Long-term variability of proglacial groundwater-fed hydrological systems in an area of glacial retreat, Skeiðarársandur, Iceland

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Abstract

Proglacial groundwater-fed features, such as seeps, substantially impact proglacial geomorphology, hydrology, and ecology. However, there is a paucity of research on the impacts of climate change and glacial retreat on the extent of these important features. This paper aims to investigate the impact of glacial retreat on proglacial groundwater levels and on the extent of groundwater-fed seeps. Research has taken place in western Skeiðarársandur, the large proglacial outwash plain of Skeiðarárjökull, a retreating temperate glacier in SE Iceland. Changes in the extent of proglacial groundwater seeps were mapped using historical aerial photographs from 1978, 1997, and 2012. Proglacial groundwater levels were monitored in shallow boreholes between 2000 and 2012. The western margin of Skeiðarárjökull has retreated approximately 1 km from its position in 1978. However, this retreat was punctuated by short periods of readvance. The geomorphology and groundwater systems at the site were substantially impacted by the 1991 glacial surge and the November 1996 jökulhlaup, whose deposits altered approximately 18% of the area of groundwater seeps.

The surface areas of groundwater seeps and lakes in the study area have declined by ~97% between 1978 and 2012. Most of the decline took place after 1997, when there was a threefold increase in the mean rate of annual retreat. Groundwater levels also declined substantially between 2000 and 2012, although this trend varies spatially. Changes in precipitation and groundwater flow, alongside glacio-isostatic uplift, are suggested as possible causes for the observed declines in groundwater levels and seep extent.

Introduction

Groundwater forms a key component of proglacial hydrology, with proglacial alluvial aquifers supporting geomorphic and ecologically-important groundwater-fed surface water bodies, such as seeps (Milner and Petts, 1994; Malard *et al*., 1999; Brown *et al*., 2006; 2007a, b; Crossman *et al*., 2011). For instance, groundwater upwellings covered ~40% of the total riverine habitat of the glacial floodplains at a field site in Alaska (Crossman *et al*., 2012). However, despite their importance, proglacial groundwater systems still suffer from a paucity of research (Robinson *et al*., 2008). Previous research on glacial retreat and proglacial groundwater systems has investigated groundwater hydrochemistry (Cooper *et* al., 2002; Robinson *et* al., 2009a, b; Dragon and Marciniak, 2010), catchment water balance (Hodgkins *et* al, 2009; Cooper *et al*., 2011) and glacier-aquifer interactions (Roy and Hayashi 2008; 2009; Gremaud *et al.,* 2009; Gremaud and Goldscheider, 2010; Langston *et al.,* 2013; Magnusson *et al*., 2014). The importance of groundwater as a geomorphic agent has also been widely recognised (Tóth, 1999; 2009; Robinson *et al.,* 2008). The importance of groundwater-fed streams to proglacial ecology has also been studied in many proglacial settings. These studies show that groundwater contributions increase the environmental stability of proglacial streams, which significantly enhances proglacial biodiversity (e.g. Milner and Petts,1994; Malard *et* al., 1999; Ward *et al*., 1999; Brown *et al*., 2003; 2007a, b; Crossman *et al.,* 2011). However, in spite of their importance, there is a severe lack of research on the impacts of climate change and glacial retreat on the extent and distribution of proglacial groundwater-fed hydrological systems.

This study aims to investigate the impact of glacial retreat on the extent of proglacial groundwater-fed hydrological systems. The study maps long term changes (between 1978 to 2012) in the spatial extent of proglacial groundwater seeps in an area of rapid glacial retreat in SE Iceland and describes changes in proglacial groundwater levels which were monitored between 2000 and 2012. This study also provides possible hypotheses for the observed changes in proglacial groundwater levels and in the extent of groundwater seeps.

Study site

This study focuses on Skeiðarársandur, the proglacial outwash plain of Skeiðarárjökull (latitude 63°57’ N, longitude 17°21’ W), a retreating temperate piedmont glacier in SE Iceland that is a southern outlet glacier of the Vatnajökull ice cap. Skeiðarársandur is reputed to be the world’s largest active sandur (~1,000 km^2) (Marren, 2002). It extends across the ~23 km wide glacier margin of Skeiðarárjökull and ~20 km from the glacier margin to the Atlantic coast (Figure 1). Several active volcanic centres are located beneath

Vatnajökull and are the source of periodic glacial outburst floods (jökulhlaups) which impact Skeiðarársandur. Skeiðarársandur is drained by three major meltwater rivers: The Skeiðará, Gígjukvísl and Sulá, located in the eastern, central and, western parts of Skeiðarársandur, respectively (Figure 1). Substantial changes in sandur drainage occurred in 2009 when ongoing glacier retreat led to a rerouting of the majority of meltwater from the Skeiðará into the Gígjukvísl river system.

Geomorphic processes at Skeiðarársandur

The Skeiðarárjökull geomorphic landsystem has been classified using the landsystem model of Evans and Twigg (2002) as a temperate, actively-receding glacier margin that also experiences periodic surge events. The main depositional domains are marginal moraines, incised and terraced glaciofluvial forms, and subglacial landforms (Robinson *et al.,* 2008). The geomorphology and hydrology of Skeiðarársandur are impacted by the interaction between high frequency, low magnitude processes and low frequency, high magnitude events. The former mainly relate to seasonal and annual accumulation and ablation processes while the latter include glacial surges and jökulhlaups (Marren, 2005).

