8.6 Water in Glaciers and Ice Sheets

NF Glasser, Aberystwyth University, Aberystwyth, UK

Abstract

Glacial meltwater is an important component of the glacial system. Water flow through glaciers and ice sheets (glacier hydrology) is an important control on the dynamics of glaciers and ice sheets. This contribution describes the sources of meltwater on glaciers and ice sheets, explains how water is stored in and moves through glaciers, describes the methods used to study glacier hydrology, outlines the principles of subglacial water pressure and evaluates the processes of glacial meltwater erosion. It also explains the characteristics and significance of glacier hydrology and how meltwater flows in supraglacial, englacial, and subglacial positions. Subglacial meltwater is particularly strongly linked to glacier motion through enhanced glacier sliding and because subglacial meltwater is required for subglacial sediment deformation. The processes of glacier erosion related to meltwater flow in ice sheets and glaciers are also described.

8.6.1 Introduction

Water flow through glaciers is important for a number of economic, social, and scientific reasons. On many glaciers meltwater is the main ablation product and runoff from these glaciers is an important economic asset in many parts of the world, providing water for drinking and sanitation, irrigation for crops, and hydroelectrical power. Where water is stored in or beside a glacier, its sudden release can constitute a glacier hazard. Rapid drainage of moraine-dammed or ice-dammed lakes can threaten lives and infrastructure downstream. Glacial meltwater removes debris from the ice–rock interface and carries it beyond the confines of the glacier, where it is deposited. Finally, glacier hydrology is an important control on the dynamics of glaciers and ice sheets. Water flow through glaciers is intimately related to glacier dynamics through glacier motion, through enhanced glacier sliding and because subglacial meltwater is required for subglacial sediment deformation (Boulton et al., 2001, 2007).

This article describes the sources of glacier meltwater, considers how water is stored in and moves through glaciers, and outlines the principles of subglacial water pressure and the processes of glacial meltwater erosion. It also explains the characteristics and significance of glacier hydrology and how meltwater is linked to glacier motion.

Glasser, N.F., 2013. Water in glaciers and ice sheets. In: Shroder, J. (Editor in Chief), Giardino, R., Harbor, J. (Eds.), Treatise on Geomorphology. Academic Press, San Diego, CA, vol. 8, Glacial and Periglacial Geomorphology, pp. 61–73.

8.6.2 Sources of Glacial Meltwater

Glacial meltwater is derived from the melting of ice in supraglacial, subglacial, and englacial positions (**Figure 1**). Melting occurs whenever there is sufficient energy to turn the ice back into water and this heat can be supplied by solar radiation, from friction generated by ice flow and from geothermal heat derived from the Earth's crust beneath the glacier. Quantitatively, supraglacial melt is the most important source of meltwater, especially on temperate glaciers (Hock, 2005).

Figure 1 Examples of glacial meltwater drainage. (a) Supraglacial stream on the surface of Morteratsch Glacier in Switzerland. Note the meandering channel planform. Figures in background for scale. (b) Abandoned moulin on the surface of austere Brøggerbreen in Svalbard. (c) Abandoned englacial tunnel melting out of stagnant ice in front of Fox Glacier, New Zealand. Note the rounded and subrounded material melting out of the tunnel. (d) Subglacial tunnel and meltwater emerging from the snout of Fox Glacier, New Zealand.

On these glaciers it is generally measured in meters per year, whereas englacial and subglacial melting may contribute only millimeters per year. The hydrology of glaciers is outlined by Paterson (1998) and in review papers by Röthlisberger and Lang (1987), Hooke (1989), and Fountain and Walder (1998). Hubbard and Nienow (1998) reviewed alpine subglacial hydrology and Hodgkins (1997) reviewed high-arctic glacier hydrology. Supraglacial melt is temporally variable because of seasonal fluctuations in solar radiation and atmospheric temperature. It is also spatially variable, creating areas of both unsaturated and saturated snow and firn on the glacier surface, supraglacial channels and ponds, as well as

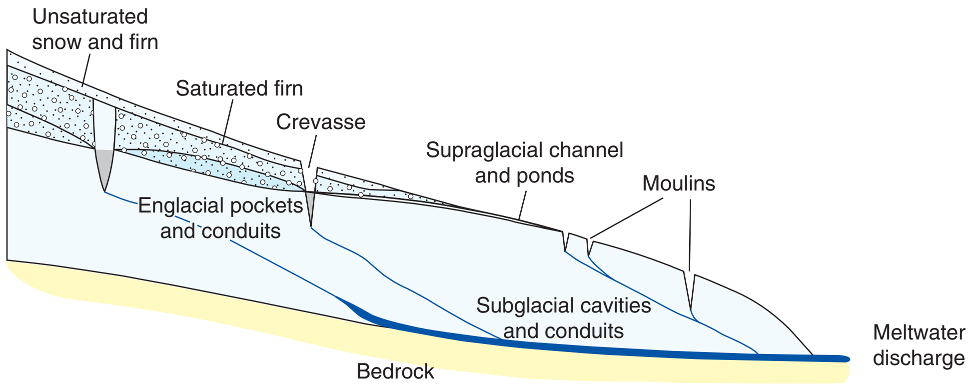

Figure 2 Sources of meltwater and principal transfer routes in a typical temperate alpine glacier. In the accumulation zone, water percolates down through the snow and firn to form a perched water layer on top of the nearly impermeable ice and then flows from the perched water layer into crevasses. Once all the seasonal snow has melted and lowers down the glacier, in the ablation zone, water flows directly across the glacier surface into the englacial pockets and conduits as well as into crevasses and moulins. Modified from Fountain, A.G., Walder, J.S., 1998. Water flow through temperate glaciers. Reviews of Geophysics 36, 299–328, with permission from Geophysics.

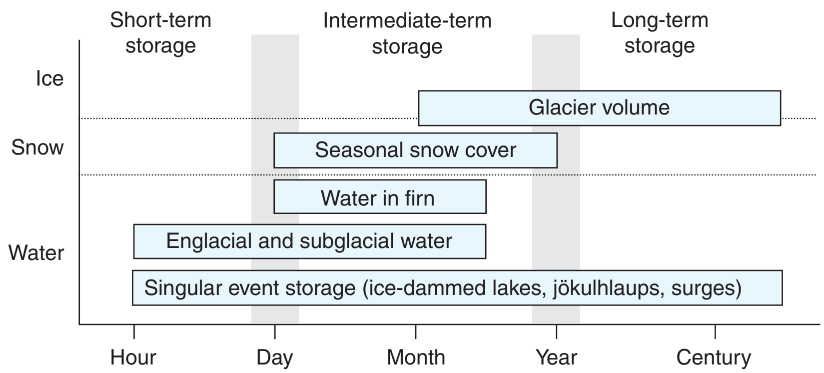

Figure 3 Different forms of water storage in glaciers and the timescales over which they are considered to operate. Modified from Figure 3 in Jansson, P., Hock, R., Schneider, T., 2003. The concept of glacier storage: a review. Journal of Hydrology 282, 116–129.

areas of bare ice (**Figure 2**). The volume of water within the meltwater system depends critically on the amount contributed by rainfall, snowmelt on the glacier surface, and from valley-side streams, all of which can add significant quantities of externally derived water.

