Chapter 4
Surface water

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As precipitation falls to the surface, parts of it may be intercepted by plants, before it ultimately reaches the ground. Once on the ground, water can infiltrate into the soil or move across the surface as runoff. Surface runoff generally occurs when the rainfall intensity exceeds the rate of infiltration, or if the soil is at its water holding capacity. Infiltration and water holding capacity are both a function of soil texture and structure. Soils composed of high percentages of sand allow water to infiltrate through them quite rapidly because they have large, well-connected pore spaces. Clay soils have low infiltration rates due to their smaller sized pore spaces. However, there is actually a smaller total amount of pore space in a unit volume of coarse, sandy soil than that of soil composed mostly of clay. As a result, sandy soils fill rapidly and generally generate runoff sooner than clay soils.

Once surface runoff occurs, water runs across the surface as either confined or unconfined flow. Unconfined flow moves across the surface in broad sheets of water often creating sheet erosion. Confined flow refers to water confined to channels. Stream flow is a form of confined flow.

Water that runs along the surface may become trapped in depressions and held as depression storage. Here water may either evaporate back into the air, infiltrate into the ground or spill out of the depression as it fills.

4.1 Stream flow

Stream flow is measured in a variety of ways, one of which is stream discharge. Stream discharge is the volume of water passing through a particular cross-section of a stream in a unit of time. Stream discharge is usually measured in cubic meters per second. The “normal”, or base flow, of a stream is provided by seepage of groundwater into the stream channel. This seepage is what keeps perennial flowing streams going all year. Note in Figure 4.1, for instance, how the water table intersects the level of the stream surface. When precipitation from a storm occurs, the stream discharge increases as water is added to the stream, either from direct precipitation into the channel or runoff.

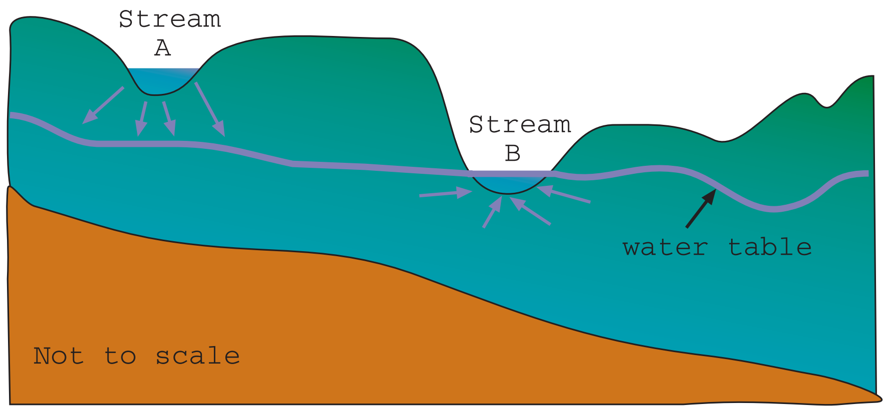

Fig. 4.1 Gaining and losing streams. Stream A is a losing stream, while stream B is a gaining one.

Events during precipitation

The amount of water intercepted by dense forests ranges from 8 - 35 % of the total annual precipitation. Water can form puddles, called *depression storage*. They ultimately evaporate or the water infiltrates into the ground. Depression storage occurs when precipitation rate exceeds the infiltration capacity (and/or when ground is frozen or saturated). Snow is an important source of water in spring in some places.

Hydrographs

A stream hydrograph shows the discharge at a single location over time. The size, shape, land use, vegetation, and geology of the watershed that the stream is found in, all determine runoff and the shape of the discharge graph.

Groundwater contribution to a stream is called *base flow*, while the total flow is *runoff*. The runoff will decay if there is no excess precipitation, *baseflow recession*, according to,

$$Q = Q_0 \exp(-at), \tag{4.1}$$

where Q is the flow at time t, Q_0 is the flow at the start of the recession, a is a recession constant, and t is the time since the recession began [5, see Figure 2.12 for example].

Storms can often be seen in hydrographs, as overland flow, direct precipitation, interflow, and baseflow increase. Separation of these components can be tricky; depends on local conditions.