Glacial margin fluctuations

The margin of western Skeiðarárjökull has been retreating since the end of the 19th Century, the LIA maxima in Iceland (Björnsson and Pálsson, 2008). Western Skeiðarárjökull has retreated a net distance of approximately 3.5 km beyond its position since monitoring began in 1932 (The Icelandic

Glaciological Society [IGS], 2013). However, this distance excludes advances during the years 1946, 1965-6, 1973-5, and 1985-6 and the 1991 surge event (Figure 2, Table 1). The short duration of the advances of western Skeiðarárjökull contrast the dynamics observed in some of the smaller outlet glaciers of southern Vatnajökull, where periods of advance have lasted for several years (Bradwell *et* al., 2013).

From 1978 to 2012, the glacier margin retreated ~2 km, at a mean rate of 30 m yr^{-1} (Table 1). However, this distance was offset by advances during the mid 1980s and the 1991 surge. Consequently, the net retreat of the glacial margin between 1978 and 2012 was approximately 1 km. Following the 1991 surge, western Skeiðarárjökull has retreated continuously. The distance of retreat between 1997 and 2012 was approximately 1.5 km. The mean annual rate of retreat during this period has increased by a threefold (from 31 m yr^{-1} to 95 m yr^{-1}) (Table 1). The rates of retreat which were measured in western Skeiðarárjökull are 2-4 times higher than those reported from smaller retreating outlet glaciers of southern Vatnajökull (Bradwell *et al*., 2013; IGS, 2013; Marren and Toomath, 2013).

Glacial surges

Glacial surging causes significant advances of the glacial margin which are coupled with a shift of the subglacial drainage from efficient, channelized system, into an inefficient, linked-cavity system (Kamb *et al.,* 1985; Björnsson, 1998). Such changes to the subglacial drainage system are likely to impact the spatial distribution and amount of water transmission into the glacial bed, which will impact subglacial groundwater recharge (Boulton *et al*., 2001; Boulton and Zatsepin, 2006).

Skeiðarárjökull has experienced glacial surges in 1929 and 1991. During the 1991 surge, the western glacial margin advanced up to one km between September-November 1991, advancing at ~9.4 m day^{-1}. The surge increased the glacier surface area by ~10 km^{2} (Pálsson *et al*., 1992; Waller *et al*., 2008). The extent of surging during the 1991 event varied across the Skeiðarárjökull margin, with a significant advance in the west (~1 km) and only minor advance in the east (Waller *et al*., 2008). This study focuses on the ice-marginal zone of the more dynamic western area of the glacier (Figure 1).

The geomorphic impacts of surges in western Skeiðarársandur include the formation of push moraines, deposition of outwash fans adjacent to the glacier and changes in the routing of meltwater drainage (Russell *et al*., 2001; Van Dijk and Sigurðsson, 2002; Waller *et al*., 2008). Surges also impact proglacial hydrology and hydrogeology by steepening the ice surface slope and the hydraulic gradient (Wiśniewski *et* al., 1997; Russell *et al*., 2001; Robinson *et al*., 2008). The steeper hydraulic gradient is expected to increase groundwater flow (Freeze and Cherry, 1979).

Jökulhlaups

The geomorphology and hydrology of Skeiðarársandur are substantially impacted by jökulhlaups, which originate from glacio-volcanic interactions with the subglacial volcanic centres beneath Vatnajökull. In addition to the small jökulhlaups which occur regularly, substantial jökulhlaups with peak discharges between 25,000-53,000 $m^3 s^{-1}$ took place in 1934, 1938, and November 1996 (Guðmundsson *et al.,* 1995; Magilligan *et al.*, 2002). Major jökulhlaup events are associated with substantial hydrogeological and geomorphic impacts. These include rearrangement of the subglacial and proglacial drainage; pressurisation of the groundwater system; and extensive sediment deposition and erosion. The latter processes can change the depth to the water table, which will also alter the groundwater response to precipitation. Jökulhlaup deposition and erosion also alters the distribution and extent of aquifer properties, which will also impact groundwater flow. The highest and most variable values of hydraulic conductivity in Skeiðarársandur were measured in the shallow subsurface zones that were inundated by the November 1996 jökulhlaup (Robinson *et* al., 2008). This event also resulted in an extensive formation of kettle holes, which originate from the melting of grounded ice blocks that were carried during jökulhlaups (Fay, 2002). Water-filled kettle holes can provide important, yet transient, ecological niches (Robinson *et al*., 2009a).

Study site topography and hydrogeology

Study site topography

This study focuses on the western section of Skeiðarársandur, which is bordered by the rivers Sulá and Gígjukvísl in the west and east, respectively. The topography of the study area is characterised by an assemblage of different landsystems (Figure 1). The western boundary of the study site is defined by an active braid plain of the River Sulá that drains from a lake that is forming at Skeiðarárjökull’s extreme western margin. The northern limit of the study area is characterised by a moraine ridge and associated outwash fans that formed at the limit of the 1991 surge event (Russell *et al.,* 2001). The southern limit of the area is associated with a zone of high-relief moraines comprising part of a larger moraine system that is a distinctive feature of this part of Skeiðarársandur and which has been related to an earlier surge event (Russell *et al.,* 2001). Whilst parts of this system feature clear moraine ridges, other parts, including the area located immediately south of the Twin Peaks Lake (TPL), are characterised by relict meltwater channels and pitted outwash surfaces indicating the influence of former jökulhlaups. The proximal boundary of the high-relief moraines is characterised by a prominent ice-contact slope.