8.6.3 Storage of Water in Glaciers

Jansson et al. (2003) recognized that water storage in glaciers occurs at three timescales (**Figure 3**). Long-term storage (years to centuries and longer) is in the form of glacier ice and firn. This storage affects the long-term water balance of glacierized catchments and has the potential to influence global sea level. Intermediate-term storage (days to years) includes the seasonal storage and release of snow and water. Intermediate-term storage affects the runoff characteristics of glacierized catchments and their downstream river flow regimes. In subglacial settings, meltwater can be stored in cavities, in the pore space of subglacial sediments, or in subglacial lakes. It can also be stored within the ice in englacial water pockets, tunnels and cavities, on the glacier surface as snow or firn, and in supraglacial lakes. Water can also be stored adjacent to a glacier in proglacial and ice-marginal lakes. Short-term storage (hours to days) includes the daily effects of drainage through a glacier including meltwater routing through snow and firn, as well as englacial and subglacial pathways. In addition to these time-dependent processes there are also event-driven storage releases, such as the drainage of subglacial, moraine-dammed or glacier-dammed water bodies (**Figure 4**).

8.6.4 Methods of Studying Glacier Hydrology

A full review of the methods used to study glacier hydrology is given in Hubbard and Glasser (2005). There are six main techniques used to investigate water flow through glacier and ice sheets.

1. Dye-tracing experiments, where fluorescent dye is injected into the drainage network at the glacier surface via moulins or crevasses, or below the surface via boreholes (Sharp et al., 1993). The dye mixes with water flowing in the glacier, and its emergence at the glacier snout is recorded using a fluorometer. The speed and space-time pattern of dye return enable inferences to be made about the structure of the drainage network. Dye traveling quickly through the glacier

Figure 4 An example of glacial meltwater storage; the rapidly expanding proglacial lake in front of the Tasman Glacier, New Zealand (see Quincey and Glasser, 2009). The lake is now large and deep enough to allow the glacier to calve icebergs into it, causing the glacier to recede further and the lake to continue to expand.

retains its identity as a well-defined packet with high dye concentration, indicating an efficient drainage network. Dye traveling slowly through the glacier loses its identity because it has more chance to become dispersed, indicating inefficient drainage and water storage within the glacier. Dye-tracing experiments can also be used to trace water transport paths from individual moulins or crevasses to the snout.
2. Studies of meltwater quality such as dissolved ions, microorganisms, and suspended sediment concentration provide information about the configuration and dynamics of subglacial drainage systems (Brown, 2002). For example, the flux of suspended sediment is related to the changing properties of the subglacial drainage network. Subglacial drainage reorganization and flood events tend to sweep large parts of the glacier bed free of sediment; thereafter the discharge of suspended sediment tends to fall because the supply of sediments is exhausted. Similarly, the chemical signature of meltwater leaving the glacier reflects the different types and speed of chemical reactions taking place under the glacier. The spatial extent and speed of water flow are important: Water that flows slowly across large areas of the glacier bed tends to pick up large quantities of solutes, whereas water that flows quickly across limited areas of the glacier bed has little chance to pick up dissolved material. Since the chemical signature in meltwater is strongly controlled by these properties of the drainage system, it is possible to distinguish between glacial meltwater that has been in contact with the bed and meltwater that has not.
3. Borehole studies allow direct measurement of parameters such as subglacial water pressure by monitoring fluctuations in the level of the water in boreholes (Hubbard et al., 1995). In this way, it is possible to follow the changing time–space pattern of water pressure, and use this to infer changes in the behavior of the subglacial drainage system. Cameras and down-borehole tele-viewers can also be employed to look at englacial and subglacial ice structures and their relationship to water flow.
4. Radar radio-echo sounding and ground-penetrating radar can be used to infer the water content of a glacier because of the differences in radar-wave velocities caused by the dielectric properties of water, air, sediment, and ice. This technique has been used to map the outline of englacial and subglacial drainage channels on glaciers and to relate their distribution to the character of the subsurface hydrology, glacier thermal, and structural conditions.
5. Mapping of the internal geometry of glacial drainage systems can be used to infer the development of these systems through time. Aspects of these drainage systems that have been mapped in this way include moulins (Holmlund, 1988) and englacial conduits (Gulley and Benn, 2007).
6. Former glacier beds can be used to infer patterns of subglacial drainage by mapping the distribution of landforms related to meltwater flow and reconstructing the former drainage pathways that they represent. Mapped landforms include the location of former cavities, ice-abraded areas, chemically altered areas, precipitate-filled depressions, and meltwater channels. This technique works particularly well on areas of hard bedrock in front of receding glaciers where meltwater landforms are most likely to be preserved (Walder and Hallet, 1979; Sharp et al., 1989).

8.6.5 Glacier Hydrological Systems

Glacial meltwater finds its way through the glacier from its point of origin along a variety of different flow paths (**Figure 2**). Meltwater derived from supraglacial, englacial and subglacial melting follow different paths through a glacier, although all types of drainage will invariably involve channel flow either within or on the glacier (Fountain and Walder, 1998; Fountain et al., 2005). Channel system development is strongly dependent on glacier thermal regime. On cold glaciers, supraglacial meltwater is unable to penetrate without freezing and therefore tends to be confined to surface and ice-marginal channels. On temperate glaciers, meltwater is able to penetrate further without freezing and water flow can occur in supraglacial, englacial, and subglacial channels. In thermally complex glaciers, water can flow through supraglacial, englacial, and subglacial channels. It can also be stored in small subglacial lakes at the junction between ices of different temperatures.

8.6.5.1 Supraglacial and Englacial Water Flow

Supraglacial channels tend to be less than a few meters wide and may exploit structural weaknesses within the ice. In plan they may adopt either meandering or straight courses, depending on the ice-surface gradient and roughness (**Figure 1(b)**). Velocities within these channels are generally high because their smooth sides offer little frictional resistance. On temperate glaciers, supraglacial channels are characteristically short and are interrupted by crevasses or vertical shafts known as moulins, which divert the water from the surface into the glacier (**Figure 1(c)**).

The internal geometry of moulins and englacial drainage routes has been studied in detail on Storglaciären in Sweden (Holmlund, 1988) and on debris-covered Himalayan glaciers

(Gulley and Benn, 2007). These studies indicate that drainage routes are strongly influenced by structures within the ice such as crevasses and other fractures. The Storglaciären moulins are near-vertical shafts, 30–40 m deep, which feed englacial tunnels that descend from the base of the moulin at angles between 0° and 45°. The moulins are structurally controlled because when a crevasse opens on the glacier surface it commonly intersects a supraglacial meltwater stream. The crevasse then fills with water, until it opens and deepens sufficiently to intersect englacial drainage passages, at which point the water drains. The orientation of the englacial tunnels is generally controlled by the orientation of the original crevasse from which the moulin formed. Detailed three-dimensional mapping of englacial drainage conduits on Himalayan glaciers shows that their location is also determined by preexisting lines of high hydraulic conductivity and that channels are graded to local base level (Gulley and Benn, 2007). Conduits enlarge by headward retreat and downcutting, producing canyon-like passages within the ice.

8.6.5.2 Subglacial Water Flow

Four subglacial drainage systems are possible.