Streams in humid regions typically recieve groundwater discharge, therefore the baseflow increases downstream; even if no tributaries enter. In arid regions, or if the bottom of the stream is above the water table, the stream will be losing, that is, water will leave the river and recharge the groundwater. A schematic of this situation is shown in Figure 4.1 (stream A).

A gaining stream may become a loosing one during floods when the banks of the river are above the water table. Some water is then stored at the banks, called *bank storage* (Figure 4.2).

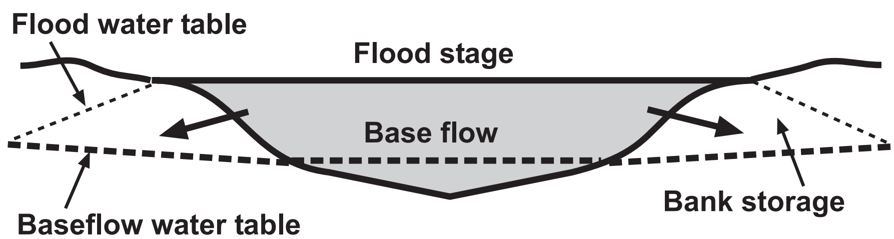

Fig. 4.2 A gaining stream may temporarly become a losing one during a flood.

The relationship between rainfall and runoff is described by the *rational equation*,

$$Q = CIA, \tag{4.2}$$

where Q is the peak runoff rate in [$\mathrm{L}^3\ \mathrm{T}^{-1}$], I average rainfall intensity in [$\mathrm{L}\ \mathrm{T}^{-1}$], A is the surface area in [L^2], and C the runoff coefficient, see Table 4.1 (modified from [5], table 2.3).

Table 4.1 Runoff factor for rational equation (4.2)

Character of surface	C
Pavement, roofs	0.70 - 0.95
Lawns (flat to steep), sandy soil	0.05 - 0.20
Lawns (flat to steep), heavy soil	0.13 - 0.35

The *Manning equation* gives the average velocity of flow of water in an open-channel,

$$v = \frac{1}{n} R^{2/3} S^{1/2}, \tag{4.3}$$

where, v is the average velocity (m s^{-1}), R the hydraulic radius (m), S the slope of the water surface, and n is the Manning roughness coefficient. The hydraulic radius R is the cross-sectional area divided by the wetted perimeter, as shown in Figure

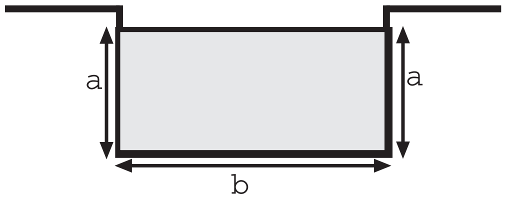

Fig. 4.3 The hydraulic radius for this open channel is $R = \frac{a \cdot b}{a+b+a}$.

4.3. The Manning coefficient n varies from 0.012 for smooth concrete to 0.05 for mountain streams with rocky beds [5, p. 59].

4.2 Iceland and the world

Iceland is special in the sense that it receives a lot of precipitation, see Figure 4.4, ranging from about 500 mma^{-1} to 2 000 mma^{-1} on lowland, up to 5 000 mma^{-1} for high elevations, but the evaporation is small. That leads to much surface- and groundwater.