The TPL area is located at the foot of this slope and is characterised by a series of enclosed depressions that feature prominent cracks suggestive of the presence and gradual melt-out of buried ice. The presence of ice on the proximal side of the high-relief moraines is consistent with the observation of buried ice in a large moraine section exposed on the western bank of the River Gígjukvísl (Everest and Bradwell, 2003). To the north of TPL, the topography is characterised by a large area of low-relief moraines. The occurrence of small moraine ridges and possible crevasse-fill ridges suggest that this is a former subglacial surface. To the east of these moraines, the study area is characterised by a braid plain that was active following the 1991 surge event and which was associated with a jökulhlaup outlet during the subsequent November 1996 outburst flood (e.g. Russell *et al.,* 2006). Progressive glacier recession and down wasting has resulted in a decrease in fluvial activity in this area. The distal part of this braid plain forms one of the lowest parts of the study area and it contains the main area of seeps.

Study site hydrogeology

The wide variability of geomorphic processes (glacial, glaciofluvial, volcanic, and aeolian) which occur on Skeiðarársandur leads to significant heterogeneity in hydrogeological parameters (Robinson *et al.,* 2008). The sandur stratigraphy forms an extensive unconfined aquifer whose thickness varies from 80-100 m near the glacial margin to ~250 m near the coast (Guðmundsson *et al*., 2002).

The main sources of groundwater recharge are local precipitation and glacial melt, which originates from several different sources including basal melt; subglacially-routed, supraglacial, and englacial melt; and the melting of buried stagnant ice. Skeiðarársandur is locally underlain by buried ice (Everest and Bradwell, 2003), which can strongly impact groundwater recharge, dynamics and routing (Robinson *et al*., 2008). Exchange between meltwater rivers and the aquifer also provides groundwater recharge (Robinson *et al*., 2009b).

The regional groundwater system generally flows from north to south. However, local, perched groundwater systems, which are imposed on the regional groundwater flow system (Tóth, 1963), were also identified. These perched groundwater systems were mainly found within moraine areas (Robinson *et al*., 2008). The groundwater table across most of the sandur is shallow, typically 2-3 m below ground level. The proximal sandur is generally dominated by groundwater recharge, while the distal sandur is dominated by groundwater discharge, with water table depths reducing to a few centimetres near the coast (Bahr, 1997; Robinson *et al*., 2008). The spring lines are generally parallel to the Skeiðarárjökull margin, which suggests that the position of the glacial margin, rather than the lateral rivers, controls their distribution. The calculated regional groundwater discharge is ~2.5 m^3 s^{-1}, with mean regional groundwater velocity of 0.15 m day^{-1} (Robinson *et al*., 2008). High sediment mobility, strong winds, and the lack of fertile soils create harsh ecological conditions in Skeiðarársandur (Marteinsdóttir *et al.,* 2013). Field observations report relatively high abundance of flora and fauna near groundwater-fed seeps, which possibly form important ecological microsites where these conditions are more favourable.

Methods

Mapping of changes in the extent of groundwater seeps

Changes in the extent of groundwater seeps in western Skeiðarársandur were mapped using historical aerial imagery (dating from 1978, 1997, and 2012), using ArcMap© 9.3.1. The photographs were georectified using Ground Control Points as described by Bennett *et al*. (2010). Groundwater seeps and groundwater-fed streams were then mapped based on water colour and shading, similar to the approach that was successfully used by Drexler *et al.* (2013) to map changes in the extent of groundwater-fed fens following changes in snowmelt.

Water colour, and hence black and white shading, is determined by the interaction between the upwelling light reflectance of suspended inorganic and organic compounds and the downwelling of solar irradiance. When black and white images are used, the high turbidity and reflectance of meltwater make them appear lighter than groundwater. When colour images are used, the high turbidity of meltwater streams makes them appear brown.

Conversely, the low turbidity of groundwater-dominated bodies makes them appear green-brown (Jerome *et al*., 1994a, b). These differences were therefore used to map groundwater seeps and meltwater streams. The likelihood of the mapped areas to be impacted by groundwater has been ground-truthed. In order to verify the accuracy and precision of the digitization, a maximum value of 40 pixels was assigned for groundwater seeps. This figure is based on values obtained from ground-truthed areas.

Measurement of groundwater levels

Groundwater levels were monitored in shallow boreholes, whose depths vary between ~<1 m to >2 m below ground level. The boreholes were installed in 2000, 2001 and 2011. The boreholes installed in 2000 and 2001 were made from either PVC or steel pipes of ~50 mm inner diameter. The length of the screened section was between 170-300 mm. The depth of the boreholes installed in 2011 was ~1.7 m below ground level. The internal diameter of the boreholes installed in 2011 was 28 mm, with a screened section length of ~600 mm. These boreholes were levelled into the 2001 datum using a Leica Total Station™. Groundwater levels were monitored using a Solinst™ acoustic dip meter or a straight rod. Monitoring took place regularly over a ~6 week period in the summers of 2000, 2001 and 2011. Additionally, spot measurements were taken in March 2001, October 2001, August 2009, April 2011, and the summer of 2012. The full technical borehole details and monitoring procedures are described in Robinson *et al*. (2008).

Meteorological data

Temperature and precipitation

Changes in water budget (precipitation - Potential Evaporation) can impact groundwater levels and the extent of groundwater seeps. The annual and seasonal water budgets in western Skeiðarársandur were therefore calculated in order to determine whether they have changed during the study period. Temperature and precipitation data were obtained from the Icelandic Meteorological Office (IMO) station at Kirkjubæjarklaustur, located ~35 km west of the site. This station was chosen because it is the closest one whose records span through the whole study period (1978-2012). The meteorological data was smoothed using Order 3 Moving Average (MA) (Makridakis *et al*., 1998).

