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The concept of glacier storage: a review

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Abstract

Glacier storage is a widely used term, applied to different processes and time-scales by different disciplines in hydrology and glaciology. We identify that storage occurs as ice, snow, and water associated with three time-scales. *Long-term storage* concerns storage of ice and firn as glaciers on time-scales of years to centuries and longer. This storage affects global sea level and long-term water balance of glacierized catchments and is especially important for water resources in arid and semiarid areas. *Intermediate-term storage* is applicable to processes such as storage and release of snow and water, in and on a glacier on a seasonal scale. This is also the most common definition in the literature implied by the term storage. Intermediate-term storage affects runoff characteristics in glacierized catchments and downstream river flow regimes. *Short-term storage* concerns diurnal effects of drainage through the glacier including routing through snow, firn and en- and subglacial pathways. In addition to these time-scale dependent processes there are also event-driven storage releases, termed *singular storage releases*, including drainage from glacier surges and drainage of glacier-dammed water. These events are associated with glaciers but do not exhibit cyclic response or have irregular occurrences. It is evident that glacier storage is not handled well by current conceptual or mathematical models and that, e.g. sub- and englacial storage are poorly constrained. Hence, holistic approaches to studying and modelling glacier storage are of major importance to fully integrate glaciers into the hydrological balance to be used for water resources and river flow predictions on all time-scales.

Keywords: Glacier hydrology; Glacier storage; Water storage

1. Introduction

Glaciers represent valuable natural reservoirs of water exerting a strong control on drainage characteristics of alpine catchments. Hence, storage and release of water from glaciers are important for various practical and scientific fields including hydroelectric power, flood forecasting, sea level fluctuations, glacier dynamics, sediment transport, and formation of landforms. Several review papers cover different aspects of glaciers and their hydrology (e.g. Lang, 1987; Röthlisberger and Lang, 1987; Hooke, 1989; Fountain and Walder, 1998; Schneider, 2000).

Most commonly glaciers are thought of as delaying runoff by preventing precipitation to run off directly. Such storage occurs on a sub-seasonal and sub-daily basis and involves both factors associated with snow accumulation and melt on the glacier and water storing capacity and characteristics of the glacier (Fig. 1).

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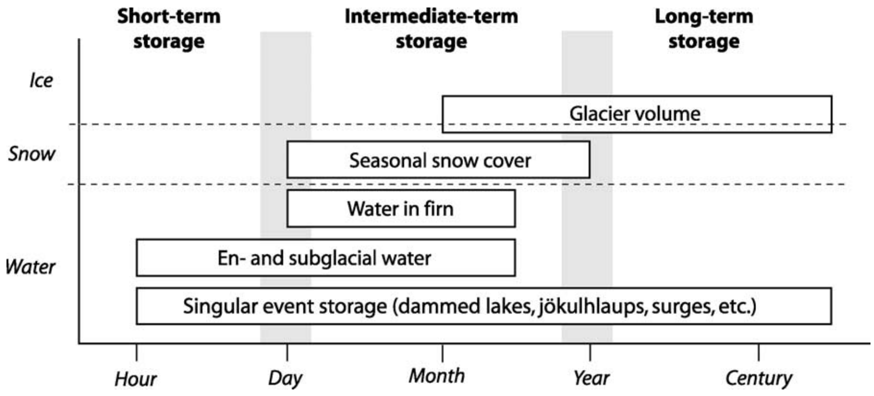

Fig. 1. Schematic graph showing different forms of glacier storage and their corresponding time-scales.

However, the glacier itself constitutes storage that is storing water as ice and releasing it when melted, depending on climatological factors. This storage varies on a time-scale comparable to climate variations, i.e. >1 year. Apart from the difference in time-scale, the most important distinction between these forms of storage is that the first primarily involves water in liquid phase (water) and the second in solid phase (ice or snow). Water can be stored in a number of ways: in surface snow and firn, crevasses, surface pools, englacial pockets, subglacial cavities, englacial and subglacial drainage network, and in basal sediments (Fig. 2). Furthermore, there are discrete events that suddenly release water that may have accumulated over months to years such as glacier-dammed lake floods, en- and subglacial floods, and glacier surges. All these aspects of storage are usually referred to by the singular term *storage* and its implicit meaning varies significantly in hydrological and glaciological literature. We suggest the use of long-, intermediate-, and short-term storage, respectively, for the different time-scales involved.

2. Long-term storage

2.1. Storage of water as ice and snow

Glacier ice contains 75% of available freshwater on the Earth (IPCC, 1996) of which 99.5% is contained, as ice, in the Greenland and Antarctic Ice Sheets. Small glaciers and ice caps thus contain a very small part of the frozen freshwater. However, they constitute a part that is well monitored and that currently contributes to sea level rise (Meier, 1984; Duyrgerov and Meier, 1997; Arendt et al., 2002).