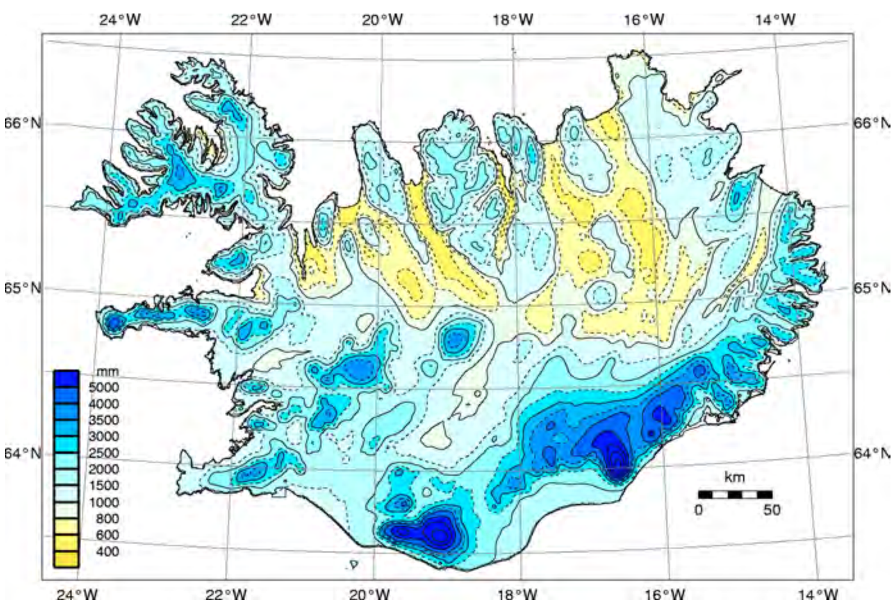

Fig. 4.4 Mean annual precipitation in Iceland for the years 1971–2000. The values are based on measurements on the ground, and calculations for the interpolation. Data from the Icelandic Meteorological Office.

The mean run-off is 55 l km^{-2}, which carries with it about 500×10^3 kg km^{-2} a^{-1} of sediments [12].

A satellite photo (NASA's Aqua satellite) from August 27, 2007 (Figure 4.5) shows the main glaciers, lakes and rivers in Iceland. Clouds cover parts of the north, and Faxaflói. Note also the muddy waters off the coast, especially along the south, and south eastern coast.

Fig. 4.5 Satellite photo from the Aqua satellite, on Aug. 27, 2007, of Iceland showing the main glaciers, lakes and rivers. Image courtesy of MODIS Rapid Response Project at NASA/GSFC.

Precipitation

The mean yearly precipitation in Reykjavík during 1961 - 2003, was about 810 mm, with a maximum of 1 095 mm in 1991 and minimum of 610 mm in 1965, see Figure 4.6. The monthly precipitation varies a lot, with a maximum monthly precipitation of 260 mm in November 1993, and a minimum of just over 2 mm in June 1971, see Figure 4.7. The greatest daily precipitation in Iceland of 293,3 mm was measured at Kvísker on January 10, 2002.

In the Himalayas some areas receive 11 m a^{-1} rainfall, most of that in 2 months [9]. The greatest measured annual precipitation is in Hawaii, on Mount Waialeale, Kauai, 11 680 mm a^{-1} (32-year average). The greatest monthly precipitation recorded was in Cherrapunji, India, 9 300 mm in one month.

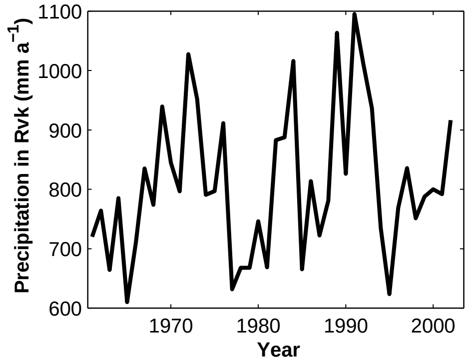

Fig. 4.6 Yearly precipitation in Reykjavík 1961 - 2003. The mean annual precipitation for the period is 810 mm a^{-1}.

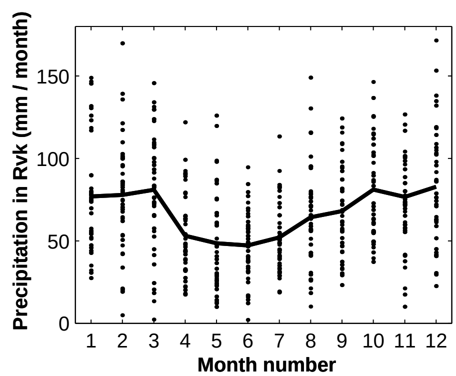

Fig. 4.7 Monthly precipitation in Reykjavík 1961 - 2003. Dots are individual years, and the solid line is the mean for each month over the period. The maximum of 260 mm in November 1993 is off the scale.

Lakes

There are many names for lakes in Iceland, but the main catagories are: Jökulvötn (glacier lakes), lindvötn (spring lakes), and dragvötn (from surface drainage).