Calculation of water budget

Potential Evaporation (PE) was calculated using the Thornthwaite (1948) equation [eq. 1].

$$E = \left(1.6 \times \left(\frac{10T_a}{I} \right)^{6.75\times10^{-7} I^3 - 7.71\times10^{-5} I^2 + 1.79\times10^{-2} I + 0.49} \right) \left(\frac{10}{d} \right),$$

Eq. 1

Where E is evaporation (mm day^{-1}), T_a is the mean monthly air temperature (°C), and I is the Annual Heat Index (AHI), which is calculated as $I=\sum i$, where $i = (T_a/5)^{1.514}$, and *d* is the number of days in each month. Due to the sparse vegetation at the field site, transpiration was omitted from the calculations. Water budget was then calculated by subtracting PE from precipitation.

Results

Temporal changes in the extent of groundwater seeps

1978 aerial photograph

Figures 3-6 illustrate changes in the extent of groundwater seeps in western Skeiðarársandur from 1978 to 2012. Figure 3 shows the extent of groundwater seeps and lakes in 1978 (the Icelandic Geodetic Survey (Landmælinger Íslands [LMÍ]), 1978). The glacier margin retreated a net distance of ~2.5 km between the start of monitoring in 1932 and the time of this image. Groundwater seeps in this image have the largest areal extent, ~2,767,200 m^2 (Table 2). The main area of groundwater seeps is bordered to the north and east by a large meltwater and groundwater-fed braided channel (“the Gígjukvísl tributary”); to the west by an area of low-relief moraines and stagnant ice that is located to the north of Twin Peaks Lake (TPL); and to the south by the high-relief moraine belt (Figure 3). In 1978, groundwater seeps covered the entire area between the Gígjukvísl tributary and the eastern limit of the low-relief moraines. The main seeps area was connected to the seeps east of TPL by an active groundwater-fed channel. Additional areas of groundwater seeps existed east of the Gígjukvísl tributary and to the north of TPL and Lake A (Figure 3).

1997 aerial photograph

Figure 4 shows the extent of groundwater seeps in 1997 and the impacts of the November 1996 jökulhlaup (LMÍ, 1997). Following the advances during the mid 1980s and the 1991 surge, the glacier margin has advanced by ~ 420 m relative to its position in 1978 (Figure 2, Table 1). The area of groundwater seeps has declined by ~20% since 1978 (Table 2). The main declines took place around the main jökulhlaup route, near jökulhlaup outlets at the glacier margin, and to the NW of TPL (Figure 4). Approximately 430,000 m^2 (~18%) of the groundwater seeps that were mapped in 1978 were altered by jökulhlaup deposits. Following the jökulhlaup, the main seep area has shrunk and moved southwards, away from the margin. However, it has also expanded to the east, with seeps replacing areas that contained braided channels in 1978 (Figure 4).

2012 aerial photograph

The 2012 aerial photograph (Google Earth, 2013) illustrates the continued recession of western Skeiðarárjökull, which retreated 845 m beyond its position in 1997. The mean annual rate of glacial retreat has also substantially increased during this period (Figure 5, Table 1). This retreat was coupled with a substantial decline in the area of groundwater seeps and lakes (Figures 4-6). The area of groundwater seeps has declined by ~97% between 1978 and 2012, with only small springs remaining within the main groundwater seep area (Figures 3-6, Table 2). The surface area and perimeters of lakes also declined substantially between 1978 and 2012, with the areas of TPL and GW2 Lake declining by 95% and 44%, respectively. Many of the smaller lakes have substantially shrunk or completely dried out, including Lake A (Table 2, Figures 3-6).

Changes in groundwater levels in western Skeiðarársandur

Groundwater levels at the study site declined substantially between July 2000 and 2012 (Figure 7). These declines were observed over both ~decadal (2000-2012) and annual (2011-2012) time scales, and have shown a considerable spatial variability (Table 3). Groundwater levels have fallen below the bottom of the borehole screened section (intake) in most boreholes at the site, meaning that only *minimum* amounts of water table decline can be measured. Such declines had already been observed at P4, P6 and WT A in August 2009 (Table 3). The largest measured declines between 2000 and 2009 were >1.97 m near the glacial margin (borehole P6) and >1.77 m in an area of dried groundwater seeps north of TPL (borehole P3) (Table 3). Groundwater levels at P13, located near the remains of the main groundwater seep area (Figure 1) fell by ~1.55 m between 2000 and 2012. However, this area contained the only borehole in the 2000 network where groundwater levels have not fallen below the intake. Falling groundwater levels were also measured in most of the boreholes that were installed in 2011 (Table 3).

Changes in water budget

The mean annual temperature at the Kirkjubæjarklaustur meteorological station during the study period (1978 to 2012) was 4.82 ± 0.65 °C. The mean annual precipitation was 1711 ± 218 mm (Icelandic Meteorological Office, [IMO], 2013). Precipitation was approximately three times higher than PE during the study period, resulting in a constantly positive annual water budget which ranged between 1080 and 1590 mm (Figure 8). The annual and most of the seasonal mean air temperature and water budgets have increased during the study period. However, seasonal variability was observed, with the highest seasonal water budgets occurring in winter and autumn and the lowest in summer. During the study period, winter and autumn water budgets increased by 140 and 216 mm respectively. Conversely, the increases in spring and summer water balance were much smaller (Table 4).

The changes in annual and seasonal water budget during the main period of decline in the extent of groundwater seeps (1997-2012) show a mixed trend. The annual and autumn water budgets have increased substantially (350-430 mm), while winter and spring water budgets have increased by ~100 mm. Conversely, summer water budget declined by 110 mm. This is mainly due to lower summer precipitation rather than higher PE. However, despite these declines, the summer water budget still remained positive (Table 4).