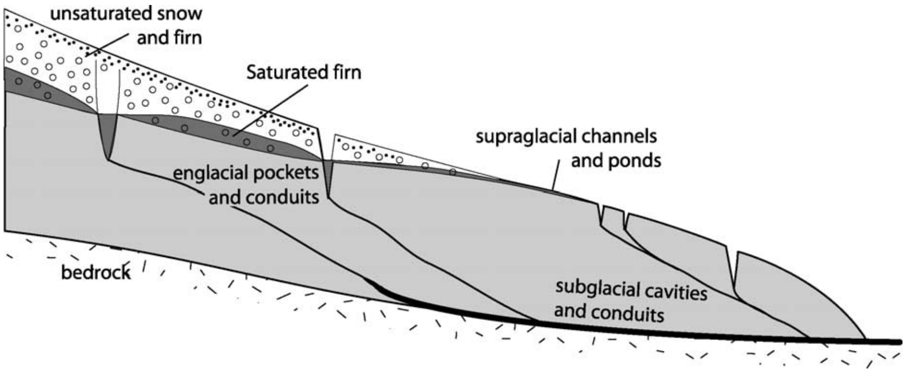

Fig. 2. The hydrological systems and locations of water storage in a temperate glacier (modified from Röthlisberger and Lang, 1987).

If melted completely, sea level would rise 0.5 m (IPCC, 2001). In contrast to the long response times of the Antarctic and Greenland ice sheets, such a rise may occur fast implying a major impact on human resources since coastal areas constitute very important agricultural areas as well as locations for habitation and industry. Hence, concern about sea level rise has increased interest in future variations of glacier volume, or long-term storage. Glacier volume is determined by a balance between accumulation of mass, usually by a combination of snow fall and wind drifting (e.g. Meier, 1973; Jansson, 1999), and ablation, primarily determined by surface energy balance (e.g. Lang, 1968; Meier, 1973; Hock, 1998) and calving (Brown et al., 1982). Climate change involves variation in one or more of these forcing variables causing changes in either accumulation, ablation or both. Chen and Ohmura (1990a) estimate that the Alpine glacier volume has decreased by ~0.57 km^3/year between the 1870s and 1970s. The estimated total volume is ~140 km^3, indicating that glaciers in the Alps could, at present rates, disappear in ~250 years. However, this figure is not be used as an accurate prediction, since the rate of volume-change varies depending on how far from equilibrium conditions each individual glacier is at the time of making the volume change estimate.

Glacier mass balance is measured on a comparatively small number of glaciers around the world (Haeberli et al., 1999a). However, these programs provide valuable data for estimating the contribution of the glacier itself to storage since the balance is a measure of net gain or loss of glacier mass. The longest continuous mass balance records to date are those from Claridenfirn (winter and summer balance measurements at two stakes since 1914; Müller-Lemans et al., 1994) and Storglaciären (spatially dense measurements of winter and summer balance since 1946; Holmlund and Jansson, 1999). The collection of mass balance records maintained by the World Glacier Monitoring Service provide a useful basis for evaluating world-wide trends in glacier volume (Haeberli et al., 1999b). Dyurgerov and Meier (1997) show that glacier volume is shrinking, however, local trends may vary (Dowdeswell et al., 1997).

Some glaciers in Scandinavia have recently grown, or even advanced (Holmlund et al., 1996). In order to obtain a better estimate of glacier fluctuations, glacier dynamics must be considered. Hence, flow models coupled to climatic models can be used both for reconstructions and predictions of glacier evolution (e.g. Oerlemans et al., 1998).

2.2. Effects on catchment hydrology

Long-term storage effect of glaciers involves net storage or release of water depending on climate (e.g. Kasser, 1973; Østrem, 1973; Fountain and Tangborn, 1985). During glacier growth less water is generated than expected from precipitation values and vice versa for glacier shrinkage. Glaciers affect catchment hydrology even at low percentages of glaciation. Summer flow is enhanced due to melting of glacier ice. In larger basins with sufficient elevation range to include melt- and rainwater-dominated runoff, glacier runoff compensates for otherwise decreasing summer discharge in lower parts of the basins (Fountain and Tangborn, 1985; Young and Hewitt, 1993). Kasser (1973) studied the change recorded discharge from Rhône drainage basin from 1876 to 1968 and demonstrated how discharge was correlated to the change in glacierized area. Hopkinson and Young (1998) studied the effects of changes in glacierized area on the runoff of the Bow River, Alberta, Canada. They found that annual glacier runoff, on average, comprised 2% of basin yield but that during a low flow year the contribution increased to 13%. For the driest month of that year glacier melt contributed 54% of basin runoff.

