great risk. This becomes more important as cities and roads move closer and closer to out-flow plaines and glaciers.
- Water at the bed affects: till deformation, sliding, and surges, for example.

Where does the water go?

Water at the surface of a glacier, that either fell as rain or melts there, can choose between several different routes before reaching the ocean. Below is a short summary of some of these routes:

1. Water in the accumulation area can percolate through the snow and firn down to the ice layer.
2. Water can flow on the surface, even all the way to the glacier terminus.
3.a A fraction flows through weins that form at the intersection of grains (liquid due to higher surface tension)

3.b Most of the water drains to the bed through moulins.
4.a Water at the bed can flow in tunnels that incise the ice, so-called R-tunnels. Eskers (malarásar) commonly form in those.
4.b Water at the bed can flow in tunnels that incise the bed, so-called N-tunnels.
4.c Water at the bed can flow as a thin sheet of water (W-sheet). (Unlikely to be stable.)
4.d Water at the bed can flow as groundwater in sediments under the ice.
4.e Water at the bed can be situated in cavities, which could be linked.
4.f Water at the bed can flow in a system of broad and shallow canals, at the top of sediments.
5. The water that emerges at the snout flows to the sea as a glacier river.

Water can also accumulate in sub-glacial lakes. Sub-glacial lakes sometimes drain in catastrophic way as glacier outburst floods, or jökulhlaup.

Surface Water, Moulins, and Tunnels

Surface melt water is the most important source of water in temperate glaciers.

Some water flows in channels at the surface, like rivers, and off to the sides or the terminus, but much disappears through cracks and vertical passages called *moulins*.

Moulins form where a stream flows into a crevasse as in Figure 8.1. If the crevasse is filled with water $h_w = h_i$ (unusual), we find that the water pressure is greater than the ice overburden pressure, $P_w = \rho_w gh > \rho_i gh = P_i$. The water can then force the crevasse to open further downwards. However, moulins do most often form in areas of extension, where the crevasse doesn't have to be completely water filled.

Small fraction (10^{-5} volume) of water resides in a network of *veins* between crystals (liquid due to surface tension effects).

Direct measurements of the water system at the bed are difficult. During summer (melt season) the glacier acts as a reservoir. During winter moulins, tunnels and such, close. In spring there is a delay for reopening, since it takes time to establish the connection between the surface and the bed.

The direction of water flow in and under glaciers is controlled by the water pressure potential, ϕ,

$$\phi = \phi_0 + p_w + \rho_w gz, \tag{8.1}$$

where
ϕ_0 is a constant,
p_w is water pressure,
z is elevation.

The water flow is perpendicular to the surfaces of constant ϕ. On such surfaces the gradient of ϕ is zero.

Figure 8.2 shows a schematic of the drainage system in a glacier.

Fig. 8.1 Picture of water flowing into an moulin (photo R. Braithwaite).

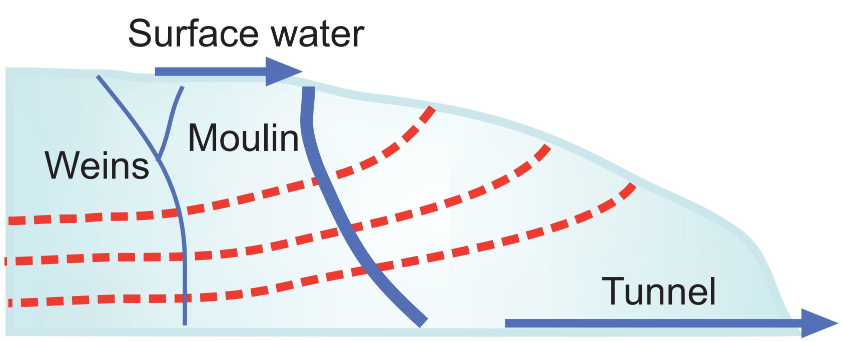

Fig. 8.2 Schematic of a drainage system in a glacier. The dotted lines are the equipotential surfaces, $\phi = constant$.