Lakes with surface area $A \geq 0.1$ km^2 are about 1 850, and cover about 1.5% of the surface area of Iceland, or 1 300 km^2. Lakes in the range $0.01 \leq A < 0.1$ km^2 have been estimated to be somewhere around 7 000, covering about 100 km^2 [12].

The largest natural lake in Iceland is Thingvallavatn (in Árnessýsla) 82 km^2, and about 114 m deep where it is deepest. The deepest water is Öskjuvatn, which reaches 220 m depth. Mývatn (37 km^2) in the north is also well known for its nesting ducks and active ecosystems. Thórisvatn (reservoir lake) is the largest lake in Iceland, it can reach 88 km^2 when full, but goes down to about 56 km^2 during low stands (www.lv.is).

Lake Vostok (Figure 4.8), Antarctica, is possibly the largest freshwater lake in the world. It is below 4 000 m of ice, and is 250 km long and 40 km wide (extremes), and reaches 800 m depth. The Caspian Sea is the largest inland body of water at 371

000 km^2. Lake Baikal is the deepest freshwater lake in the world, with a maximum depth of 1 637 m (encarta.msn.com).

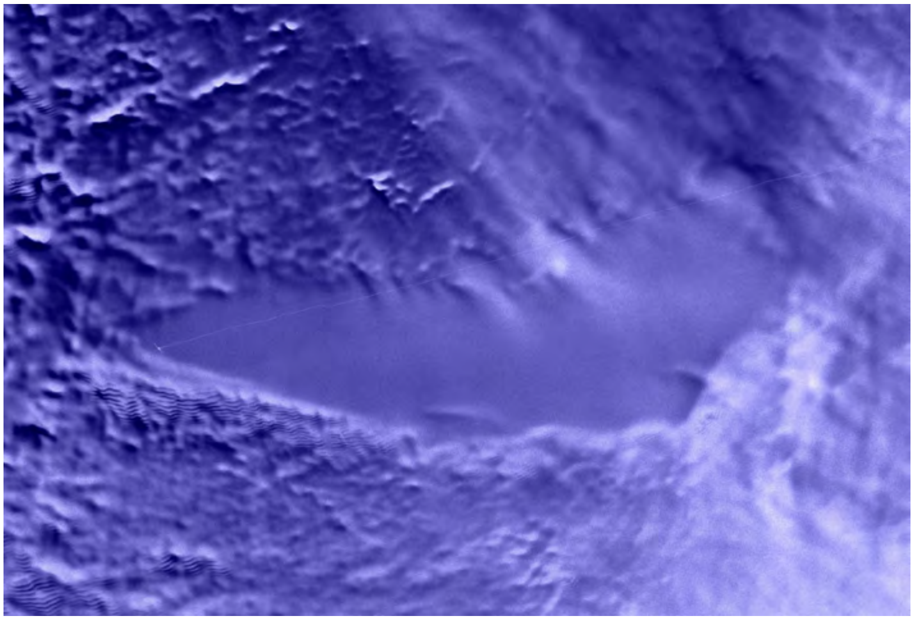

Fig. 4.8 Lake Vostok, Antarctica. Radarsat image from NASA/Goddard Space Flight Center Scientific Visualization Studio.

Rivers

The total number of rivers in Iceland is about 750 and their cumulative length is about 14 000 km [12]. Of that, direct run-off rivers account for 85% of the number and 75% of the length.

The longest rivers are Thjórsá about 230 km, Jökulsá á Fjöllum 206 km, and Ölfusá / Hvítá 185 km (www.sumarbustadur.is/upplysingar/tolfraedilegar.htm). The mean discharge (flux) is about 423 m^3 s^{-1} for Ölfusá near the town Selfoss.

The world's longest rivers are: Amazon 6 762 km, Nile 6 690 km, and Yangtze 6 380 km (en.wikipedia.org/ wiki/ River). Figure 4.9 shows the Nile river as it runs through Egypt. Note especially the strip of agriculture on either side of the river in the middle of the desert.

The Yellow river (Huang He) carries more than a billion tons of loam (sediments) to sea every year, 12% of the world's river sedimentary load, but it accounts for only 0.1% of the world's river flow (volume of water) [9].

Fig. 4.9 The Nile river running through Egypt in 2004 (MODIS image from NASA).