Glacier cover also affects year-to-year variability of runoff. Variability is lowest at moderate percentages of glacier cover (roughly 40%) and increases as glacier cover both decreases and increases (Fountain and Tangborn, 1985; Röthlisberger and Lang, 1987; Braithwaite and Olesen, 1988; Chen and Ohmura, 1990b). Annual variability is also less for basins with ‘typical’ glacier cover than for glacier-free basins.

The main difference between glacierized and glacier-free catchments is that runoff from glacier-free is dominated by precipitation whereas glacierized basins are energy dominated (Lang, 1987; Chen and Ohmura, 1990b). This highlights the importance of glaciers since they produce most water during hot, dry periods when precipitation is lacking.

Occasionally, attempts are made to increase runoff by enhancing melt, by decreasing albedo through dusting of the glacier surface. Kotlyakov and Dolgushin (1973) report on an experiment to decrease albedo on a glacier by spreading dark materials on the surface in order to increase ablation and thereby runoff. With coal powder, an increase in melting of 25–30% was accomplished. However, new powder had to be spread every week to maintain a steady high ablation since the material was washed away with the melted water. Such enterprises are not sustainable for long-term water production when considering the storage effect of glaciers. If maintained under a given climate scenario, storage is finite and not renewable without an accompanying reduction in runoff.

Climate change can cause glaciers to shrink and possibly vanish causing dry-season discharge to decrease dramatically. During prolonged periods of net mass loss, specific runoff will first increase until the glacier has retreated so that the decrease in glacier volume will lead to reduced flow rates (Fig. 3). Braun et al. (2000) modelled the effect of shrinking glacier cover. Large discharge peaks will occur when the excess melting augments rainfall peaks.

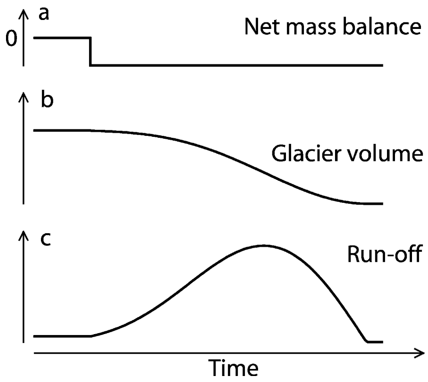

Fig. 3. Schematic representation of the long-term effect of negative glacier net mass balance (a) on glacier volume (b) and annual glacier runoff (c). Volume response lags forcing due to the time required to remove ice by melting. Note that discharge is larger during the first portion of the response period until the glacier is small enough to reduce excess runoff.

3. Intermediate-term storage

3.1. Seasonal runoff variations

Large volumes of precipitation are stored on glaciers in winter and released by summer melting. This produces a pronounced seasonality in discharge. The ratio of summer to total runoff rises strongly with increasing glacier cover. Lang (1987) provides a good summary of these processes. In Vernagtferner basin, Austria (81% glacierized), 90% of annual discharge is concentrated to the summer months June–October (Escher-Vetter and Reinwarth, 1994). Glaciers in Scandinavia release 85% of their annual average discharge during the three summer months June–August (Østrem, 1973). By comparing runoff from glacier-free areas and glacierized areas, Pertziger (1990) showed how maximum contribution from glacier-free areas precedes that from glacierized areas. Presumably, this is due to hypsographic differences as glaciers tend to have higher elevations than glacier-free valleys. The time of maximum seasonal runoff is delayed with increasing glacier cover (Meier and Tangborn, 1961; Stenborg, 1970). Fountain and Tangborn (1985) demonstrated that the delay is about a month if the glacier cover changes from 0 to 7%, and only about two weeks if the glacier cover increases from 50 to 100%.

3.2. Seasonal water balance

Water balance studies have revealed significant internal water storage through the year. The timing of storage and release varies between studies (Fig. 4).

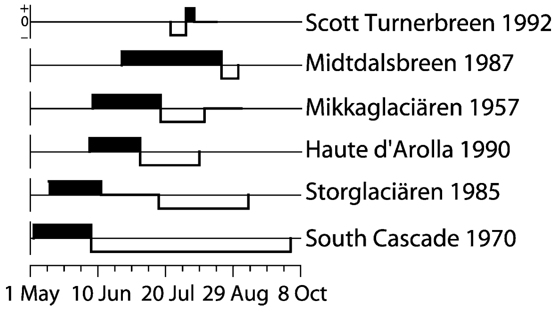

Fig. 4. Periods of storage gain (positive, filled, square), storage loss (negative, white, square) or approximate balance (solid line at zero). Data from sources discussed in the text.