If we assume that the water pressure is $p_w = \rho_i g(z_s - z)$, that is due to ice overburden pressure in Equation 8.1, we get

$$\phi = \phi_0 + \rho_i g z_s + g(\rho_w - \rho_i)z.$$

As an example we use data about surface elevation and bed topography from Breidamerkurjökull (Figure 8.3) to calculate the water potential ϕ (Eq. 8.1) and direction of water flow $-\nabla\phi$. The results are shown in Figure 8.4.

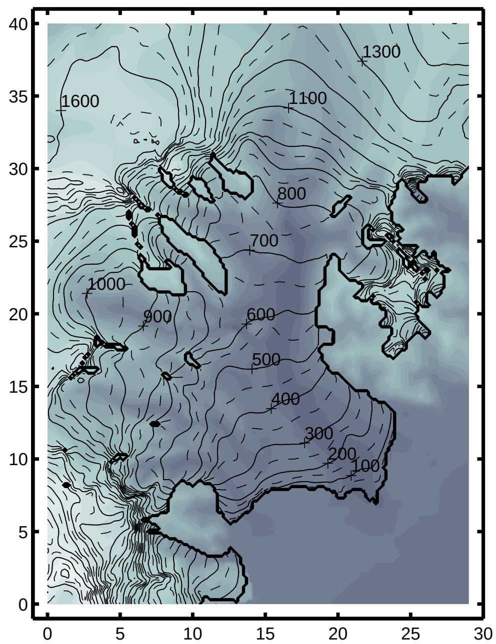

Fig. 8.3 Breidamerkurjökul and surrounding area. Contour-lines show the surface elevation, while the shading shows the bed elevation. The bed goes from -30 m below sea level, and up to 1807 m above sea level. The surface elevation ranges up to 2012 m above sea level. Data from Helgi Björnsson and Finnur Pálsson.

It is sometimes convenient to define the generalized pressure potential gradient,

$$G = \frac{dp_w}{ds} + \rho_w g \sin\theta, \tag{8.2}$$

the sum of the gradient of water pressure and gravitational potential energy. It is this pressure gradient that drives water flow in the glaciers.

Steady flow in a tunnel

Size of conduit determined by the balance of a) melting due to viscous dissipation and friction against the walls, and if the water above 0°C release of latent heat, and b) closure if the overburden pressure is greater than the water pressure. The response time is slow, on the order of week. Figure 8.5 shows a schematic of a tunnel.

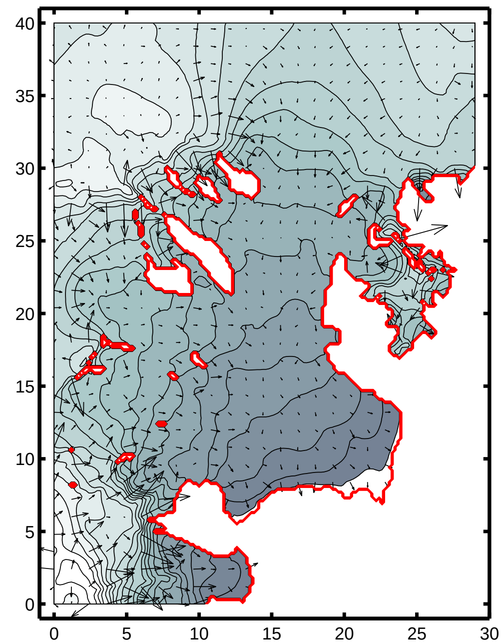

Fig. 8.4 Breidamerkurjökul and surrounding area (as in Figure 8.3). Water potential (Eq. 8.1) and water flow direction (using $-\nabla\phi$).