1. Water can flow widely across the bed in a thin film (millimeter thickness) between the glacier and its bed, often known as a Weertman film. A Weertman film is most likely to develop where meltwater is derived primarily from basal melting and in situations where there are restricted inputs of surface meltwater. Theoretical analyses suggest that a water film is unstable because the film tends to rapidly organize itself into networks of small channels (Bindschadler, 1983; Iken and Bindschadler, 1986). The presence of a thin film of meltwater is central to theories of glacier sliding because the meltwater acts as a lubricant between the ice and its substrate (Creyts and Schoof, 2009). This meltwater film can also refreeze, entraining debris as it does so (Roberts et al., 2002; Cook et al., 2006).
2. Conduit or tunnel networks discharge meltwater through a small number of large channels. Tunnel networks cover a limited area of the glacier bed and are efficient in transferring meltwater through the glacier. These channels can be englacial or subglacial. Where channels at the glacier bed cut upwards into the ice they are termed Röthlisberger channels or R-channels. In plan view, this type of drainage network is generally dendritic. The size of the tunnels is determined by the balance between the processes that act to enlarge them (i.e., ice melt of tunnel walls from flowing water) and processes that act to close them (i.e., ice deformation). The natural shape for a tunnel or conduit, well away from the bed, is near-circular due to these two opposing factors. More importantly, the size of a conduit will vary with temporal changes in discharge. As meltwater discharge increases, the conduits grow in size.
3. Linked-cavity systems occur where water collects in bedrock cavities, for example, behind obstacles. These cavities cover much of the glacier bed, and are connected by a tortuous network of small links to create a more-or-less continuous drainage network (**Figure 5**). The links can be cut down into bedrock, where they create Nye or N-channels and water-worn or smoothed rock surfaces (**Figure 6**), or they can be cut upward into the ice as small R-channels. In this drainage configuration, meltwater is spread across a wide area of the bed and, because the channel geometry is relatively inefficient, meltwater transit time is less.
4. Meltwater can also flow within subglacial sediments if sufficiently permeable sediment exists (Boulton and Hindmarsh, 1987; Boulton and Caban, 1995). When saturated and subjected to stresses transmitted to the bed by the overlying glacier, subglacial sediment can deform (Boulton et al., 1993, 2001). Suggested mechanisms include advection (the water within the sediment layer is carried forward as the sediment deforms), Darcian flow (water moves through the pore spaces of the sediment from areas of high water pressure to low water pressure under the influence of the hydraulic potential gradient), within

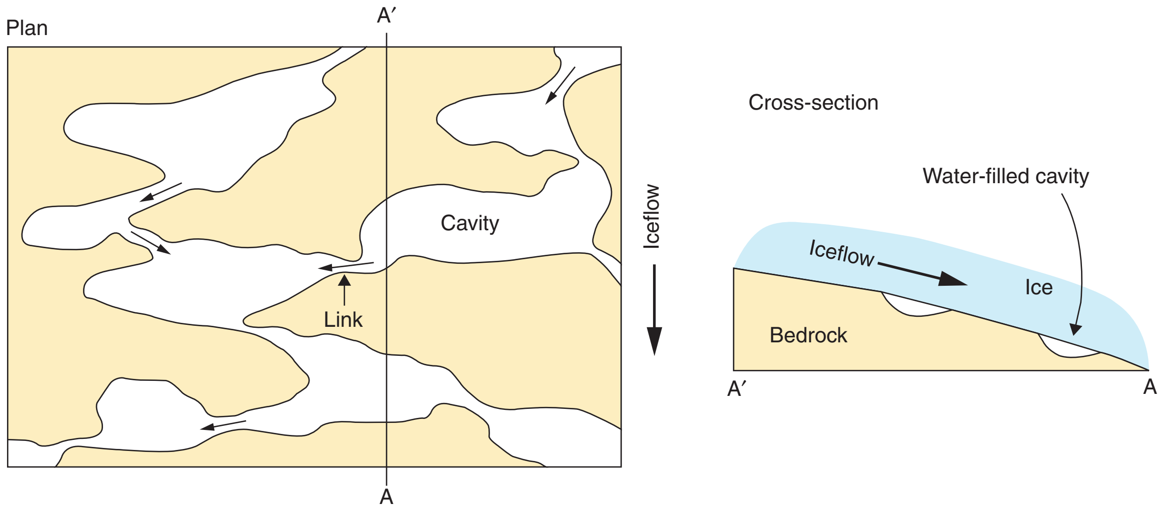

Figure 5 A network of linked basal cavities in plan view and in cross-section. Each cavity is linked by N- or R-channels. Diagram modified from Figure 5 in Hooke, R.LeB., 1989. Englacial and subglacial hydrology: a qualitative review. Arctic and Alpine Research 21, 221–233, with permission from Arctic and Alpine Research.

Figure 6 An ice-smoothed and water-worn bedrock wall at the margin of the San Rafael Glacier in Chile. Former ice-flow direction was left to right.

pipes and small channels in the subglacial sediment itself, or as a thin film or sheet of meltwater at the upper surface of the sediment.

An important distinction in subglacial hydrology is between distributed and discrete drainage systems. The Weertman film is commonly referred to as a distributed drainage system because the meltwater is widely distributed across the glacier bed. Conduit or tunnel networks and linked-cavity systems are generally referred to as discrete drainage systems because the meltwater is confined to discrete channels and tunnels at the glacier bed. Meltwater flow within subglacial sediments can be regarded as either a distributed or discrete drainage system, depending on whether the water flows through the sediment as Darcian flow or in a sheet (distributed) or in tunnels and pipes in the sediment (distributed).

The drainage system in most glaciers evolves spatially and temporally so that the drainage system can vary greatly through space and time. For example, many temperate valley glaciers undergo an early-melt-season high-velocity event (the so-called 'spring event'), where glacier velocities increase suddenly (Mair et al., 2003). During these events there is widespread ice-bed decoupling, particularly along the axes of known subglacial drainage channels. This link between subglacial hydrology and glacier velocity has also been established for polythermal glaciers (Copland et al., 2003). These spring events demonstrate that changes in subglacial hydrology are intimately linked to changes in glacier dynamics. The overall conclusion of these studies is that there is a close association between: (1) the timing and spatial distribution of the temporal pattern of surface water input to a glacier; (2) the formation, seasonal evolution, and distribution of subglacial drainage pathways; and (3) horizontal and vertical glacier velocities.

Spatially, most glacier beds are patchy and composed of a discontinuous sediment cover of variable thickness over bedrock. Glacier drainage also varies through time; for example, seasonally where there is a well-documented transition from an early melt-season within an inefficient drainage system to a more efficient drainage system later in the melt season (Mair et al., 2003). Rapid transitions between different subglacial drainage configurations are also possible where water flow is nonsteady-state, for example, beneath surge-type glaciers.

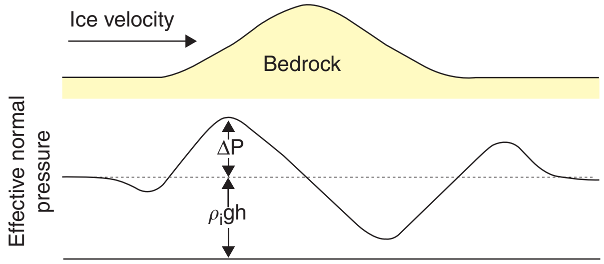

Figure 7 Schematic diagram of the distribution of effective normal pressure at the glacier bed as it flows over a bedrock obstacle. Modified from Figure 7 in Boulton, G.S., 1974. Processes and patterns of glacial erosion. In: Coates, D.R. (Ed.), Glacial Geomorphology. George Allen and Unwin, London, pp. 41–87, with permission from Allen and Unwin.

8.6.6 Subglacial Water Pressure

8.6.6.1 Subglacial Water Pressure and Effective Normal Pressure

Subglacial water pressure plays an important role in subglacial processes because it controls the effective normal pressure beneath a glacier. Effective normal pressure is the force per unit area imposed vertically by a glacier on its bed. For a cold-based glacier it is effectively equal to the weight of the overlying ice; thick ice imposes a greater pressure than thin ice.

This is summarized by

$$N = pgh$$

where N is the normal effective pressure, p the density of ice, g the acceleration due to gravity, and h is the ice thickness.

If water is present at the glacier bed, however, the effective normal pressure is reduced by an amount equal to the subglacial water pressure. The greater the water pressure the more it can support the weight of the glacier and thereby reduce the effective normal pressure.

The equation is modified to

$$N = pgh - wp$$

where N is the effective normal pressure, p the density of ice, g the acceleration due to gravity, h the ice thickness, and wp is the subglacial pressure.