Tangborn et al. (1975) showed that storage of water in South Cascade Glacier, USA, occurred during May while release from storage occurred June–September. Since the calculated losses for the period May–September indicate a net loss six times the storage in early summer they suggest that water must already be in storage by May. Östling and Hooke (1986) showed that storage of water in Storglaciären, Sweden, occurred during May–June and net loss occurred in late July and September. The net storage was positive, indicating that release during winter is needed to balance storage occurring during summer. Winter discharge has been observed from many glaciers. Of the two proglacial streams at Storglaciären which drain different parts of the glacier (e.g. Seaberg et al., 1988; Kohler, 1995), only the stream that carries all water generated in the accumulation area was observed to flow in winter (Stenborg, 1965). Stenborg (1970) concluded that the early summer delay seen in discharge curves from Mikkaglaciären, Sweden, most likely was the result from water remaining in snow and firn.

Subglacial water pressure measurements in Storglaciären (Jansson, 1996) indicate that water pressures close to floatation are maintained beneath large parts of the glacier not connected to subglacial tunnel systems. Hence, winter release of water can originate from both basal water systems and from firn storage. To date no estimates have been made of the size of the subglacial storage.

Willis et al. (1992) reported net storage during the summer observation period on Midtdalsbreen, Norway. They furthermore observed that storage changes were correlated with variation of surface input and inversely correlated to volume already in storage, implying a finite storage capacity. On Midtdalsbreen storage occurs throughout the period of measurement (22 June–30 August, 1987), also implying that net release must occur during the cooler part of the year. Similarly, Richards et al. (1996) show water balance calculations for Haut Glacier d'Arolla, Switzerland where storage occurs during the first part of the drainage season only to revert to release during the later half of the melt season. They attribute this change to the seasonal reorganisation of subglacial drainage rather than firn and snow storage. A study on Scott Turnerbreen, Svalbard, (Hodgkins, 1997) shows a reversed picture with a build-up of storage towards the end of summer and winter storage of water to be released the following summer.

Generally, storage of water occurs when rain and melt water input increases at a rate greater than the glacier drainage system can transmit. As the system develops during the course of the melt season, conditions will become more favourable for net release of stored water. Most studies generally agree with this scheme and show that storage is built over the first part of the summer melt period and may be released later in the summer and during fall and winter. Short-term changes from storage gain to loss and vice versa are superimposed on the general seasonal pattern depending on water input. High and rapidly rising water input is associated with storage while losses are associated with sharp reductions in water input. A problem with all field studies is that they do not cover the entire hydrological year and in some cases cover only part of the melt season. Furthermore, no studies cover more than one season which means interannual variability is not captured. More is evidently needed to resolve the water balance on glaciers. However, recently developed models (Verbunt et al., 2003) can help to fill up the gaps to some extent.

3.3. Location and processes of water storage

3.3.1. Firn storage

Water storage in firn is generally considered as a major factor causing runoff delay from glaciers. Schneider (2000) provides a comprehensive review of the processes in the firn and wet-snow zone of glaciers. In the firn area of temperate glaciers, melt water and rain infiltrate the firn surface and percolate through the unsaturated firn layer. Because permeable firn is underlain by practically impermeable ice, an aquifer develops (e.g. Sharp, 1951; Behrens et al., 1976; Lang et al., 1977; Schommer, 1977; Oerter and Moser, 1982; Oerter et al., 1982; Fountain, 1989; Schneider, 1999). Thickness of the firn aquifer depends on the hydraulic gradient of the firn layers and efficiency of the englacial drainage system. For example, on Storglaciären the firn aquifer reaches a maximum thickness of 5 m (Fig. 5). On Aletschgletscher, Switzerland, the firn aquifer becomes even thicker (7 m; Schommer, 1978).

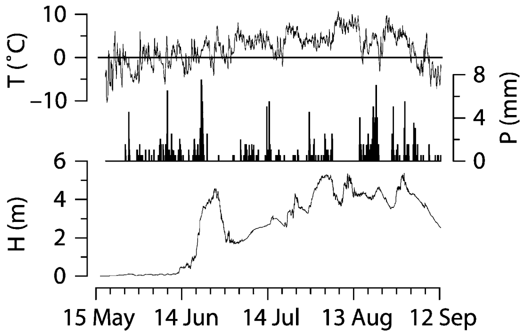

Fig. 5. Fluctuations in hourly water level, H, in a borehole in firn, precipitation, P, and air temperature, T, on Storglaciären, 1996.

In the saturated firn aquifer, only 40% of the pore space can be used for water storage because isolated air-filled pores account for ~60% of total pore volume (e.g. Fountain, 1989). Water storage in the firn aquifer of South Cascade Glacier (Fountain, 1989) accounted for 12% of maximum total water storage in the glacier (Tangborn et al., 1975). On Storglaciären a value of 44% was obtained (Schneider, 2000). On both glaciers, total water storage decreased during mid-summer (Östling and Hooke, 1986) whereas firn storage was high during the entire ablation season, indicating drainage of englacial and subglacial sources rather than drainage from the firn aquifer. The water balance calculation of Östling and Hooke also indicate that water entering the glacier in response to a rain storm caused storage requiring 1–2 weeks to return to the storage level prior to rain fall.