Interpretation and discussion

The spatial distribution of changes in groundwater levels

Groundwater levels in western Skeiðarársandur have generally declined between 2000 and 2012, with groundwater levels falling below the intake in most boreholes. However, these declines showed a considerable spatial variability (Table 3, Figure 7).

Groundwater levels near the glacial margin

The largest decline in groundwater levels between 2000 and 2009 was measured at P6, located near the Skeiðarárjökull margin, adjacent to an area of ice-cored moraines and stagnant ice (Table 3). This fall in groundwater levels is accompanied by a reduction in the extent of the main groundwater seeps area (Figures 3-6). The importance of ice melt as a source for groundwater recharge increases with proximity to the glacial margin, as evidenced by $\delta^{18}O$ and δD compositions (Robinson *et* al., 2009b). Therefore, the fall in groundwater levels at P6 should provide a good indication for changes in recharge from glacial melt. Groundwater levels near the glacial margin previously showed large declines in autumn and early spring, seasons during which ablation is low (Robinson *et al*., 2008). This shows that only a small component of the groundwater at these sites originates from subglacial melt, as such melt should not be significantly impacted by seasonal ablation (Flowers *et al*., 2003; Robinson *et al*., 2008). This suggests that the zone of dead and stagnant ice near the margin is the likely source of groundwater recharge during the summer months. This hypothesis is also supported by comparing the extent of groundwater seeps and the position of the glacial margin in 1978 (Figure 3) with those in 1997 (Figure 4), which showed that the extent of groundwater seeps fell in 1997 despite the advance in the position of the glacier margin.

Groundwater levels in areas of groundwater seeps

The only location from the 2000 monitoring network where groundwater levels did not fall below the borehole intake is located near the remains of the main groundwater seep area (Figure 1, Table 3). The smallest annual (Figure 7) and seasonal variability in groundwater levels were also measured in this environment (Robinson, 2003). The relatively small variability is also supported by observations of groundwater discharge, which suggest that the seeps are fed by a local groundwater flow system that is imposed on the regional one (Tóth, 1963; Robinson *et al*., 2008). This small variability illustrates the relatively consistent water supply which groundwater-fed systems provide (Tague and Grant, 2009; Muir *et al.,* 2011).

Groundwater levels near moraine lakes

Groundwater levels near lakes have generally declined, with levels falling below the borehole intake in many locations. These falls were coupled with substantial declines in lakes' surface areas (Figures 3-6, Table 2). The decline of groundwater levels near lakes has also shown considerable spatial variability (Table 3).

Lake A shrank continuously during the study period, and then completely dried out after 2007 (Figure 6). Groundwater levels near Lake A also declined substantially (Table 3). Observations suggest that the area of Lake A consists of either a perched aquifer or an impermeable lake bed, underlain by either clay or buried ice (Robinson *et al*., 2008). This hypothesis is supported by observations of buried ice in Skeiðarársandur (Everest and Bradwell, 2003) and the complex and heterogeneous internal hydrology of moraines (Roy and Hayashi, 2009; Langston *et al*., 2011). It is suggested that the lake may have drained due to a catastrophic failure of the underlying ice layer (Robinson *et al*., 2008).

Groundwater levels near GW2 Lake have shown different dynamics. The area of this lake declined by 44% since 1978 (Table 2). However, there is a much smaller fall in groundwater levels, with only a 0.1 m decline between August 2011 and 2012 (Table 3). These differences illustrate the substantial variability in the patterns of decline in groundwater levels around lakes in western Skeiðarársandur.

Possible controls for the observed declines in groundwater levels and seeps

This section suggests various hypotheses for the substantial declines in groundwater levels and in the extent of groundwater seeps in western Skeiðarársandur.

Changes in water budget

Lower water budgets could possibly explain the observed declines in groundwater seeps and levels. Figure 8 and Table 4 show that the annual and most of the seasonal water budgets have increased over the study period, especially during winter and autumn. Conversely, summer water budget has fallen by ~100 mm since 1997. Air temperature has also generally increased (Table 4).

The fall in summer water budget can partially explain the declines in groundwater seeps and levels. However, this fall is expected to be offset by the increases in winter and autumn precipitation. Higher rainfall can also increase groundwater recharge indirectly by enhancing glacial ablation (Wolfe and English, 1995), with rainfall becoming especially effective in debris-covered glaciers such as Skeiðarárjökull (Kellerer-Pirkblauer *et al.*, 2008; Nield *et al.*, 2013). The rise in autumn and winter precipitation is therefore expected to increase groundwater recharge and storage. Conversely, higher cold season temperature can reduce groundwater recharge and storage by increasing evaporation and the rain/snow ratio and by altering the timing of melting (Okkonen *et al*., 2009; Stewart, 2009; Crochet, 2013). These mixed trends suggest that, despite their possible contrasting outcomes, changes in water budget are important factors in the decline of groundwater levels and groundwater seeps.

Changes in glacial melt

$\delta^{18}O$ and δD isotopic evidence has shown that the contribution of glacial melt to groundwater recharge increases with proximity to the glacier margin, highlighting the important role for groundwater recharge (Robinson *et al*., 2008; 2009b). Falls in groundwater levels during periods of low ablation suggest that changes in melt from buried ice and ice-cored moraines, rather than changes in the position of the glacial margin, are probably the main reason for the decline in groundwater levels at this area. However, the role of changes in glacial melt is difficult to infer, as this parameter was not measured directly in this study.