This holds only where the glacier has a flat bed but in reality effective normal pressure is modified by the flow of ice over obstacles (Figure 7). As ice flows against the up-stream side on an obstacle, the effective normal pressure increases by an amount proportional to the rate of glacier flow against the obstacle. Effective normal pressure is also reduced in the lee or on the down-stream side of the obstacle (Figure 7). The pressure fluctuation caused by the flow of ice against the obstacle is, therefore, positive on the up-stream side and negative on the down-stream side. The negative pressure fluctuation on the down-stream side of an obstacle may cause a cavity to form in the lee of obstacle if it exceeds the effective normal pressure at this point (Figure 8). Cavity formation is favored by high subglacial water pressures, which reduce effective normal pressure, and by high rates of basal sliding, which give large pressure fluctuations over obstacles. Theoretical calculations show that cavities can open at sliding velocities of about 9 m per year beneath a thickness of 100 m of ice, whereas velocities of 35 m per year are required with ice thickness on the order of 400 m.

Subglacial water pressure is controlled by four variables:

1. Glacier thickness: the greater the weight of the overlying ice, the greater is the subglacial water pressure.
2. The rate of water supply: inputs of large amounts of meltwater may increase the subglacial water pressure.
3. The rate of meltwater discharge: an efficient subglacial drainage system will reduce subglacial water pressure.
4. The nature of the underlying geology: permeable bedrock will allow water to drain through it and therefore reduce subglacial water pressure.

Variations in the rate of water supply and the rate of meltwater discharge are responsible for much of the seasonal variation in water pressure present at some glaciers. Early in the melt season, water pressure may be very high due to the abundance of meltwater and the relative inefficiency of the channel network (Mair et al., 2003). As the subglacial channel network develops during the ablation season discharge becomes more efficient and the subglacial water pressure generally falls.

Figure 8 Small subglacial cavity in the lee of a rock step beneath the margin of the Tschierva Glacier in the Roseg Valley, Switzerland. Ice flow is from left to right over the rock step. The photograph was taken in late summer and the size of the cavity has probably been increased by ablation during the warm summer months.

Variations in subglacial water pressure and its influence on effective normal pressure and cavity formation are very important for the processes of glacial erosion. Subglacial water pressure is also important in determining the rate of basal sliding. Effective normal pressure determines the friction between a glacier and its bed. If the subglacial water pressure rises, effective normal pressure will fall, reducing basal friction, and consequently increasing the rate of basal sliding. This explains why sliding velocity characteristically increases during the summer melt season or after a large rainfall event. Variations in subglacial water pressure have also been linked to glacier surges. For example, the surge of the Variegated glacier in Alaska, during 1982–83 is believed to have been triggered by a change in the subglacial drainage system (Kamb et al., 1985). Prior to the surge the glacier had a subglacial drainage system dominated by a few large tunnels. This appears to have changed to a system dominated by linked subglacial cavities causing an increase in subglacial water pressure due to the lower rate of discharge possible from such a system. This rise in subglacial water pressure facilitated rapid glacier flow during the surge. At the end of the surge this water was released as a large flood and the subglacial system reverted to a large integrated tunnel system. The cause of this change in drainage system is unclear, but it is believed to be central to the rapid glacier flow of this surge.

8.6.6.2 Water Pressure Gradients

The orientation of this network of conduits and tunnels is controlled by the water pressure gradient within the glacier. Water will flow down the pressure gradient from areas of high to low pressure. It is possible to determine the nature of this pressure gradient within a glacier and therefore the direction of water flow within it. Figure 9 shows a hypothetical water-filled tube beneath a glacier. The weight of ice above point A is equal to the weight of the water column BC which it forces up. A line between A and C defines a surface of equal potential

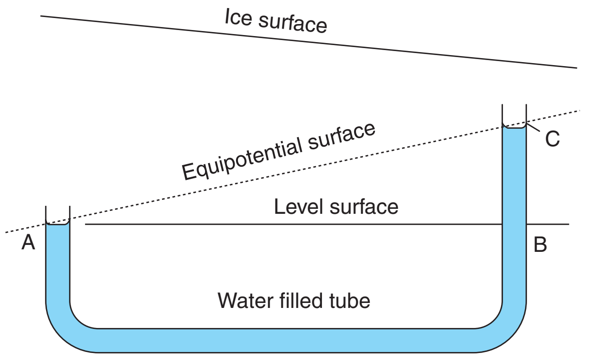

Figure 9 Diagram to illustrate the hydraulic head which drives water flow within a glacier. The weight of the ice above point A is equal to the elevation of the water column BC. The thinner the ice above point A, the less the hydraulic head. Consequently the hydraulic head or potential will fall toward the ice margin or in the direction of glacier slope. Water flows from areas of high hydraulic potential to areas of low hydraulic potential. Modified with permission from Bennett, M.R., Glasser, N.F., 2010. Glacial Geology: Ice Sheets and Landforms, Second ed. Wiley, Chichester.

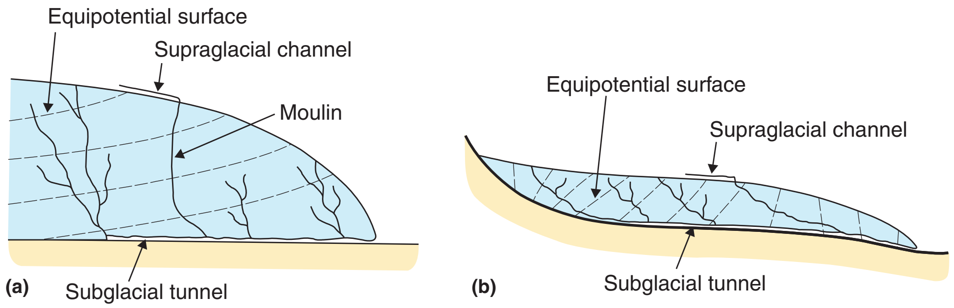

Figure 10 The pattern of equipotential surfaces within a glacier (i.e., surfaces of equal hydraulic potential). Water will always flow from areas of high hydraulic potential to areas of low hydraulic potential, and therefore it will flow at right angles to the equipotential surfaces as depicted here. Modified with permission from Bennett, M.R., Glasser, N.F., 2010. Glacial Geology: Ice Sheets and Landforms, Second ed. Wiley, Chichester.

pressure. Along this line the pressure due to the weight of the overlying ice is equal to the water pressure it generates. If we now move the tube toward the right, closer to the ice margin, the weight of the ice above point A will fall and consequently the water column BC will be lower. A new lower equipotential surface is defined. Water will flow at right angles to these equipotential surfaces from a surface of higher potential pressure to one of lower potential pressure. As a consequence englacial conduits and tunnels will be orientated perpendicular to the surfaces of equipotential pressure (**Figure 10**). The geometry of the equipotential surfaces within a glacier is determined by the variation in ice thickness, which is controlled primarily by the surface slope of the glacier and secondarily by the slope of the underlying topography. The surface of a glacier does not always slope in sympathy with the slope of the glacier bed. As a consequence subglacial meltwater may not always flow directly down the maximum slope beneath the glacier and may in some cases even flow up-hill. Under an ice sheet water flow will be approximately radial in sympathy with the surface slope and the direction of ice flow, but will deviate around hills and bumps and be concentrated in topographic depressions such as valleys.

It is possible to calculate the water pressure potential at a series of points at the base of a glacier from knowledge of the variation in ice thickness Shreve (1972, 1985a, b). These points can be contoured to define a surface known as the subglacial hydraulic potential surface (**Figure 10**). Provided that any subglacial tunnel is completely water filled then the tunnel should be orientated at right angles to this hydraulic surface. The subglacial hydraulic potential surface is a useful tool in the interpretation of the glacial landform record (Sugden et al., 1991; Syverson et al., 1994).