In early melt season some melt water is retained in the unsaturated firn layer due to capillary and adhesive forces and by re-freezing of such water as the cold wave penetrates into the firn pack during winter. Mean irreducible water content (water volume divided by total volume, when all free water has drained) was 3% in a firn core drilled in late winter on Storglaciären (Schneider, 2001). Estimates show that about 10% of annual glacial runoff is retained in the snow and firn cover by the processes described above. Since parts of the snow pack melt during summer, some of the retained water is again released, on Storglaciären corresponding to 2% of annual runoff.

Re-freezing of capillary water during winter and of percolating water in spring in the firn layer causes internal accumulation. This may be significant for traditional mass balance measurements if the winter cold wave penetrates below the summer surface from the previous year. Trabant and Mayo (1985) estimate internal accumulation in firn to be 7–64% of annual accumulation on different glaciers in Alaska. On Storglaciären, internal accumulation can account for ~0.05 m we corresponding to ~4% of annual specific accumulation (Schneider, 2001).

When the firn layer becomes temperate and the capillary deficit is filled, water content rises above irreducible water content and water starts to drain. Kawashima et al. (1993) determined water content on Hisago snow patch, Japan, to 3–7% during summer. Assuming 3% of irreducible water content, percolating water can account for up to 4% of total volume. Water percolation through the unsaturated firn layer delays outflow of water, generated at the glacier surface but also, and perhaps equally important, smooths the surface recharge signal yielding dampened fluctuations in firn water level (Fig. 5). Velocity of a percolating wetting front through the unsaturated firn layer of temperate glaciers usually ranges between 0.1 and 0.3 m h^{-1} (Schneider, 2000). Dye tracing on Aletsch gletscher (Lang et al., 1979), on Vernagtferner (Behrens et al., 1982) and on storglaciären (Schneider, 2000) indicate delays in runoff from the firn area ranging from several days to weeks whereas ice-covered areas yield delays of a few hours (e.g. Behrens et al., 1982; Kohler, 1995; Nienow et al., 1996). Percolating water can be re-directed by surface parallel ice lenses in the firn layer, which might explain extended delay of runoff early in the melt season (Bøggild, 2000).

Generally speaking, firn is a major component in the storage effect of glaciers and should be proportional to the proportion of the firn area to total area of the glacier (AAR) or drainage basin area.

3.3.2. Subglacial storage

Iken et al. (1983) described how the surface of Unteraargletscher rises significantly at the start of the melt season. They attributed this to subglacial storage and uplift of the glacier by water. Similar events, referred to as a mini-surge from observations on Variegated Glacier (Humphrey et al., 1986), have also been observed elsewhere, e.g. on Storglaciären (Jansson and Hooke, 1989) and on Black Rapids and Fels Glaciers (Raymond et al., 1995). Iken et al. (1996) performed slug tests in bore holes on

Gornergletscher, Switzerland, and yielded results indicating storage changes in cavities and channels beneath the glacier. The change in storage is attributed to a sudden shift in the subglacial drainage. A spring flood event on Bench Glacier, Alaska, indicated a change in storage corresponding to 0.13 m water averaged over the 9 km^2 glacier (Anderson et al., 1999). Schuler et al. (2002) compared measured discharge and calculated melt volume during a 18 day period on Unteraargletscher, Switzerland, and found that water storage occurred during this period. The discharge station was destroyed in a flood that drastically altered the basal drainage system, probably flushing out the stored water in the process. Most of these studies have strong indications of stored water in or beneath the glacier. However, the question still remains where this water is located.

On Storglaciären, water pressure in the overdeepening remains high throughout the year (Hooke, 1991; Jansson, 1996). In the case of Storglaciären the glacier bed in the overdeepening is, at least partially, covered by a till layer (e.g. Brand et al., 1987). This till layer probably constitutes a subglacial aquifer which may be fed by water from the firn area and marginal crevasses. Hooke et al. (1988) showed that englacial and subglacial drainage through the overdeepening was not coupled. It thus seems as if water level in the overdeepening is maintained by release of stored water from the firn area.