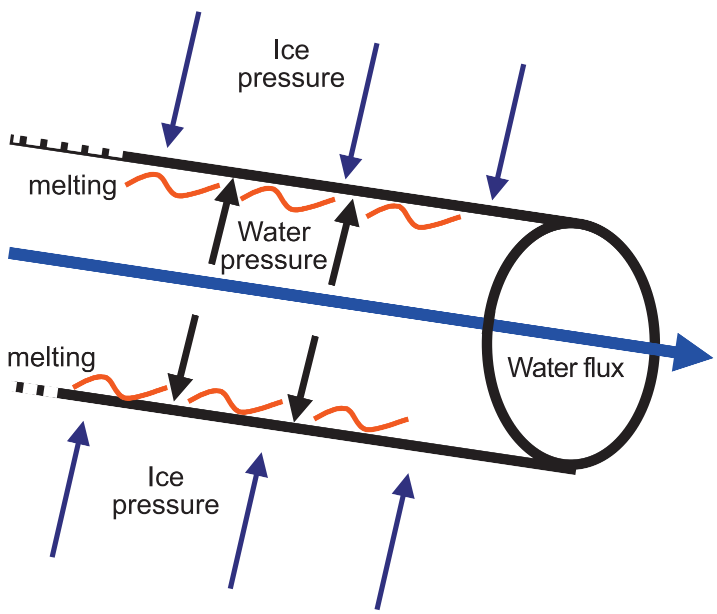

Fig. 8.5 Schematic of a tunnel. There is competition between melting (and water pressure) expanding the tunnel, and ice deformation trying to close it.

Large tunnels grow, since for increasing flux Q the water pressure p_w goes down. Closure rate due to ice deformation is given by,

$$w_c = \frac{dr}{dt} = rA\left(\frac{P}{n}\right)^n, \tag{8.3}$$

where

$$P = p_i - p_w,$$

$p_i = \rho g(z_s - z)$ is the ice overburden pressure, and p_w is the water pressure, and A is the constant from Glen's flow law, n is usually 3, and a circular hole has been assumed. For a constant P at any given depth, we find

$$r_c = r_0 \exp\left(At\left(\frac{P}{n}\right)^n\right), \tag{8.4}$$

from which we define a time-scale,

$$\tau = \left[A\left(\frac{P}{n}\right)^n\right]^{-1}. \tag{8.5}$$

Figure 8.6 shows the expected time-scale for a vertical bore-hole closure assuming that there is a) no water in the hole, b) that the water table is 50 m below the ice surface, and c) that the water table is 100 m below the ice surface. The closure time is nearly infinite near the surface, since the overburden pressure is low. Deeper in the borehole the closure time can get very short, close to a day at 400 m depth when no water. If there is water, it will provide a pressure that counteracts the ice overburden pressure. Thus, if the water level is 50 m below the surface, the borehole will take much longer to close than if there is no water, or if the water level is 100 m below surface.

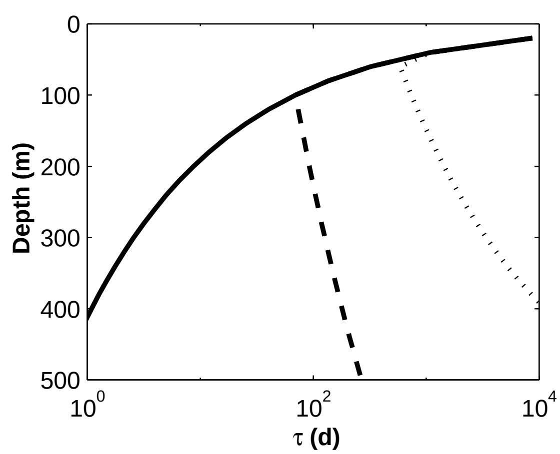

Fig. 8.6 The time-scale for closure assuming that there is no water in the bore-hole (solid line), that the water table is 50 m (dotted line) and 100 m (dashed line) below the ice surface.

In steady state the radius must be constant, so we need to melt away all the ice that enters the perimeter of the tunnel. Then the ice melted per unit length (mass) has to be,

$$M = 2\pi r\dot{r}\rho_i, \tag{8.6}$$

substituting r from Equation 8.3, we get

$$M = 2\rho_i SA\left(\frac{P}{n}\right)^n,$$

where $S = \pi r^2$, is the cross-sectional area, and $P = p_i - p_w$.