Changes in proglacial groundwater flow

Changes in the hydraulic gradient

Glacial retreat is projected to substantially alter the hydrology of Vatnajökull, reducing runoff and diverting river routes. Such changes are also projected to impact subglacial groundwater systems (Flowers *et al*., 2003; 2005). Glacial retreat can lower the ice overburden pressure and hydraulic gradient, which will reduce groundwater flow (Haldorsen and Heim, 1999; Piotrowski, 2007). Such changes could be an important cause for the declines depicted in Figures 3-7. However, at present the effect of the glacially-induced hydraulic gradient on the proglacial zone is not fully understood.

Lowering of the glacier bed

Changes in proglacial groundwater flow can also be caused by the lowering of the glacier bed and river outlets. Sandur development models suggest that glacial retreat leads to an upstream lowering of river equilibrium profile, which encourages fluvial incision and alluvial terraces (Thompson and Jones, 1986; Thompson, 1988). The lowering of the equilibrium profile would then direct flow unto the lowest channel (Thompson 1988, Marren 2002; Marren and Toomath 2013). The impact of the lowering of the equilibrium profile can be augmented when glaciers retreat into subglacial overdeepenings. Such retreat can increase the sensitivity of the proglacial zone to glacial margin fluctuations, where relatively small fluctuations in the position of the glacier margin cause fairly large changes in the upstream long profile of proglacial rivers (Marren and Toomath, 2013).

The lowering of river outlets due to an overdeepening is a possible cause for the observed declines in groundwater seep extent and levels. Radio echo soundings have identified two principal overdeepenings associated with Skeiðarárjökull (Figure 1B). The larger overdeepening extends from the glacier's centreline to the eastern margin. The second one is located in the western margin, associated with the drainage of the river Sulá (Björnsson *et al.,* 1999). However, neither of these overdeepening impacts the study area. The emergent ice-marginal geomorphology from this part of the Skeiðarárjökull margin also refutes the role of an overdeepning, as this area is characterised by dead ice topography, which is associated with the melt-out of a surge-related basal ice layer and streamlined subglacial topography (Waller *et al.,* 2008). This is in marked contrast with the geomorphology of ice-marginal areas associated with overdeepenings, whose retreat is associated with the development of large proglacial lakes (Cook and Swift, 2012). Therefore, whilst over deepened basins are clearly influential in some parts of the glacier margin, the authors do not believe that this specific part of the margin is significantly impacted by an overdeepening.

Changes in river-aquifer exchange

Groundwater recharge from meltwater rivers, through river-aquifer exchange, is an important control on proglacial groundwater levels (Cooper *et al*., 2002; Magnusson *et al*., 2014). The location of meltwater rivers exerts an important control on such exchange, hence a reduction in river-aquifer exchange, due to changes in the position of meltwater rivers, provides another possible explanation for the observed changes in the proglacial groundwater systems. However, the location of the main Gígjukvísl and Sulá river channels did not change considerably during the study period, which suggests that river-aquifer exchange should not have decreased. Additionally, the recent drainage changes in Skeiðarársandur have substantially increased the discharge in the Gígjukvísl. These changes are expected to augment, rather than reduce groundwater recharge from meltwater through river-aquifer exchange. Therefore, although river-aquifer exchange has not been measured directly, its decrease is probably not the main cause for the declines depicted in Figures 3-7.

Glacio-Isostatic uplift

Deglaciation and isostatic uplift have been previously shown to impact topography, hydrology, hydrogeology, and ecology (Glaser *et* al., 2004; Solberg *et al*., 2008). The rates of vertical glacio-isostatic uplift in response to glacial retreat around southern Vatnajökull range between 9-25 mm yr^{-1} (Pagli *et al*, 2007). These rates suggest that the study area has risen by 0.31 to 0.85 m during the study period (1978-2012) and between ~0.14 m to 0.38 m during the main decline in groundwater seeps and levels (1997 to 2012). Even when the higher rates of these estimations are used, the uplift rates remain below the observed decline in most boreholes (Table 3). Hence, although glacio-isostatic uplift may have contributed to the decline in groundwater levels and seeps, it is probably not its main cause.

Deposition of volcanic tephra

The deposition of volcanic tephra buries groundwater seeps and deepens the distance between the water table and the surface, which reduces the aquifer's responsiveness to precipitation. These processes may also explain some of the declines in groundwater levels and seeps in western Skeiðarársandur. Grímsvötn, situated under the Vatnajökull ice cap, ~ 40 km north of the site, is Iceland's most active volcanic system in historical times (Thordarson and Larsen, 2007). During the study period, it has erupted in 1996, 1998, 2004, and May 2011 (Jude-Eton *et al*., 2012). The eruption in May 2011 released 0.6-0.8 km^3 of tephra (Guðmundsson *et al*., 2012). Tephra deposits buried many groundwater-fed channels and seeps. Measurements taken at western

Skeiðarársandur in August 2011 showed a wide spatial variability in the depths of tephra deposits. The mean depth of tephra deposits near boreholes was 0.055 (±0.031) m. The depth of tephra deposits near groundwater-fed channels and seeps exceeded 0.40 m. However, these measurements were obtained three months after the eruption; hence, the tephra had been subjected to extensive fluvial and aeolian entrainment and deposition. In addition to the fairly transient nature of tephra deposition, groundwater levels have declined between August 2011 and August 2012 (Table 3), during which there was no volcanic activity. Therefore, burial by tephra deposits was not a major cause for the declines depicted in Figures 3-7.