3.3.3. Modelling runoff

Because of the markedly different runoff response of a glacier compared to non-glacierized areas, modelling glacier runoff requires accounting for the specific effects of water being internally stored in and released from a glacier. However, only few runoff models specifically adopt separate procedures for routing and delaying melt and rain water through the glacier system. Most of these models employ the concept of linear reservoirs generally using one to three linear reservoirs coupled parallel or in series (Quick and Pipes, 1977; Gottlieb, 1980; Baker et al., 1982; Tangborn, 1984; van de Wal and Russel, 1994). Despite of their simplicity these models tend to perform remarkably well, as exemplified in Fig. 6 showing hourly discharge simulations for a melt season on Storglaciären. The glacier surface was divided into three areas corresponding to three parallel reservoirs, one for firn, snow, and ice, respectively, taking into account the markedly different hydraulic properties of these media (Hock and Noetzli, 1997, Fig. 7). Highest storage coefficients, k, are allocated to the firn area accounting for largest delay of water, lowest coefficients are assigned to the exposed ice area corresponding to fast throughflow of water and intermediate values to the snow-covered ablation area. This hierarchy of k-values generates the pronounced difference in diurnal discharge amplitudes between the outflow of the three reservoirs as evident in Fig. 6.

Often storage coefficients are assumed time-invariant, thus neglecting the effects of seasonal evolution of the glacial drainage system. Moore (1993) presented a model attempting to incorporate this process by varying the outflow coefficient

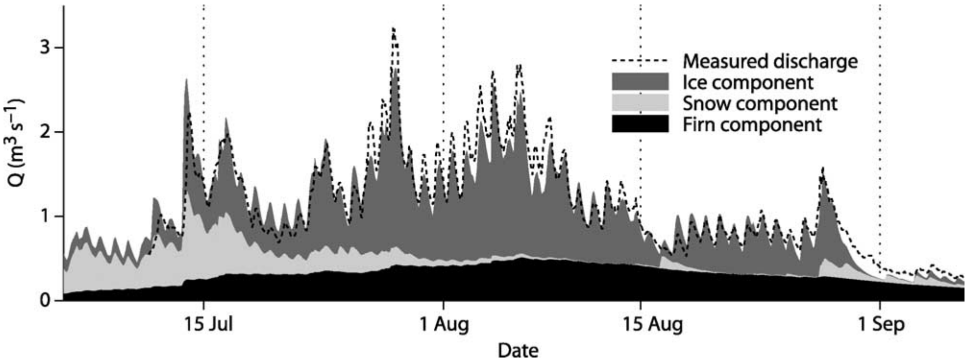

Fig. 6. Simulated and measured hourly discharge at Storglaciären 1994 assuming storage coefficients $k_{\mathrm{firn}} = 350$ h, $k_{\mathrm{snow}} = 30$ h, $k_{\mathrm{ice}} = 16$ h. The shaded areas mark the contributions of the firn, snow and ice reservoirs to total discharge. The snow reservoir contribution decreases as the snow line moves upglacier. Melt is computed from a distributed energy balance model (Hock, 1998).

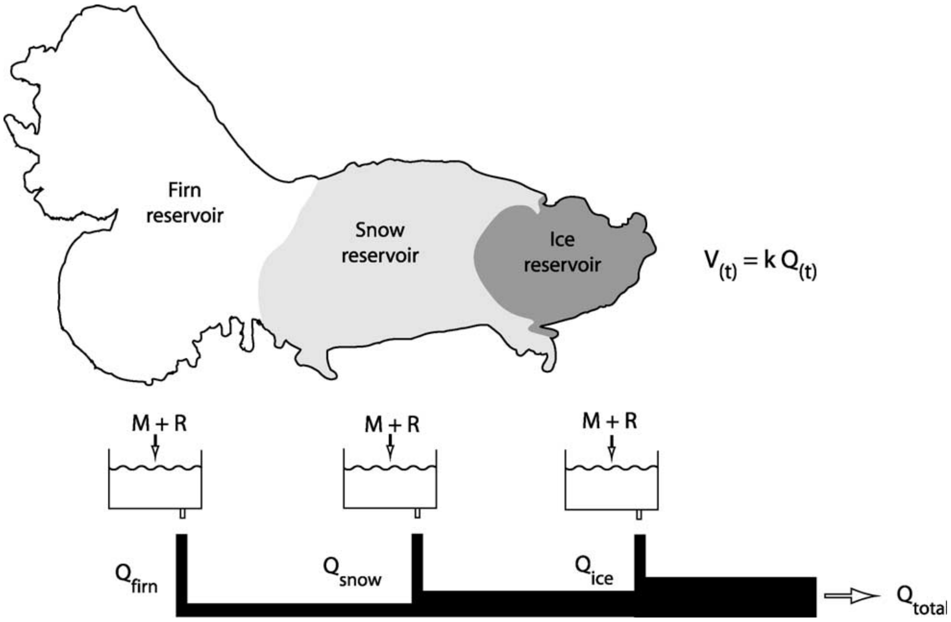

Fig. 7. Concept of three parallel linear reservoirs as applied to Storglaciären (Hock and Noetzli, 1997). The area of the firn reservoir is kept constant, while the areas of the snow and ice reservoir vary inversely, the latter expanding at the expense of the former, as the snow line moves upglacier during the melt season. The reservoirs are supplied by melt, *M*, and rain water, *R*. Outflow, *Q*, is proportional to reservoir volumes, *V*.

according to inflow. A runoff model including seasonal cyclic storage and release of water has been proposed by Tangborn (1984). Inflow to an englacial storage reservoir is assumed from November to mid-July and release from storage for the remainder of the year, the rates being controlled by the storage level of the reservoir. Although simulation error was considered reduced, prescribing fixed dates for switches between storage and release is a major draw-back of this approach.