Heat is produced by the work done by gravity and pressure, and is used to warm and melt the ice. So per length ds and unit time the heat produced is $Q(\rho_w g\sin\theta + dp_w/ds)$. But when water flows a distance ds its pressure drops by dp_w, so surrounding ice warmer by Cdp, where C is the change in melting temperature with pressure. Need to warm the water, which requires $Q\rho_w c_w Cdp/ds$, the heat used for melting is ML_f, where L_f is the latent heat of fusion,

$$Q\left(\rho_w g\sin\theta + \frac{dp}{ds}\right) = Q\rho_w c_w C\frac{dp}{ds} + ML_f, \tag{8.7}$$

or $ML = Q\left(G - E\frac{dp}{ds}\right)$, where $G = \rho_w g\sin\theta + \frac{dp}{ds}$, and $E = \rho_w c_w C = 0.3131$, where $\rho_w = 1000$ kgm^{-3}, $c_w = 4.22$ kJkg^{-1}K^{-1}, $C = 7.42\times 10^{-8}$ KPa^{-1}.

Size S can be related to Q and dp/ds by the empirical Manning formula for the mean velocity in turbulent flow,

$$\frac{Q}{S} = \frac{R^{2/3}}{m}\sqrt{\frac{G}{\rho_w g}}, \tag{8.8}$$

where R is the hydraulic radius (cross sectional area divided by perimeter), m the Manning roughness parameter $\sim 10^{-2} - 10^{-1}$ m$^{-1/3}$ s. For circular pipe,

$$R = \frac{\pi r^2}{2\pi r} = \frac{r}{2}.$$

Eliminating M and S we can relate Q, dp/ds, p. The net result being that increase in flux Q leads to reduced water pressure p_w (Figure 8.7), which means that large tunnels capture water from small tunnels [14, see chapter 6].

Water at the bed

Water at the bed of a glacier can flow there in several configurations:

- Channels cut upward into the ice, Röthlisberger -, or R-channels.

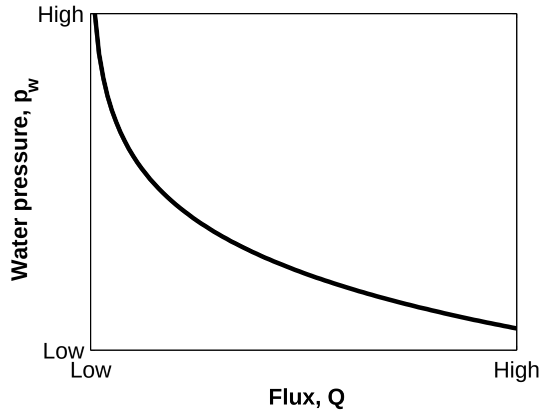

Fig. 8.7 As the flux Q in tunnels increases, the water pressure p_w drops.

- Channels in the bedrock, Nye -, or N-channels.
- Canals on soft bed, broad and shallow. If flux increases, the water pressure also increases, so they stay separate and small.
- Linked cavities. Closure rate w_c and melt rate w_m the same as for tunnels. Assuming that the length l is much greater than the height r of the cavity, then the time it takes a particle to move from the top of the cavity to the end (from A to B in Fig. 8.8) is, for the vertical movement, $t = r/(w_c - w_m)$, but also, for the horizontal displacement, $t = l/u$, where u is the horizontal velocity of the ice, therefore

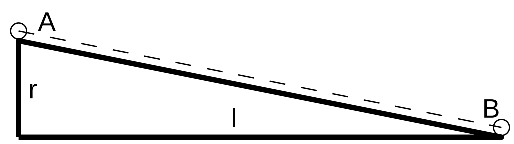

Fig. 8.8 Highly simplified geometry of a cavity. By calculating how fast the particle moves vertically and horizontally, from point A to point B, we can estimate the lenght l (see Eq. 8.9).

$$l = \frac{ru}{w_c - w_m}. \tag{8.9}$$

If the flux increases, the pressure increases.