8.6.7 Discharge Fluctuations

The discharge of meltwater from glaciers varies dramatically both on a diurnal (daily) and seasonal basis (Collins, 1979). Diurnal discharge variations reflect atmospheric air temperatures and therefore the pattern of daily ablation on a glacier (**Figure 11**). Discharge is usually low in the early morning and rises in the late afternoon or evening. This diurnal fluctuation is suppressed in winter, but increases toward the late summer when the rate of daily ablation reaches its maximum. Seasonal fluctuations are equally dramatic (**Figure 11**). They reflect two factors: (1) the seasonal nature of ablation; and (2) the seasonal development of the internal drainage network within warm-based glaciers. In areas with a strong seasonal climate the following annual cycle tends to dominate:

1. *Spring melt*: Ablation of winter surface snow begins in the spring and, as a consequence, glacier water pressure also increases.
2. *Late spring melt*: Ablation of winter snowfall is well advanced on the glacier surface. Discharge in all channels, conduits, and tunnels increases. The conduits grow in size and the internal drainage network within the glacier develops. Discharge from the glacier into the proglacial channel system steadily increases.
3. *Early summer*: With the development of a well-connected internal drainage network, any stored water can be released. The daily discharge continues to grow. This increase in discharge may be associated with a sudden rise in glacier velocity, during the spring event.
4. *Late summer*: The drainage network within the glacier has reached its optimum efficiency. All the stored water within the glacier has been discharged. Daily discharge matches the amount of melt achieved each day. Water pressures within the glacier are usually at their minimum.
5. *Autumn*: Reduced melting of the glacier causes a dramatic drop in discharge. Conduits and tunnels within the glacier begin to collapse and close due to ice deformation as the water flowing within them declines. The largest drainage arteries may remain open if they contain sufficient water flow.
6. *Winter*: The degree to which the drainage network shuts down depends on the climate and severity of the winter. Meltwater, if present, is derived from subglacial and internal melting.

The degree to which the internal drainage network of conduits and tunnels within a glacier collapses each year is highly variable. Some shut down will occur in all cases, but in large ice sheets the major discharge arteries are likely to be remaining open because the rate of water flow due to melt generated by internal deformation and geothermal heat is likely to be large. Until recently it was thought that the smaller and thinner the glacier, the more likely it is that the drainage system evolves each year. For example, Nienow et al. (1998, 2005) documented how the drainage system on the Haut Glacier d'Arolla in Switzerland evolved over the course of a melt season from an initially inefficient system to a more

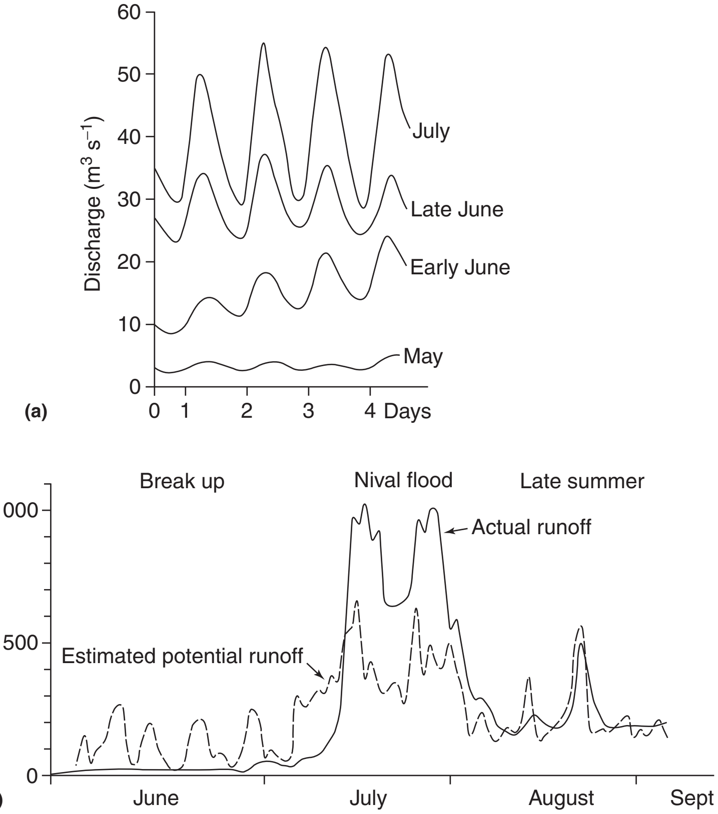

Figure 11 Schematic discharge fluctuations for alpine glacial meltwater streams. (a) Diurnal (daily) fluctuations, which become more pronounced as the melt season proceeds. (b) Seasonal fluctuations. The difference between estimated potential runoff and actual runoff reflects the efficiency of the subglacial drainage network. At the start of the melt season the channel and tunnel network is poorly developed and therefore actual runoff is less than potential (i.e., water is stored in the glacier). As the melt season proceeds, the drainage network grows in efficiency so that actual and potential runoffs become similar. Modified with permission from Bennett, M.R., Glasser, N.F., 2010. Glacial Geology: Ice Sheets and Landforms, Second ed. Wiley, Chichester.

efficient system of large subglacial channels and tunnels. However, it is now also clear that similar subglacial drainage reorganization changes take place on much larger scales and that subglacial drainage can influence basal ice motion (Bartholomew et al., 2010).

8.6.7.1 Jökulhlaups

On some glaciers the normal pattern of diurnal and seasonal discharge fluctuations are interrupted by catastrophic subglacial floods known as jökulhlaups (Roberts, 2005). These are high magnitude events, often several orders of magnitude greater than normal peak flows (Russell et al., 2006; Evatt et al., 2006). Jökulhlaups may occur when ice-dammed lakes drain suddenly or when heat generated by subglacial volcanic activity increases subglacial melt rates.

Jökulhlaups created by the sudden drainage of ice-dammed lakes are probably most common (Russell, 1989; Tweed and Russell, 1999). Ice-dammed lakes occur wherever a glacier blocks the down-valley flow of water (**Figure 12**). When it occurs, the outburst from an ice-dammed lake is typically catastrophic for a number of reasons: (1) vertical release of the ice dam by flotation causes rising water levels in the lake; (2) overflow of an ice dam, causes rapid melting of the dam due to friction from the water flow; (3) destruction or fissuring of an ice dam by earthquakes; and (4) enlargement of preexisting tunnels beneath the dam by increased water flow and melt-enlargement due to frictional heating.

Figure 12 A partially drained ice-dammed lake in South West Greenland. Note the stranded icebergs that indicate the lake level has dropped during a drainage event.

In many situations the maximum water level in a lake is limited by a spillway or channel through which the lake can drain. In these cases some other mechanism is required to trigger catastrophic lake drainage. The shape of the jökulhlaup hydrograph is determined by the nature of the trigger and the volume of water that is drained (**Figure 13**). Jökulhlaups induced by volcanic activity tend to produce high-magnitude, short-duration floods whereas jökulhlaups caused by the drainage of ice-dammed lakes may produce floods with a greater duration and lower magnitude (**Figure 13**).

The size of the flood peak from a jökulhlaup caused by the drainage of ice-dammed lakes is proportional to the volume of water within the lake and can be approximated by a regression equation based on the relationship between peak discharge and the volume of the ice-dammed lake (Clague and Mathews, 1973). This equation gives good results and has been used widely to predict jökulhlaup flood magnitudes. The high magnitude nature of jökulhlaups makes them of considerable geomorphological significance (Clayton and Knox, 2008). In certain parts of the world such as the Himalayas, ice- or moraine-dammed lake drainage can have huge geomorphological impacts (**Figures 14** and **15**).

