Below is our responses to the reviewers in blue and then our changes to the document in red. Please see the marked up version of the document to see where the changes have been made. We thank the reviewers for such useful comments and think we have now made a much clearer manuscript

Reviewer 1

Thanks for the comments the time taken to go through the article:

General Comments

Thanks for the assessment of the high quality of the science, significance and presentation.

Specific comments

- Shouldn't subsection 2-1 "Study site" be included in the introduction section rather than the Methodology section? And 2 subsections are labelled "2-1": the "Study site"one and the "Aquifer characterisation" one.

Thanks for the comment. I find its generally 50/50 whether to put the explanation of the study site in the introduction or methods. Happy to put it into the Introduction if that makes it clearer

We have moved to the introduction and numbered it 1.1

- section 3-1: line 5: Could you explicit what define the groundwater catchment boundaries? Except for one indication on Figure S1 there is no discussion of this.

We have used the surface water catchment boundary as it extends from the defined glacial valley onto the sandur as an approximate indication of the groundwater catchment boundary. It is marked on Figure 1 – but I note that we have not put it in the legend – which we'll correct. Later in the paper – the SIs are much more powerful at defining the zone of interaction between the river and the groundwater – so the groundwater catchment is only used to help give an approximation of groundwater flow within the Sandur

Included a section in 1.1 to show how we estimated the groundwater catchment

- section 3-1: line 21: How do you know that the underlying bedrock has very low transmissivity? Thanks to tests in the 2 dedicated piezometers?

Yes – two piezometers drilled into the lavas – and the experience of local community in trying to get water supplies form the lava.

We have modified the sentence to make this clearer

- section 3-2: lines 26-31: Could you explicit how you calculate the mean estimated annual groundwater flow through the shallow part of the aquifer and the total depth of the aquifer?

The groundwater flow methodology is explained in the methods section (p 5 lines 5 – 10). We use Darcy's equation and parameterise with the head – which we have measured, the permeability which is measured in the top 15 m of the aquifer, the width of the aquifer from the approximate groundwater catchment taken from the surface water catchment using dGPS. The measurement of the total depth of the aquifer is discussed in page 5 (lines 13 – 19). There is some limited evidence that the

5   aquifer may become more consolidated at depth – so we quote a flow through the shallow depths (<40 m) as well as through the full depth. We can modify the methods section to explicitly mention the darcy equation

We have repeated in the results section that we have used Darcy's equation.

- Just to be sure I got this right: if there are tills under Virkisjökull glacier, they are not in continuity with the sandur downstream?

10   That right – there is negligible direct contact between the glacier and the sandur – primarily because of a bedrock high between the glacier and the sandur

No changes made

Technical sections

15   Thanks – we will modify as suggested

See track changes version

Reviewer 2

20   Review of Dochartaigh et al., "Groundwater / meltwater interaction in proglacial aquifers"

Although there is growing recognition of the importance of groundwater in glacierized watersheds, there have been relatively few studies that directly characterize groundwater in such systems. This study serves to help fill that gap by using groundwater wells and isotope data to quantify groundwater storage, groundwater discharge, and the contribution of glacial meltwater to groundwater.

25   *While on their own, these methods are relatively straightforward, applying them in glacierized, mountainous settings can be challenging, and thus their findings about meltwater-groundwater interactions is a valuable contribution to our understanding of glacierized watersheds. This manuscript is overall well-written.*

We thank the reviewers for their comments and appreciate the time to carefully examine the document

There are some aspects of the presentation that need clarification, however.

30   1. *Clarify "meltwater". Ultimately, I believe the authors use the term "meltwater" to refer to glacier melt (not snowmelt), and they assume the river water consists of glacier melt. This was confusing, however. First of all, there are some references to "snowmelt", so I was unsure at times whether "meltwater" should also include "snowmelt". Also, the authors at times discuss groundwater/meltwater interactions after presenting results about river water-groundwater interactions, and it was not obvious that the reader is supposed to assume the river water*

35   *and meltwater are treated as being the same (I pointed out specific lines below). I suggest the following. Be explicit*

about glacier meltwater (which could include snowmelt on the ice?) vs. local snowmelt. Also, be explicit about the assumption that the river water is glacier melt. However, I would caution against treating river water and meltwater as interchangeable, because the authors point out that the river water can consist of groundwater (during the wet season in middle elevations and all year in the lower elevations).

Thanks for this observation of ambiguity in the language. We mean glacier meltwater (ice + snow on glacier) when we discuss meltwater, rather than low level snow melt on the sandur aquifer which melts quickly (within a few days or weeks) of winter precipitation events. We take your suggestion of referring to glacier meltwater throughout and defining this as ice + snowmelt.