Implications of the declines in groundwater seeps and levels

This study observes major declines in proglacial groundwater levels and groundwater seeps in an area of rapid glacial retreat. It is suggested that these declines substantially impact sandur aquatic ecology as groundwater significantly enhances proglacial biodiversity by increasing the thermal and channel stability, temperature, and nutrient levels of proglacial streams (e.g. Milner and Petts, 1994; Crossman *et al.,* 2011). Additionally, field observations have shown relatively high abundance of flora and fauna near groundwater seeps in Skeiðarársandur. This suggests that groundwater seeps form important microsites, which enhance terrestrial ecological establishment and provide ameliorated conditions from the frequent high sediment mobility, strong winds, and lack of fertile soils which often prevail in recently-deglaciated areas (Jumpponen *et al.,* 1999; Marteinsdóttir *et al.,* 2010; 2013).

However, proglacial ecology is vulnerable to glacial retreat and climate change, with projected impacts of decreasing meltwater contributions and increasing contributions from rainfall, snowmelt and groundwater (Brown *et al.,* 2006; 2007a, b; Blaen *et al.,* 2013; 2014). Proglacial groundwater flow, spring discharge, and groundwater contributions to runoff and storage are also projected to alter due to glacial retreat (Haldorsen *et al.,* 2010; Rutter *et al.,* 2011; Finger *et al.,* 2013). These changes are projected to adversely impact proglacial ecosystems and possibly lead to the redistribution and extinction of endemic species (Brown *et al.,* 2007b; Milner *et al*., 2009; Jacobsen *et al*., 2012). Therefore, due to the importance of groundwater to proglacial ecology, it is suggested that further decline in groundwater levels and in the extent of groundwater seeps in Skeiðarársandur will adversely impact sandur ecology.

Conclusions

Western Skeiðarárjökull has retreated approximately 1 km during the study period (1978-2012). This retreat was coupled with a decline of ~95% in the areas of groundwater seeps and many of the lakes at the site. Most of these declines took place after 1997, when the rate of glacial retreat has increased by a threefold. Groundwater levels at the study area have also fallen substantially between 2000 and 2012, although the extent of these declines varies spatially. The largest declines were observed near the glacial margin. The smallest declines in groundwater levels were observed near current groundwater seeps. The annual water budget has increased substantially between 1978 and 2012. Seasonal water budgets have also increased in every season except summer, where it has declined.

The geomorphology, hydrology and groundwater systems of Skeiðarársandur are substantially impacted by glacial fluctuations, surges, and jökulhlaups. The 1991 surge steepened the topography and transformed surface and subsurface drainage at Skeiðarársandur. The November 1996 jökulhlaup resulted in a likely pressurization of the groundwater system, kettle hole formation, and extensive sediment erosion and deposition. Jökulhlaup deposits buried ~18% of the area of groundwater seeps that were mapped in 1978.

It is suggested that the combination of rapid geomorphological changes, changes in water budget and groundwater flow, alongside vertical glacio-isostatic uplift is probably the cause for the observed declines in groundwater seeps and levels. However, further research is needed in order to verify and quantify the contribution of each factor. Groundwater seeps support important ecological microsites in this harsh proglacial environment. A continuous decline in groundwater levels and seeps is therefore suggested to adversely impact Skeiðarársandur's proglacial ecology. This research will benefit further from numerical modelling of the impact of future glacial retreat and climate change on proglacial groundwater levels and on the extent of groundwater-fed systems.

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Figure 1. A. Location map of Skeiðarárjökull in Iceland. **B**. The Skeiðarársandur outwash plain and the study area (denoted in solid white line) in western Skeiðarársandur (from Google Earth, 2013). OD_1 and OD_2 show the locations of the overdeepenings in eastern/central and western Skeiðarárjökull, respectively. These locations are based on Björnsson *et al*. (1999). **C**. The field site in western Skeiðarársandur (**the Icelandic Geodetic Service, Landmælinger Íslands [**LMÍ], 1997). The study area is denoted by the dashed white line. Shallow boreholes are denoted in white with the different shapes denoting the different hydrogeological environments in which the boreholes were installed (see legend). The solid white line denotes the main area of groundwater seeps.

Figure 2A. The cumulative retreat distance of western Skeiðarárjökull from 1932 to 2012. The arrows show the years of the aerial images. The data was obtained from the database of the Icelandic Glaciological Society (IGS), 2013. **2B.** Annual changes in the position of the glacial margin of Western Skeiðarárjökull (1932-2012). The figure also shows the full length of this study and the period of groundwater monitoring. The data was obtained from the database of the IGS, 2013.

Figure 3. The extent of groundwater seeps in western Skeiðarársandur in 1978 (LMÍ, 1978). Groundwater seeps are denoted in white with black outline. Lakes are denoted in grey. The position of the glacial margin is only an approximation, due to the extensive amounts of buried ice in this area.

Figure 4. The extent of groundwater seeps in western Skeiðarársandur in 1997 (LMÍ, 1997). Groundwater seeps are outlined in white. Lakes are denoted in grey. The figure also shows the main route (denoted by the black arrow) and outlets of the November 1996 jökulhlaup. The position of the glacial margin is only an approximation, due to the extensive amounts of buried ice in this area.

Figure 5. The extent of groundwater seeps in western Skeiðarársandur in 2012 (Google Earth, 2013). Groundwater seeps are outlined in white. The lakes are marked in grey. The position of the glacial margin is only an approximation, due to the extensive amounts of buried ice in this area.

Figure 6. The decline in the extent of groundwater seeps in western Skeiðarársandur (1978-2012). The figure shows the extent of groundwater seeps in 1978 (red), 1997 (blue) and 2012 (green). The position of the glacial margin is shown by the solid lines of the respective colours. Changes in the area of Twin Peak Lake are also illustrated for the following years: 1978 (turquoise), 2012 (orange). The 1997 extent was very similar to that in 1978. Hence, it was omitted for clarity.