8.6.8 Glacial Meltwater Erosion

Glacial meltwater erosion beneath ice sheets and glaciers may result from either mechanical or chemical processes (Willis et al., 1996; Singh et al., 2004; Swift et al., 2005). The effectiveness of meltwater as an agent of erosion depends on: (1) the susceptibility of the bedrock involved, in particular the presence of structural weaknesses or its susceptibility to chemical attack; (2) the discharge regime, in particular the water velocity and the level of turbulent flow; and (3) the quantity of sediment in transport.

8.6.8.1 Mechanical Erosion

Mechanical erosion occurs through two processes; fluvial abrasion and fluvial cavitation (Drewry, 1986).

Figure 14 Erosional scar indicating the track taken by a recent glacial lake outburst flood (GLOF) from a moraine-dammed lake in the Nepal Himalayas.

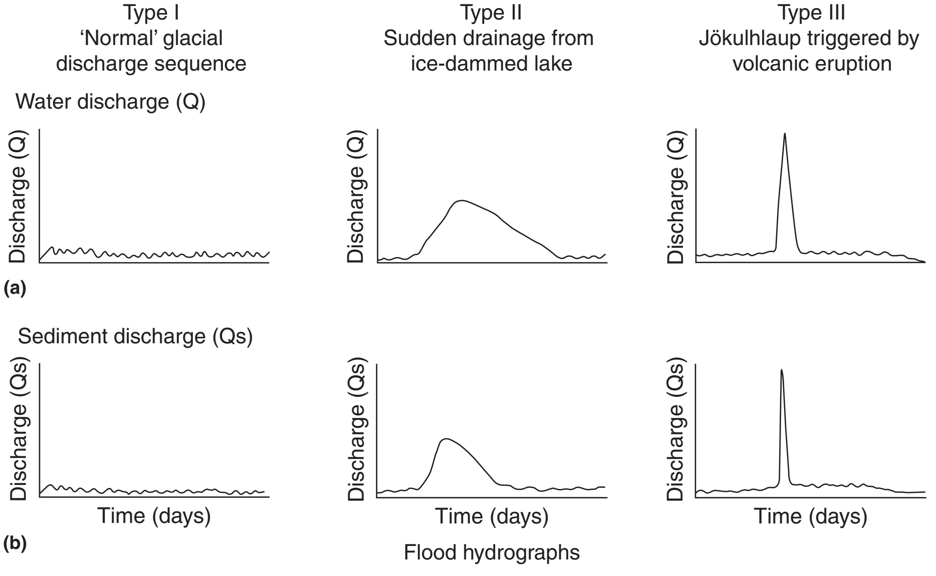

Figure 13 Flood hydrographs illustrating the different discharge regimes recorded in a normal glacial river (Type I), during drainage of an ice-dammed lake (Type II) and during a jökulhlaup (Type III). Modified from Maizels, J.K., Russell, A.J., 1992. Quaternary perspectives on jökulhlaup prediction. Quaternary Proceedings 2, 133–152, with permission from NHBS.

Figure 15 Coarse boulder gravel deposited in an alluvial fan during a moraine-dammed lake drainage event in the Nepal Himalayas. Note figure in centre of photograph for scale.

Fluvial abrasion occurs during the transport of both suspended sediment and sediment in traction within the meltwater. This sediment impacts on the walls of rock channels or on the bed of subglacial tunnels striating and grooving the rock surface. The rate of meltwater abrasion is controlled by the properties of the sediment in transport (e.g., the hardness of the sediment relative to the bedrock surface over which the meltwater is flowing), the flow properties (e.g., the rate of fluvial abrasion increases with the flow velocity and turbulence), and the properties of the channel. The roughness and orientation of facets within a channel as well as its plan-form all affect the rate of fluvial abrasion. Erosion is greatest where sediment-charged water impacts at a near normal angle. Consequently, obstructions within the channel, such as large boulders, will be rapidly abraded.

Fluvial cavitation occurs wherever the meltwater velocity exceeds about 12 m s^{-1}. It involves the creation of low pressure areas within turbulent meltwater as it flows over a rough bedrock surface. These low pressure areas form as the flow is accelerated around obstacles on the channel floor. If the pressure within the water drops is sufficient to allow the water to vaporize, bubbles of vapor (cavities) form. The cavitation bubbles grow and are moved along in the fluid until they reach a region of slightly higher local pressure where they will suddenly collapse. If cavity collapse occurs adjacent to a channel wall localized but very high impact forces are produced against the rock. Repetition of these impact forces may lead to rock failure. In particular the shock waves are often forced into microscopic cracks within a rock or between mineral grains causing them to loosen and allowing their removal.

8.6.8.2 Chemical Erosion

Glacial meltwater can also erode bedrock by the processes of chemical solution (Brown, 2002). Soluble components of rock and rock debris are dissolved and removed in solution. This process is particularly important on carbonate-rich lithologies such as limestone and chalk (Fairchild et al., 1994), but is not restricted to them. Chemical denudation beneath glaciers is generally neglected as a process of glacial erosion, although, in recent years its importance has been increasingly recognized (Sharp et al., 1995). Chemical denudation is particularly effective beneath glaciers, despite the low temperatures and therefore reaction rates, for three main reasons:

1. High flushing rates: meltwater passes through the glacial system rapidly and is rarely stored subglacially for long; its residence time is therefore short, and this ensures that it does not have time to become chemically saturated.
2. Availability of rock flour: turbulent meltwater can transport large quantities of freshly ground rock particles in suspension, which provide a very high surface area, or reaction surface, over which solution can occur.
3. Enhanced solubility of carbon dioxide at low temperatures: solution of carbon dioxide by meltwater produces a weak acid. The solubility of carbon dioxide increases at low temperatures and consequently meltwater becomes more acidic and therefore more aggressive.

Chemical denudation is restricted to warm-based ice with abundant meltwater and may be particularly important in maritime areas where high rainfall adds significantly to the volume of water passing through the glacial system.

8.6.9 Hydrological Effects on Glacier Motion

In recent years it has become apparent that glacier hydrology has profound effects on the processes operating in the subglacial environment (Bindschadler, 1983; Iken and Bindschadler, 1986; Anderson et al., 2004; Bartholomaus et al., 2007; Harper et al., 2007). For example, many of the outlet glaciers that drain the Greenland and Antarctic Ice Sheet have accelerated and thinned in the last decade and it has been inferred that this is partly due to glacier acceleration in response to ice-bed decoupling events including drainage of supraglacial lakes (McMillan et al., 2007) connected to the subglacial environment (Zwally et al., 2002; Das et al., 2008; Shepherd et al., 2009), water exchanges between cavities at the bed (Wingham et al. 2006; Fricker et al., 2007), and subglacial lake drainage events (Bell et al., 2007; Stearns et al., 2008).

It has been proposed that some Greenland and Antarctic outlet glaciers might speed up as a direct consequence of increased surface meltwater penetrating to the bed (proposed by Zwally et al. (2002) and subsequently known as the 'Zwally effect'). This effect, which relies on surface meltwater reaching the bed of the ice sheet and reducing friction through a higher basal water pressure is summarized in **Figure 16**. Surface meltwater on the ice sheet below the equilibrium line drains through moulins, crevasses, or other fractures to the glacier bed. This meltwater provides lubrication and reduces friction so that the glacier velocity due to sliding increases. This process has been observed to cause a brief seasonal acceleration of Greenland outlet glaciers lasting two to three months but it remains to be seen if this process is responsible for longer term velocity increases on the ice sheet. It also remains to be seen

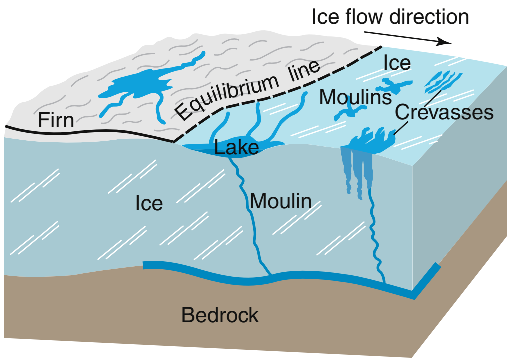

Figure 16 Glaciological features of the Greenland Ice Sheet including surface lakes, crevasses, and moulins. Meltwater descends through crevasses and moulins to bedrock below the equilibrium line, lubricating the bed and contributing to the movement of the ice sheet by sliding over bedrock. http://www.gsfc.nasa.gov/topstory/20020606greenland.html

whether the trend toward increased atmospheric temperatures observed in Greenland in the last few decades continues into the future, and whether these increased atmospheric temperatures continue to produce longer or more widespread surface melting and consequent glacier velocity increases.