Figure 8.9 shows these four types of possible pathways at the ice/bed interface.

8.2 Jökulhlaup

Definition 8.1. Jökulhlaup are catastrophic events where large amounts of water are suddenly discharged.

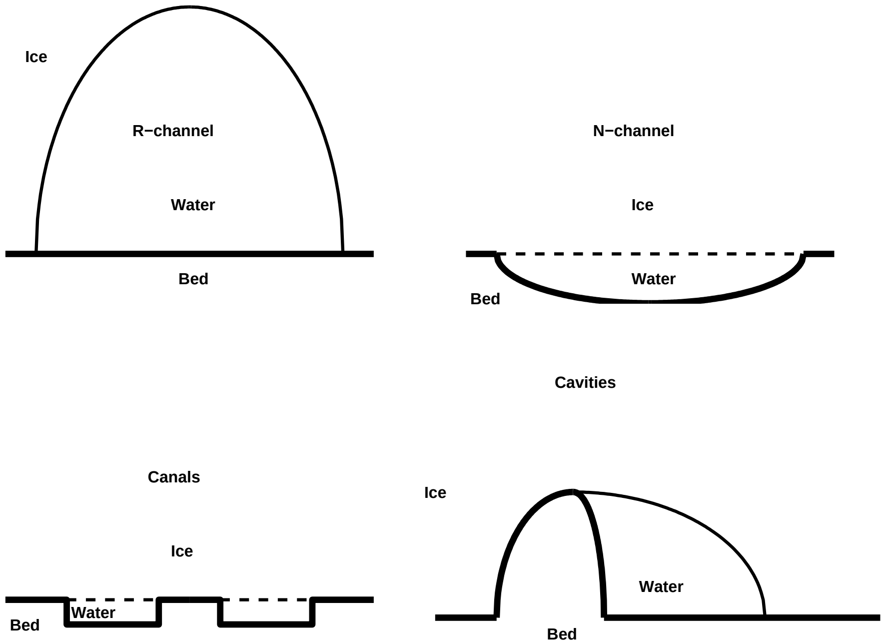

Fig. 8.9 Schematic of tunnels and channels at the bed. Röthlishberger-channels are cut up into the ice, Nye-channels are cut into the bedrock, canals are shallow and broad features in sediments, and cavities form on the lee side of bedrock bumps.

Jökulhlaup's are a sudden and rapid draining of a glacier dammed lake or of water impounded within a glacier. What causes jökulhlaup: 1) Glacier blocks a stream in a valley, 2) geothermal melt collects beneath the glacier, 3) water collects behind a moraine left by retreating glacier.

Effects of jökulhlaup's are for example: a) Flooding, fast and without much warning, b) loss of life, c) destruction of roads, railways etc.

How big are jökulhlaup's:

- Grimsvötn, Iceland, 1996: Peak flow $5 \cdot 10^4$ m^3 s^{-1} (about 1000 times the normal Snohomish river, WA USA, discharge).
- Katla, Iceland: 10^6 m^3 s^{-1}.
- Lake Missoula: 10^7 m^3 s^{-1} estimated.

Mechanics of jökulhlaup

When the ice is thick and the lake shallow, the glacier is a very good dam. The flow of ice can seal cracks; as long as the pressure from the overlying ice is much larger than that of the water trying to get out through the cracks. If the lake is deep the glacier is not a good dam. Water can flow englacially in tunnels. If the water pressure is close to or higher than the ice overburden pressure, there is nothing the tunnel can do to reduce the pressure, but to grow.

As water starts to push through the crack, a tunnel forms. Then it grows as more water flows through it, since the flowing water also melts the inside of the tunnel. The melting process is much more rapid than the tunnel closure, so the tunnels can grow very rapidly.

Ice floats in water, so the water may actually lift up its dam.