Bangladesh

Bangladesh is on the flood plain of three rivers, the Brahmaputra, the Meghna and the mighty Ganges (called Padma in Bangladesh), see Figure 4.10. These great rivers are practically Bangladesh's only natural resource. Although almost two metres of rain fall on Bangladesh each year, more than two-thirds arrive in just four months. The area is very heavily populated, with 920 people per km^2, a total of 400 million people [4]; Bangladesh alone has over 150 million people, and population density of 1 045 per km^2 in 2007 (www.wikipedia.com).

Although there is lots of water, there are many problems related to sanitation and access to clean water in Bangladesh; especially during floods. There was a huge international effort to drill for groundwater, and that worked well at first. But many of the wells soon got poisoned by arsenic. The arsenic is naturally derived from the Himalaya sediments. Therefore there is strickt monitoring of water quality in those wells.

At the same time, much effort and resources were used to build dams and walls to control flooding. That resulted in even bigger problems, the water has to reach the ocean somehow. More recent plans are concerned with timely evacuations to prevent loss of life during floods.

Waterfalls

The most voluminous waterfall in Europe is Dettifoss, which is 44 m high. Other well known waterfalls in Iceland are Gullfoss (32 m) in Hv́ítá-river (Figure 4.11), and Skógarfoss (60 m) (digicoll.library.wisc.edu/cgi-bin/IcelOnline/). The highest waterfall in Iceland is Glymur in Botnsá-river, 190 m.

The highest waterfall in the world is Angel (Salto Angel) in Venezuela 979 m high. Tugela in S-Africa is the second highest, 850 m. Two waterfalls in Norway are next on the list, Utigordsfoss 800 m and Mongefoss 774 m high.

Wetlands

The soil in wetland areas is saturated with moisture, such as in swamps, marshes and bogs.

In Iceland the permeability of wetland areas is typically around $10^{-4} – 10^{-9}$ m s^{-1}, and the slope $10^{-3} – 10^{-1}$ [18].