8.6.10 Conclusions

Glacial meltwater is a very important component of the glacial system. It is the main ablation product of most ice sheets, it is intimately linked to glacier motion through sliding and subglacial sediment deformation, and it is responsible for removing debris from the ice–rock interface and carrying it beyond the confines of the glacier. The type of drainage network carrying glacial meltwater within an ice sheet or glacier is dependent on its thermal regime. In cold glaciers drainage is supraglacial, whereas in warm glaciers drainage it is supraglacial, englacial, and subglacial. On hard substrates subglacial drainage occurs through either a linked system of cavities or through a few major subglacial conduits or tunnels. On soft substrates subglacial drainage either occurs through the deforming sediment or via shallow channels cut in the surface of the sediment. The direction of englacial and subglacial drainage within a glacier follows the water pressure gradient, which is perpendicular to the lines of equal water pressure potential. These are controlled primarily by the surface slope of the glacier and to a lesser extent by subglacial topography. Meltwater discharge varies diurnally and seasonally. High-magnitude, low-frequency events, known as jökulhlaups, may be superimposed on this discharge fluctuation. These catastrophic events are caused either by subglacial volcanic activity or by the drainage of ice-dammed lakes. Glacial meltwater has a profound effect on the processes operating in the subglacial environment erosion and has been intimately linked to glacier motion where there is increased surface meltwater penetration to the bed. This effect is likely to be increased in the future if the predicted rises in atmospheric air temperatures in polar regions prove to be correct (Bell, 2008).

References

Anderson, R.S., Anderson, S.P., MacGregor, K.R., Waddington, E.D., O'Neel, S., Riihimaki, C.A., Loso, M.G., 2004. Strong feedbacks between hydrology and sliding of a small alpine glacier. Journal of Geophysical Research 109, F03005.

Bartholomaus, T.C., Anderson, R.S., Anderson, S.P., 2007. Response of glacier basal motion to transient water storage. Nature Geoscience 1, 33–37.

Bartholomew, I., Nienow, P., Mair, D., Hubbard, A., King, M.A., Sole, A., 2010. Seasonal evolution of subglacial drainage and acceleration in a Greenland outlet glacier. Nature Geoscience 3, 408–411.

Bell, R.E., 2008. The role of subglacial water in ice-sheet mass balance. Nature Geoscience 1, 297–304.

Bell, R.E., Studinger, M., Shuman, C.A., Fahnestock, M.A., Joughin, I., 2007. Large subglacial lakes in East Antarctica at the onset of fast-slowing ice streams. Nature 445, 904–907.

Bindschadler, R., 1983. The importance of pressurized subglacial water in separation and sliding at the glacier bed. Journal of Glaciology 29, 3–19.

Boulton, G.S., Caban, P., 1995. Groundwater flow beneath ice sheets: part II – its impact on glacier tectonic structures and moraine formation. Quaternary Science Reviews 14, 563–587.

Boulton, G.S., Dobbie, K.E., Zatsepin, S., 2001. Sediment deformation beneath glaciers and its coupling to the subglacial hydraulic system. Quaternary International 86, 3–28.

Boulton, G.S., Hindmarsh, R.C.A., 1987. Sediment deformation beneath glaciers: rheology and sedimentological consequences. Journal of Geophysical Research 92B, 9059–9082.

Boulton, G.S., Lunn, R., Vidstrand, P., Zatsepin, S., 2007. Subglacial drainage by groundwater-channel coupling, and the origin of esker systems: Part 1 – glaciological observations. Quaternary Science Reviews 26, 1067–1090.

Boulton, G.S., Slott, T., Blessing, K., Glasbergen, P., Leijnse, T., Van Gijssel, K., 1993. Deep circulation of groundwater in over-pressured subglacial aquifers and its geological consequences. Quaternary Science Reviews 12, 739–745.

Brown, G.H., 2002. Glacier meltwater hydrochemistry. Applied Geochemistry 17, 855–883.

Clague, J.J., Mathews, W.H., 1973. The magnitude of jökulhlaups. Journal of Glaciology 12, 501–504.

Clayton, J.A., Knox, J.C., 2008. Catastrophic flooding from Glacial Lake Wisconsin. Geomorphology 93, 384–397.

Collins, D.N., 1979. Quantitative determination of the subglacial hydrology of two alpine glaciers. Journal of Glaciology 23, 347–362.

Cook, S.J., Waller, R.I., Knight, P.G., 2006. Glaciohydraulic supercooling: the process and its significance. Progress in Physical Geography 30, 577–588.

Copland, L., Sharp, M.J., Nienow, P.W., 2003. Links between short-term velocity variations and the subglacial hydrology of a predominantly cold polythermal glacier. Journal of Glaciology 49, 337–348.

Creyts, T.T., Schoof, C.G., 2009. Drainage through subglacial water sheets. Journal of Geophysical Research 114, F04008.

Das, S.B., Joughin, I., Behn, M.D., Howat, I.M., King, M.A., Lizarralde, D., Bhatia, M.P., 2008. Fracture propagation to the base of the Greenland Ice Sheet during supraglacial lake drainage. Science 320, 778–781.

Drewry, D., 1986. Glacial Geologic Processes. Arnold, London.

Evatt, G.W., Fowler, A.C., Clark, C.D., Hulton, N.R.J.H., 2006. Subglacial floods beneath ice sheets. Philosophical Transactions of the Royal Society 364, 1769–1794.

Fairchild, I.J., Brady, L., Sharp, M., Tison, J., 1994. Hydrochemistry of carbonate terrains in Alpine glacial settings. Earth Surface Processes and Landforms 19, 33–54.

Fountain, A.G., Schlicting, R.B., Jacobel, R.W., Jansson, P., 2005. Fractures as main pathways of water flow in temperate glaciers. Nature 433, 618–621.

Fountain, A.G., Walder, J.S., 1998. Water flow through temperate glaciers. Reviews of Geophysics 36, 299–328.

Fricker, H.A., Scambos, T.A., Bindschadler, R., Padman, L., 2007. An active subglacial water system in West Antarctica mapped from space. Science 315, 1544–1548.

Gulley, J., Benn, D.I., 2007. Structural control of englacial drainage systems in Himalayan debris-covered glaciers. Journal of Glaciology 53, 399–412.

Harper, J.T., Humphrey, N.F., Pfeffer, W.T., Lazar, B.T., 2007. Two modes of accelerated glacier sliding related to water. Geophysical Research Letters 34, L12503.

Hock, R., 2005. Glacier melt: a review of processes and their modelling. Progress in Physical Geography 29, 362–391.