Jökulhlaups often end suddenly. That is because rock level for the lake has been reached, all the water has drained, or the collapse of tunnels due to reduced pressure.

Types of glacier-dammed lakes

Moraine-dammed lakes

Ice retreats from a large terminal moraine, and a lake forms between the moraine and glacier.
Examples: 1) Nostetuko Lake, BC. The Little Ice Age moraine dammed a lake that drained catastrophically by cutting a channel through the moraine in 1983, see Figure 8.10. 2) Manang, Nepal. The town of Manang is across the valley and above is the moraine dammed lake, see Figure 8.11.

Marginal lakes

Glacier blocks a normal drainage channel. In Peru, the lake Laguna Parron, is formed by a debris covered glacier terminus that forms the dam, see Figure 8.12. The lake level has been lowered by drilling a tunnel through the bedrock.

Lake Russell, Alaska, formes when a glacier block off a fjord, see Figure 8.13. Hubbard glacier is a large glacier ending in the ocean near Yakutat, Alaska. In May 1986 a surge of the Valerie glacier, a tributary of Hubbard glacier caused Hubbard to advance across the entrance of Russell fjord, turning the fjord into a lake. The lake rose to 25.5 m above sea level. On October 8, 1986, the ice dam burst and Lake Russell drained in a few hours back down to sea level. The peak flow was about 100,000 m^3.

Sub-glacial lakes

A geothermal area (possibly volcano) melts the glacier ice. A good example of such lakes is Grimsvötn, Iceland.

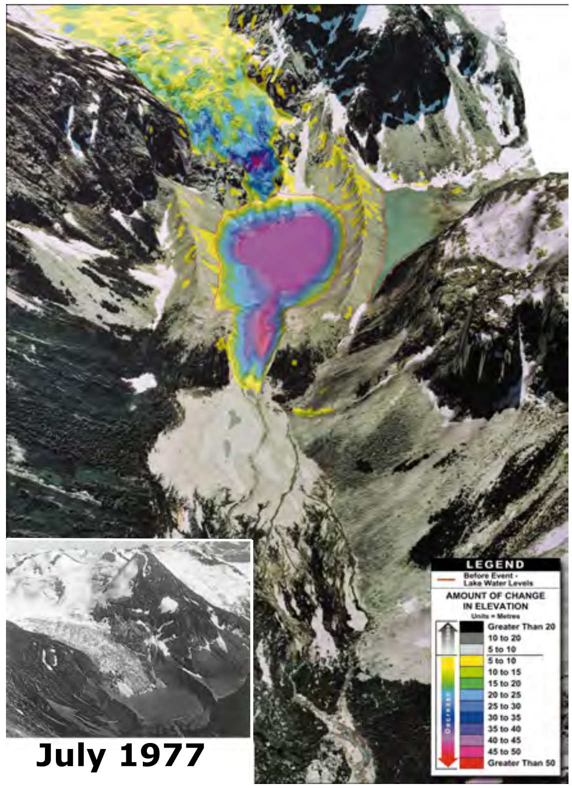

Fig. 8.10 Nostetuko Lake, BC. Drained catastrophically in 1983 [3].

Jökulhlaups from Grimsvötn have been monitored extesively since the 1930's. Much is known about the geometry and conditions leading to jökulhlaups from Grimsvötn.

Let us first consider the geometry of the lake:

- A geothermal area melts ice from the base to form a lake which leads to a depression at the surface which collects surface melt-water into the lake.
- The lake is almost completely covered with a 250 m thick ice shelf.
- Drains through a sub-glacial passage 50 km long.
- Typical hydrographs: Rise $\sim$10 days, Fall $\sim$2 days.
- Water level drops by $\sim$60 m.

Some typical numbers of jökulhlaups from Grimsvötn are:

- Peak flow: 600 - 40 000 $m^3 s^{-1}$
- Total volume: 0.5 - 4.0 km^3
- Size of tunnel: 25 - 85 m radius (1996 flood)
- The 1996 flood: 3.2 km^3 of water in 40 hrs
- Periodicity: 1 - 10 yrs

Initiation of flow occurs when:

Fig. 8.11 Manang village, Nepal. Above the village is the moraine dammed lake formed behind the morain left by the Gangapurna glacier.