Figure 7. A time series of changes in groundwater levels in western Skeiðarársandur between August 2000 and August 2012. Open shapes denote boreholes where groundwater levels have fallen below the intake. For the location of the boreholes see Figure 1.

Figure 8. Moving Average (MA) of annual and seasonal water budget at the study area. The data was obtained from the IMO (2013).

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Period	**Retreat/ Advance**	**Distance of retreat/ Advance (m)**	**Mean rate of annual retreat (m yr^{-1})**	**Min. annual retreat (m)**	**Max. annual retreat (m)**	**Cumulative distance (m)**
1932-1945	Retreat	-1680	129	-3	-336	-1680
1946	Advance	+84				-1596
1947-1984	Retreat	-968	25	(+40)	-199	-2564
1985-1986	Advance	+441				-2123
1987-1990	Retreat	-335	84	-20	-114	-2458
1991-1992	Advance (1991 surge)	+515				-1943
1993-2012	Retreat	-1603	80	-10	-200	-3546
	Total retreat (m)	**Total advance (m)**	**Net retreat (m)**	**Mean annual retreat (m yr^{-1})**	**Min. annual retreat (m) (year)**	**Max. annual retreat (year)**
Total monitoring period (1932-2012)	-4755	1209	-3546	44	+429 (1991)	-336 (1940)
Period covered in this study (1978-2012)	-2030	+962	-1068	31	+429 (1991)	-200 (2006)
Period of observed decline in groundwater seeps (1997-2012)	-1513	0	-1513	95	-10 (2005)	-200 (2006)

Table 1. Glacial margin fluctuations for western Skeiðarárjökull (1932-2012). The table shows the main periods of retreat and advance (IGS, 2013). Positive values for the minimum retreat column denote the maximum advances during the period. The data below the grey row summarizes the data for the total monitoring period, the study period and the period of observed declines in groundwater seeps (1997-2012).

	1978	1997	2012	% change (1978-1997)	% change (1978-2012)
			Area (m^2)		
Seeps	2,767,200	2,195,800	90,600	-21	-97
TPL	119,000	106,500	5,900	-10	-95
Lake A	15600	12800	0	-18	-100
GW2 lake	16600	18800	9,200	13	-44
			Perimeter (m)		
Seeps	110200	121000	9,300	-10	-91
TPL	2900	2400	300	-18	-88
Lake A	650	525	0	-19	-100
GW2 lake	740	746	500	-1	-33

Table 2. Changes in the areas and perimeters of groundwater seeps and lakes in western Skeiðarársandur (1978, 1997, 2012).

Borehole	August 2000	August 2001	August 2009	April 2011	August 2011	August 2012	Change (m)
Water table elevation (m)							
Groundwater seeps							
P13$_2$m	78.577	78.385	76.890			77.025	-1.552
P4$_2$m	85.993	85.828	<84.975	<84.975			->1.063
P3$_2$m	82.283	82.227	81.270	81.275		<80.510	->1.773
GW3					77.771	77.506	-0.265
Near margin							
P6$_2$m	91.486	91.178	<89.820	<89.820			->1.971
Moraine lakes							
WT A	81.1605	80.951	<80.235				->0.926
GW1					78.948	<78.575	->0.373
GW2					75.582	75.592	-0.100
P5					76.317	<75.71	->0.606
GW13					78.662	<78.147	>0.515
Meltwater channels							
GW7 (5 m from the channel)					69.680	69.610	-0.070
PT$_A$ (40 m from the channel)					69.923	68.777	-1.146
PT$_C$ (70 m away from channel)					70.139	68.847	-1.292

Table 3. The spatial variability of changes in groundwater levels for different hydrogeological settings (July 2000-August 2012). Boreholes in italics were installed in July 2011. Water table elevation with < show the elevation of the bottom of the borehole, meaning that groundwater fell below this level. Values of change with > means that groundwater levels have dropped below the borehole intake, hence only the minimum levels of decline are shown.

1978-2012				1997-2012		
	start of period	end of period	change	start of period	end of period	change
	Temperature (°C)			Temperature (°C)		
Annual	4.15	5.83	1.68	5.04	5.62	0.58
Winter (Dec.-Feb.)	-0.59	1.12	1.71	0.486	1.05	0.57
Spring (March-May)	2.76	4.59	1.83	4.02	4.77	0.75
Summer (June-August)	10.44	11.63	1.19	10.83	11.40	0.57
Autumn (Sept.-Nov.)	4.00	6.09	2.09	4.83	5.66	0.83
	Precipitation (mm)			Precipitation (mm)		
Annual	1490	1958	468	1667	2126	460
Winter	316	542	226	468	714	246
Spring	333	385	53	314	397	83
Summer	336	338	2	453	346	-106
Autumn	505	740	235	432	743	311
	PE (mm)			PE (mm)		
Annual	396	454	59	422	446	24
Winter	7	23	17	15	21	6
Spring	83	105	23	92	111	19
Summer	209	209	0	205	207	2
Autumn	97	117	20	110	107	-3
	Water budget (mm)			Water budget (mm)		
Annual	1197	1592	396	1221	1654	433
Winter	311	451	140	458	575	117
Spring	240	282	42	229	332	102
Summer	130	138	8	245	135	-110
Autumn	399	615	216	320	672	351

Table 4. Changes in the MA of annual and seasonal temperature, precipitation, Potential Evaporation (PE), and water budget in the study area from 1978-2012 and 1997-2012. The data was obtained from the IMO (2013).