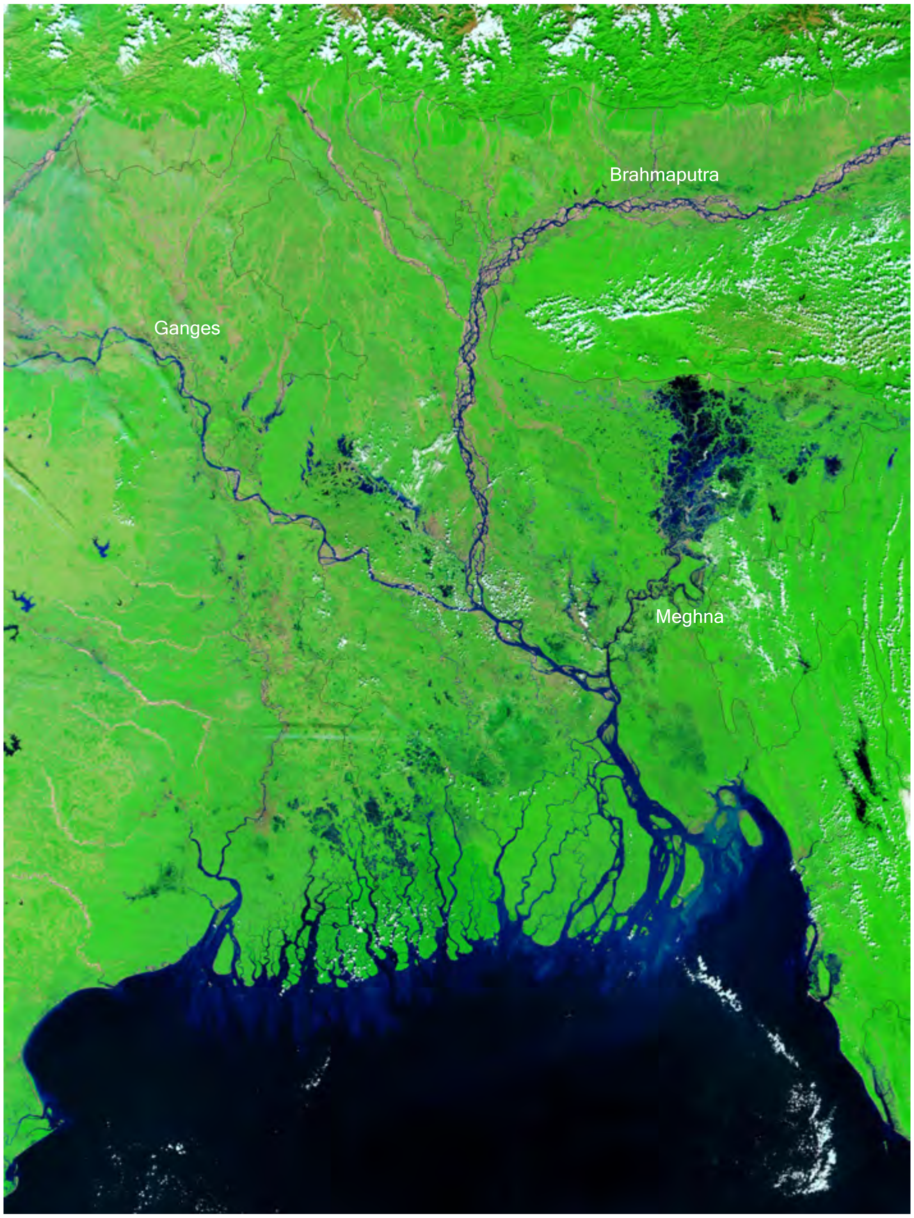

Fig. 4.10 Bangladesh and adjacent area on August 5, 2002. The three main rivers, the Brahmaputra, Ganges and Meghna, are clearly visible. Image from NASA (www.nasa.gov).

Fig. 4.11 The Gullfoss waterfall (photo Throstur Thorsteinsson, 2006).

Geothermal areas

Active, high-temperature geothermal areas (háhitasvædi), are were the temperature at depths shallower than 1 km is above 200°C. Geysir's (Figure 4.13) are found in those areas, Geysir in Iceland, and Old Faithful in Yellowstone National Park, being the most famous examples. Low-temperature geothermal areas (láhitasvædi) are where the temperature for $z < 1$ km is $T < 150$°C.

Fig. 4.12 The Salto Angel waterfall in Venuzuela (www.wikipedia.com).

Fig. 4.13 The Strokkur Geysir in Haukadal, Iceland (Throstur Thorsteinsson, 2006).

In low-temperature geothermal areas, the springs are called *hverir* if $T > 70°C$, *laugar* if $T \simeq 30 - 70°C$, and *volgrur* if if $T \simeq 10 - 30°C$ [21].

Geyser activity

Geyser activity, like all hot spring activity, is caused by surface water gradually seeping down through the ground until it meets rock heated by magma. The geothermally heated water then rises back toward the surface by convection through porous and fractured rock. Geysers differ from non-eruptive hot springs in their subterranean structure; many consist of a small vent at the surface connected to one or more narrow tubes that lead to underground reservoirs of water.

As the geyser fills, the water at the top of the column cools off, but because of the narrowness of the channel, convective cooling of the water in the reservoir is impossible. The cooler water above presses down on the hotter water beneath, not unlike the lid of a pressure cooker, allowing the water in the reservoir to become superheated, that is, to remain liquid at temperatures well above the boiling point.

Ultimately, the temperatures near the bottom of the geyser rise to a point where boiling begins; steam bubbles rise to the top of the column. As they burst through the geyser's vent, see Figure 4.14, some water overflows or splashes out, reducing the weight of the column and thus the pressure on the water underneath. With this release of pressure, the superheated water flashes into steam, boiling violently throughout the column. The resulting froth of expanding steam and hot water then sprays out of the geyser.

Eventually the water remaining in the geyser cools back to below the boiling point and the eruption ends; heated groundwater begins seeping back into the reservoir, and the whole cycle begins again. The duration of eruptions and time between successive eruptions vary greatly from geyser to geyser; Strokkur in Iceland erupts for a few seconds every few minutes, while Grand Geyser in the USA erupts for up to 10 minutes every 8-12 hours.

Glaciers

Iceland is home to the largest glacier in Europe, Vatnajökull which about 8 300 km^2. Some of the other large glaciers are Langjökull 953 km^2, Hofsjökull 925 km^2, Mýrdalsjökull 596 km^2, see Figure 4.15.