Fig. 8.12 Laguna Parron, Peru, is a marginal lake where a glacier terminus forms the dam.

- Water level is still ∼20 - 70 m below floatation, so floatation is not necessary.
- Excess pressure shear stress at 45 deg to vertical wall. If shear stress larger than 100 kPa (200 m water level) then plastic flow of ice. But jökulhlaup happen at lower lake levels; would have reached the floatation level of the ice before this could applys.
- Flow through tunnels, and melting out of tunnels.

Figure 8.14 shows two hydrographs for jökulhlaups from Grimsvötn.

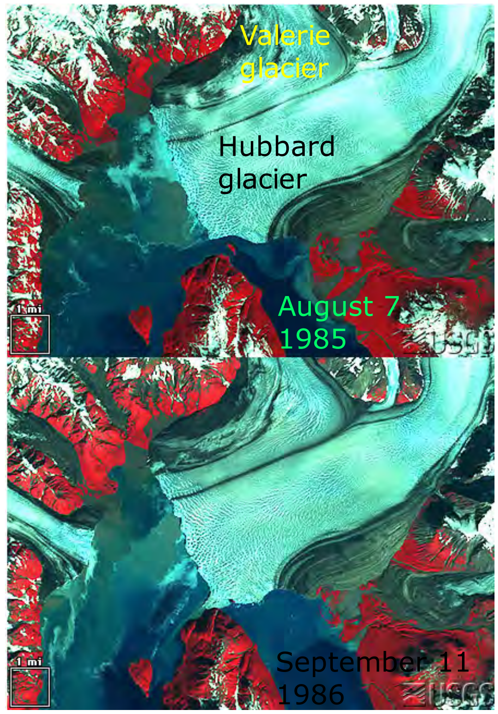

Fig. 8.13 Lake Russell, Alaska. Formes when the Hubbard glacier blocks off Russell fjord (lower right); often due to a surge in Valerie glacier.

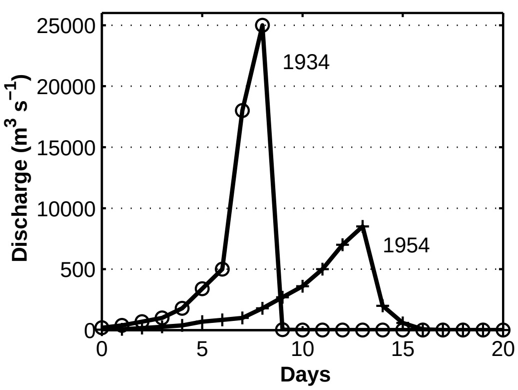

Fig. 8.14 Hydrographs from the 1934 and 1954 jökulhaups from Grímsvötn.

Further Reading

- Baker, V. (1995). Surprise endings to catastrophism and controversy on the Columbia. GSA Today, 15(9).
- Björnsson, H. (1992). Jökulhlaups in Iceland: predictions, characteristics and simulation. Annals of Glaciology, 16, 95 - 106.
- Björnsson, H. (1998). Hydrological characteristics of the drainage system beneath a surging glacier. Nature, 395, 771 - 774.
- Krimmel, R. M. and D. C. Trabant (1992). The terminus of Hubbard Glacier, Alaska. Annals of Glaciology, 16, 151 - 157.
- Parfit, M. (1995). The floods that carved the West. Smithsonian, 26(1), 48 - 59.

8.3 Problems

Hydraulogy Problems

8.1. In 2-D, what is the slope of the equipotential surfaces? Find the gradient ($\frac{d}{dx}\phi = 0$) of $\phi = \phi_0 + \rho_i g z_s + g(\rho_w - \rho_i)z$, where z and z_s are functions of x.