Hodgkins, R., 1997. Glacier hydrology in Svalbard, Norwegian High Arctic. Quaternary Science Reviews 16, 957–973.
Holmlund, P., 1988. The internal geometry and evolution of moulins, Storglaciären, Sweden. Journal of Glaciology 34, 242–248.
Hooke, R.LeB., 1989. Englacial and subglacial hydrology: a qualitative review. Arctic and Alpine Research 21, 221–233.
Hubbard, B.P., Glasser, N.F., 2005. Field Techniques in Glaciology and Glacial Geomorphology. Wiley, London.
Hubbard, B.P., Nienow, P., 1998. Alpine subglacial hydrology. Quaternary Science Reviews 16, 939–955.
Hubbard, B.P., Sharp, M.J., Willis, I.C., Nielsen, M.K., Smart, C.C., 1995. Borehole water-level variations and the structure of the subglacial drainage system of Haut Glacier d'Arolla, Valais, Switzerland. Journal of Glaciology 41, 572–583.
Iken, A., Bindschadler, R.A., 1986. Combined measurements of subglacial water pressure and surface velocity of Findelengletscher, Switzerland: conclusions about drainage system and sliding mechanism. Journal of Glaciology 32, 101–119.
Jansson, P., Hock, R., Schneider, T., 2003. The concept of glacier storage: a review. Journal of Hydrology 282, 116–129.
Kamb, B., Raymond, C.F., Harrison, W.D., et al., 1985. Glacier surge mechanism: 1982–1983 surge of Variegated Glacier, Alaska. Science 227, 469–479.
Mair, D., Willis, I., Fischer, U.H., Hubbard, B., Nienow, P., Hubbard, A., 2003. Hydrological controls on patterns of surface, internal and basal motion during three "spring events": Haut Glacier d'Arolla, Switzerland. Journal of Glaciology 49, 555–567.
McMillan, M., Nienow, P., Shepherd, A., Benham, A., Sole, A., 2007. Seasonal evolution of supraglacial lakes on the Greenland Ice Sheet. Earth and Planetary Science Letters 29(262), 484–492.
Nienow, P., Hubbard, A., Hubbard, B., Chandler, D., Mair, D., Sharp, M., Willis, I., 2005. Hydrological controls on diurnal ice flow variability in valley glaciers. Journal of Geophysical Research 110, F04002.
Nienow, P., Sharp, M., Willis, I., 1998. Seasonal changes in the morphology of the subglacial drainage system, Haut Glacier d'Arolla, Switzerland. Earth Surface Processes and Landforms 23, 825–843.
Paterson, W.S.B., 1998. The Physics of Glaciers, Third ed. Pergamon, Oxford.
Quincey, D.J., Glasser, N.F., 2009. Morphological and ice-dynamical changes on the Tasman Glacier, New Zealand, 1990–2007. Global and Planetary Change 68, 185–197.
Roberts, M.J., 2005. Jökulhlaups: a reassessment of floodwater flow through glaciers. Reviews of Geophysics 43, RG10002.
Roberts, M.J., Tweed, F.S., Russell, A.J., et al., 2002. Glaciohydraulic supercooling in Iceland. Geology 30, 439–442.
Röthlisberger, H., Lang, H., 1987. Glacial hydrology. In: Gurnell, A.M., Clark, M.J. (Eds.), Glacio-Fluvial Sediment Transfer. Wiley, Chichester, pp. 207–284.
Russell, A.J., 1989. A comparison of two recent jökulhlaups from an ice-dammed lake, Søndre Strømfjord, West Greenland. Journal of Glaciology 35, 157–162.
Russell, A.J., Roberts, M.J., Fay, H., Marren, P.M., Cassidy, N.J., Tweed, F.S., Harris, T., 2006. Icelandic jökulhlaup impacts: implications for ice-sheet hydrology, sediment transfer and geomorphology. Geomorphology 75, 33–64.
Sharp, M., Gemmell, J.C., Tison, J.-L., 1989. Structure and stability of the former subglacial drainage system of the Glacier de Tsanfleuron, Switzerland. Earth Surface Processes and Landforms 14, 119–134.
Sharp, M., Richards, K., Willis, I., Arnold, N., Nienow, P., Lawson, W., Tison, J., 1993. Geometry, bed topography and drainage system structure of the Haut Glacier D'Arolla, Switzerland. Earth Surface Processes and Landforms 18, 557–571.
Sharp., M., Tranter, M., Brown, G.B., Skidmore, M., 1995. Rates of chemical denudation and CO_2 drawdown in a glacier-covered alpine catchment. Geology 23, 61–64.
Shepherd, A., Hubbard, A., Nienow, P., King, M., McMillan, M., Joughin, I., 2009. Greenland ice sheet motion coupled with daily melting in late summer. Geophysical Research Letters 36, L01501.
Shreve, R.L., 1972. Movement of water in glaciers. Journal of Glaciology 11, 205–214.
Shreve, R.L., 1985a. Late Wisconsin ice-surface profile calculated from esker paths and types, Katahdin esker system, Maine. Quaternary Research 23, 27–37.
Shreve, R.L., 1985b. Esker characteristics in terms of glacier physics, Katahdin esker system, Maine. Geological Society of America Bulletin 96, 639–646.
Singh, P., Haritashya, U.K., Ramasastri, K.S., Kumar, N., 2004. Diurnal variations in discharge and suspended sediment concentration, including runoff-delaying characteristics, of the Gangotri Glacier in the Garhwal Himalayas. Hydrological Processes 19, 1445–1457.
Stearns, L.A., Smith, B.E., Hamilton, G.S., 2008. Increased flow speed on a large East Antarctic outlet glacier caused by subglacial floods. Nature Geoscience 1, 827–831.
Sugden, D.E., Denton, D.H., Marchant, D.R., 1991. Subglacial meltwater channel system and ice sheet over riding of the Asgard range, Antarctica. Geografiska Annaler 73A, 109–121.
Swift, D.A., Nienow, P., Hoey, T.B., Mair, D.W.F., 2005. Seasonal evolution of runoff from Haut Glacier d'Arolla, Switzerland and implications for glacial geomorphic processes. Journal of Hydrology 309, 133–148.
Syverson, K.M., Gaffield, S.J., Mickelson, D.M., 1994. Comparison of esker morphology and sedimentology with former ice-surface topography, Burroughs Glacier, Alaska. Geological Society of America Bulletin 106, 1130–1142.
Tweed, F.S., Russell, A.J., 1999. Controls on the formation and sudden drainage of glacier-impounded lakes: implications for jökulhlaup characteristics. Progress in Physical Geography 23, 79–110.
Walder, J.S., Hallet, B., 1979. Geometry of former subglacial water channels and cavities. Journal of Glaciology 23, 335–346.
Willis, I.C., Richards, K.S., Sharp, M.J., 1996. Links between proglacial stream suspended sediment dynamics, glacier hydrology and glacier motion at Midtdalsbreen, Norway. Hydrological Processes 10, 629–648.
Wingham, D.J., Siegert, M.J., Shepherd, A., Muir, A.S., 2006. Rapid discharge connects Antarctic subglacial lakes. Nature 440, 1033–1036.
Zwally, H.J., Abdalati, W., Herring, T., Larson, K., Saba, J., Steffen, K., 2002. Surface melt-induced acceleration of Greenland Ice Sheet flow. Science 297, 218–222.

Biographical Sketch

Neil Glasser is professor of Physical Geography in the Institute of Geography and Earth Sciences at Aberystwyth University in Wales, UK. He works on a number of topics relating to glaciology, glacial geomorphology, and glacial sedimentology including using glacial erosional landforms to reconstruct former ice sheets, reconstructing patterns of meltwater flow in former ice sheets and the role of structural glaciology in debris entrainment, deposition and landform development. He is also currently working on large data sets concerned with Quaternary glaciations in southern South America and the response of Antarctic Peninsula ice shelves to recent climate change. In 2006–07 he was a Fulbright Distinguished Scholar at the National Snow and Ice Data Center in Boulder, Colorado. He also serves as an editor of two major international journals: the *Journal of Glaciology* and *Quaternary Science Reviews*.