Fig. 4.14 The Strokkur Geysir in Haukadal bursting, Iceland. Photo: Throstur Thorsteinsson, 2006.

4.3 Problems

Surface water problems

4.1. Use the Manning equation (4.3) to calculate the flow velocity of a river. Assume a circular river bed (half a circle), with a radius $r = 1$ m, and a roughness coefficient $n = 0.02$. The river surface drops by 10 m vertically for every 100 m horizontal.

4.2. Calculate the coefficient a in the base flow recession equation $Q = Q_0 \exp(-at)$ (4.1), from the values given for the decrease in flow rate as a function of time in Table 4.2.

Table 4.2 Base flow recession data

Time, t (months)	**Flow**, Q (m^3s^{-1})
0	500.00
1	183.93
2	67.67
3	24.89
4	9.15
5	3.37
6	1.24

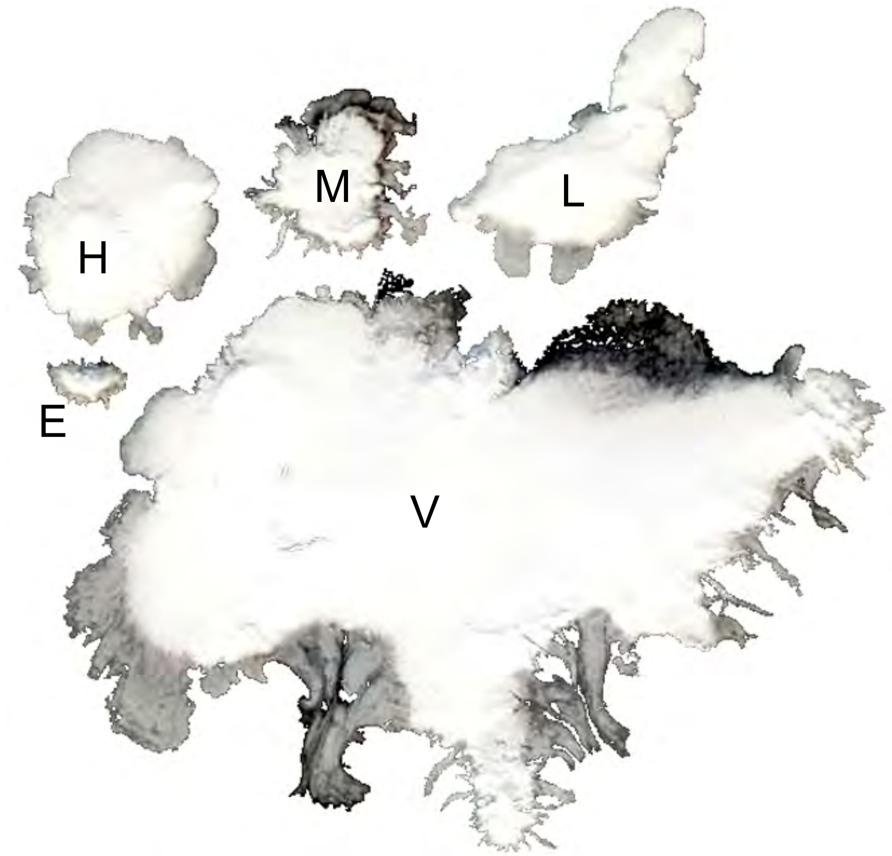

Fig. 4.15 Some of the main glaciers in Iceland. The outlines and shapes are taken from Fig. 4.5. Here E is for Eyjafjallajökul, H is Hofsjökull, M is Mýrdalsjökull, L is Langjökull, and V is for Vatnajökull.

Hint: Rewrite the equation as Q/Q_0 *and take the logarithm off both sides, which gives* $\ln(Q/Q_0) = -a \times t$.

4.3. Now it starts to rain heavily. Using the rational equation (4.2), how much discharge can we expect from a 100 m^2 area if it is: a) a parking lot, b) flat lawn (grass), or c) grassy hill?

4.4. Using realistic numbers for the width and depth of some Icelandic river, calculate the average velocity assuming a) a rocky bed, and b) smoothed concrete.


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