8.2. Can water flow uphill? If yes, what are the limitations?
The dircetion of flow in R-channels at the bed is determined by the gradient of ϕ, and is $-\nabla\phi$. In the given equation above put $z = z_b$, the bed elevation. Should get an equation in the format $\nabla\phi = a(\nabla z_s + b\nabla z_b)$, where a, b are constants.

8.3. Discuss the limitations of using ϕ to determine the direction of water flow.

8.4. Length of cavity. Consider a glacier where we know that the melting rate was 10 m a^{-1}, and the closure rate 50 m a^{-1}. We also measure the length of a cavity at the bed, and it is $\sim$4 m behind a boulder that is 1 m high. How fast was the glacier moving (horizontally) ?

8.5. a) Calculate the closure rate of a circular hole at a depth of 200 m. Use $A = 6.15 \cdot 10^{-15}$ s^{-1} kPa^{-3}, $n = 3$, $\rho_i = 917$ kg m^{-1}, and $g = 9.82$ m s^{-2}.
b) How long would it take to close a hole with a radius of 2 m?
c) How much needs to be melted per unit length?

Jökulhlaup Group Questions

8.6. Hydrographs are the records of discharge in rivers over time. The flux is calculated from the “stage” or height of a river in its banks.
(a) Suppose a watershed has no glaciers or lakes. When a rainstorm occurs in the watershed, water gets into the main channel in several ways:

- rainfall directly into channels
- direct over-land flow into tributary streams and channels which then flow into the main channel
- seepage raising the groundwater table (storage), followed by slow seepage out into streams as the water table falls back over the course of hours or days.

What does a typical hydrograph on the main channel look like after a rainstorm in this valley ?
Does the river rise rapidly or slowly?
Does it fall rapidly or slowly?
(b) Suppose a glacier dammed lake is about to fail. A glacier outburst flood starts with a very small leak from the lake as the dam approaches the flotation level.
What does a typical hydrograph on the main channel look like after an outburst flood up the valley ?
Does the river rise rapidly or slowly?
Does it fall rapidly or slowly?
(c) ***As a Park Ranger, how might you tell if an outburst flood is starting?***

8.7. Building up to a jökulhlaup.
Your group will describe the events leading to a jökulhlaup from a glacier-dammed river.
(a) Suppose the river is running freely out of the valley when a nearby glacier surges.
What happens when the glacier blocks the river?
Behind the dam, in front of the dam
(b) ***When can we expect an outburst flood?***
How much water (think about the height of the water column as a fraction of ice thickness) has to accumulate ?
If the water is 45 m deep, how thick is the ice dam ?
How long would it take to fill the lake to this level ?
- Assume that you have dammed a reasonably big river with normal river flow of 45 m^3s^{-1} (Snohomish $\sim$47 m^3 s^{-1})
- you can estimate the volume of water that is needed before a flood will happen if you know that the lake covers an area 1 km wide and 10 km long ($\sim 10^7$ m^2)
- use 1 yr $\sim 3 \cdot 10^7$ s
(c) ***How will the area where the river used to run be affected ?***
What is the river flow be like, what would happen to a salmon hatchery in ponds downstream ?
Would the turbulent current be likely to deposit something ?

8.8. Initiation of jökulhlaup. Describe the final moments of the ice dam.
(a) ***What happens when the water level reaches the critical height ?***
Think in terms of floatation, leakage, tunnels
(b) ***Why do the tunnels grow rapidly ?***
Is the pressure high or low ?
Is the water moving slowly or quickly, what does that mean for melting ?

(c) ***Why the sudden end to the jökulhlaup ?***
Where is the water ?
What happens to the tunnels ?

8.9. ***Flow rate***. A standard faucet runs 1 l every 10 seconds.
How long would it take to discharge 50$\cdot 10^3$ m^3 of water ?
The total discharge during a jökulhlaup is sometimes $\sim$4 km^3, and normal river flow is 40 m^3 per sec (1/1000 of jökulhlaup discharge rate).
How long would it take to discharge the 4 km^3 (compare to 2.5 days during jökulhlaup)?

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