4. Short-term storage

Presence of diurnal variations in discharge from a glacier is well known (e.g. Lang, 1967). Most of these variations can be attributed to ice melt (e.g. Meier and Tangborn, 1961; Elliston, 1973; Oerter et al., 1980a,b).

Collins (1982) analyzed the hydrographs from the stream draining the Gornergletscher, Switzerland, and found that storage in a slow reservoir contributed ~50–90% of total runoff during initial stages of recession. The volumes of water stored tended to decrease through the summer season which is consistent with much storage occurring in snow and firn (of which there is less as the season progresses). En- and subglacial storage should also decrease during a season since the drainage system of a glacier tends to become more efficient at carrying large discharges through the glacier as the melt season progresses (e.g. Seaberg et al., 1988; Hock and Hooke, 1993). The subglacial drainage system imposes short-term storage effects on runoff. Seaberg et al. (1988) show that water velocity in the subglacial drainage system increase linearly with discharge, implying that effective sinuosity decreases. Thus the response changes with discharge.

Singh et al. (2000) showed that recession is slower under large snow storage in a drainage basin and that it increases through the season as the snow pack thins. Hence recession varies during a year. Snow and firn constitute a major portion of the glacierized area which changes during a season (Krimmel et al., 1973; Fountain, 1996). Collins (1998) points at changing transient snow line to explain the seasonal variations in runoff from the Gornera drainage basin in Switzerland. Nienow et al. (1998) also couples this change in transient snow line to a change in characteristics of the subglacial hydrological system assuming an up-glacier–directed conversion of a distributed system into a channelized system as the snow line retreats. In addition, lapse rates affect the portion of the area under melting conditions for any given datum level temperature. Hence, spatial temperature variations may effectively shut off ablation in higher areas of the glacier. It is evident that rapid changes occur during the early part of the season but that the change in AAR-value affect runoff generation during summer.

Singh et al. (1997) showed that precipitation moved several times faster through snow than melt-induced water under precipitation-free conditions. Accelerated metamorphism and formation of preferential flow paths probably cause this difference. However, input rates are commonly higher from precipitation than from melt alone. Melt-induced water was also found to run off faster during precipitation conditions. Hence delay of run off on a diurnal scale varies depending on the intensity and the maturity of drainage channels in the snow and firn on the glacier.

Internal storage and release mechanisms operating on a diurnal time-scale have been inferred on several glaciers from dye tracer experiments and other investigations (e.g. Collins, 1979; Iken and Bindschadler, 1986). On Aletschgletscher (Hock et al., 1999) and on Storglaciären (Schneider, 2001), dye flux at the terminus occurred in multiple peaks and in general correlated inversely with discharge suggesting that short-term storage and release is triggered by the diurnal cycles of melt water input and corresponding water pressure variations.

5. Singular storage release

Singular storage release refers to phenomena like outburst floods and surges where these directly relate to glacier storage effects but fail to be categorized by the time-scales discussed above. Common to these are long-term build-up of storage followed by short-term release. The dynamic nature of glaciers allows temporary storage of water in a multitude of locations. Lakes can form beneath glaciers and at glacier margins. Sudden outbursts from such lakes can cause severe damage and cause irregular events in runoff from glacierized basins. Glacier surges are often associated with increased discharge and also redistributed mass within a glacierized basin, thereby altering melting conditions.

5.1. Outburst floods

Release of subglacially stored water can occur suddenly. Hagen (1987) reports on a large outburst flood occurring in winter on Tillbergfonna, Svalbard. The drainage of $\sim 1.0 \times 10^6$ m^{3}was accompanied by the formation of a crevassed depression on the glacier surface indicating a large subglacial storage. Drainage of a 40×10^6 m^3 largely subglacial lake beneath Kongsvegen, Svalbard, has also been observed by Liestøl (1977). The drainage occurred in May and subsequent filling of the lake took about three years. Such events are rare but occur on glaciers and constitute a highly irregularly occurring storage phenomena. Outburst floods probably originating from subglacial storage have occurred frequently from South Tahoma Glacier, USA, (Driedger and Fountain, 1989; Walder and Driedger, 1995). They consider a linked cavity system (Kamb, 1987) the most likely subglacial setting for the storage. In this case geothermal heat is probably not the cause for water production since outburst floods correlate with meteorological parameters.

The 1995 outburst flood releasing 1.9×10^9 m^3 of water from the Grimsvötn subglacial lake beneath Vattnajökull, Iceland, (Björnsson, 1998) is an exceptional example of non-systematic repeated release events. Water creation beneath Vattnajökull occurs because of high geothermal heat fluxes. Glaciers in areas of high geothermal heat fluxes are hence more prone to such behaviour than in other areas.

Ice-dammed lakes also contribute to storage effects of glaciers and have been intensively studied since the 19th century due to their damage to human activities in particular in the European Alps (e.g. Huber et al., 1950). Ape Lake, British Columbia, Canada, drained in 1986 discharging 46×10^6 m^3 in 24 h (Desloges et al., 1989). Similar events have become increasingly more common in the Himalayas (Richardson and Reynolds, 2000a) as the size and number of supraglacial lakes has increased dramatically over the past ~50 years (Ageta et al., 2000). Glacier lake outburst floods occur from the heavily debris covered Himalayan glacier as supraglacial thermokarst lakes and lakes formed between the terminus and sometimes ice-cored terminal moraines drain catastrophically (e.g. Yamada and Sharma, 1993; Richardson and Reynolds, 2000b; Sakai et al., 2000). Because of increasing glacier retreat rates lakes become more common and drainage events increasingly more frequent.

5.2. Glacier surges

A unique aspect of long-term storage and release concerns glacier surges (e.g. Dolgushin and Osipova, 1973; Krenke and Rototaev, 1973). A surging glacier experiences periodic, 1–2 year long, active phases preceded by a significantly longer quiescent phase where building up for the advance (e.g. Paterson, 1994, tab. 14.1, p. 359). The surge redistributes mass from the upper, higher, reaches to lower, advancing the glacier sometimes kilometers. At lower elevation the ice melts more rapidly. At higher elevation mass is added to compensate for the lost mass by flow (Raymond and Harrison, 1988). Depending on the melt rate at lower elevation and rate of accumulation at higher elevation, such surging glaciers may yield more or less cyclic long-term fluctuations in runoff.

On temperate glaciers, the surge phase is governed by hydrological conditions at the glacier base. The surge front moves downglacier with a speed several times the ice velocity (Kamb et al., 1985). Water pressures beneath the surge front and before the surge are close to overburden pressure. A turbid discharge peak follows the surge front marking the end of the surge phase. The reason for the discharge peak is still unresolved. Hence, surging glaciers have several ways to influence the runoff characteristics of glacierized catchments.

6. Concluding comments

Although widely used in connection with glaciers, the term *storage* is associated with a variety of meanings encompassing both different media (snow, ice, and water) and time-scales (short-, intermediate-, and long-term). From a glaciological perspective the glacier itself is considered as *storage*, as water, in the form of snow and ice, forms the glacier. The associated time-scale is long-term, ranging from years to thousands of years. Major implications of this storage concern effects on global sea level. From a hydrological point of view, storage is generally thought of as water runoff being delayed by the glacier system. Precipitation is stored as snow in winter and released during summer by melting. In addition, water in liquid phase is temporarily stored at various locations in the glacial system and thus delayed depending on the characteristics and evolution of the internal glacier drainage system. These processes mainly operate on a seasonal time-scale. As such storage distinctly modifies catchment hydrology, main implications concern any issues in water resources management. Short-term storage and release of water from glaciers are important for diurnal discharge characteristics as well as glacio-hydrological issues related to glacier dynamics.

Several issues concerning glacier storage remain largely unanswered or poorly investigated. First, it seems evident that glacier storage should be considered in a wider concept than at present to encompass storage on all time-scales. This is especially important because questions in widely different fields such as water resources and hydraulic engineering are connected to storage concepts but typically on different time-scales. Secondly, many studies have been carried out which imply storage of liquid water within glaciers. In some cases storage can be traced to permeable firn and snow aquifers. However, many studies imply sub- or englacial storage. In these cases large volumes of water are stored in glaciers but the location of the water remains mostly unknown. Research into the location of stored sub- and englacial storage should be considered an area of importance.

Few studies attempt to assess seasonal variations of water balance in order to quantify seasonal storage effects. Timing of periods of storage and release varies between studies. However, the question of interannual variability remains unsolved, as studies generally only cover short periods. More research is needed combining direct measurements and modelling efforts as a base for incorporating these effects in operational runoff models.

Even a low fraction of glacier cover within a basin has tremendous impact on hydrology. However, only few conceptual runoff models incorporate explicit routines to route water through the glacier, although the general hydrological effects of glaciers due to storage mechanisms are well known. Employing linear reservoirs approaches generally yields good results, but refined concepts are needed to account for temporal variations of storage processes as the internal drainage system develops throughout the melt season.

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