We have referred to glacial meltwater generally – unless referring to the river directly

2. *Clarify the isotope mixing model implementation. The methods section describes taking winter and summer water samples for isotope analysis, but no seasons are identified in the results. Isotope values can be very seasonally dependent – was this taken into account for the mixing model implementation? Also, what isotope value was used for the precip end-member? Was it the range of values indicated on Fig. 4 for precip at sea level? How well does isotopic value for precip at sea level apply to local precip on the mountain slope? Finally, and most importantly: why is the mixing model applied to estimate river contributions to groundwater in the middle and lower elevations (this is what Fig. 4c appears to show)? This contradicts elsewhere in the manuscript that describes flow to occur from groundwater to the river during the wet season in mid-elevations, and at all times in lower elevations.*

Seasonality

Although seasonal samples were taken for groundwater there was no significant seasonal variation See the means and standard deviations in Table S4. This is because of the long residence times of in the aquifer >> 1year which integrates the seasonal cycle.

Two sentences have been added to the results section to explain that the seasonal variation is low – and point to the table in the supplementary material which demonstrates this

End members

The end points of glacial melt and weighted annual mean of local rainfall were used in the analysis, and the data and explanation behind this discussed in an earlier paper (MacDonald et al. 2016: 10.1017/aog.2016.22). Here is a summary of this discussion. The glacier is an excellent location to carry out these studies as there is such a marked contrast between the stable isotope composition of the two end members -76.1 ± 2.6 ‰ δ2H, for glacier meltwater and -58.5 ± 6‰ δ2H, for rainfall. The composition for rainfall was calculated from the weighted annual mean from the nearest IAEA station and compared to a two other published results from the snouts of glaciers at Öræfajökull– which all suggest an annual weighted mean for rainfall of approx. -58‰ Árnason (1977), Sveinbjörnsdóttir and others (1995). MacDonald et al. 2016: 10.1017/aog.2016.22 also collected samples from local shallow springs unaffected by the river and got similar results of 58.5 ± 6‰ for shallow groundwater- which integrates the annual rainfall signal.

The glacier meltwater endpoint is determine from the weighted mean of river water stable isotopes as the river leaves the small proglacier area before reaching the Sandur. There is a small variability in the signature measured from both summer melt and winter melt. -76.1 ± 2.6‰ δ2H. Summer melts can be slightly more depleted (-77 – 78‰ δ2H) reflecting a higher component

of ice melt – For example a large survey of ice stable isotopes gave a mean of $-77.3 \pm 3.7‰$ $\delta 2H$ (MacDonald 2016). However this variability is negligible when comparing to the signature of local precipitation of $-58.5 \pm 6‰$.

No further explanations are given in the text. The reference to the earlier work of MacDonald 2016 should be sufficient for readers who are interested in more of the detail

5 *why is the mixing model applied to estimate river contributions to groundwater in the middle and lower elevations?*

The stable isotope signature of glacier meltwater contributions is determined from samples taken from the river as it leaves the glacier proglacial area – before entering the sandur with the complex surface water groundwater interactions. Because of the permeability of the aquifer, much of the flow in the aquifer is sub parallel to the river and the main contribution of glacier meltwater to the aquifer is likely to be just as the river enters the sandur. The stable isotope composition of the river is not

10 monitored downstream for this particular study. Therefore the assumptions of using the glacier meltwater stable isotope signature and local precipitation as endmembers for groundwater in the Sandur – however downstream – still holds true.

We have ensured that we refer to glacier meltwater as the end member here which should help avoid confusion of the potential evolution in river water SI composition as it travels down the Sandur. We have also added a sentence to the methods section to clarify that glacier meltwater is used and that evolution of river for isotopes downs stream in summer is negligible and

15 insignificant when compared to the difference between river and local precipitation isotopic composition .

3. *Clarify the interpretation of comparing groundwater discharge to stream discharge. Your wording seems to imply that the groundwater discharge is all from glacier meltwater (even though it also includes recharge from local precip), and that stream discharge is all glacier meltwater (even though lower sections include groundwater).*

20 *Perhaps this is not what is intended, but, for example, point 2 in the Conclusions makes it sound like the 0.19 m3/s groundwater discharge is meltwater. And the abstract mentions "meltwater river flow", implying that the river only consists of (glacier?) meltwater. I suggest rewording.*

Thanks for this. It is certainly not our intention to suggest that groundwater is discharge is from meltwater only – quite the opposite. We demonstrate the local precipitation is very important for groundwater recharge.

25 L21-22 in the abstract. Groundwater in the aquifer is actively recharged by local precipitation, both rainfall and snowmelt, and strongly influenced by individual precipitation events

I assume its line 18 - 20 in the abstract that causes confusion? Here we compare the groundwater flow to the river flow.

E.g. Line 20 Groundwater flow through the entire aquifer thickness represents 9.8% (3.6 – 21%) of annual meltwater.

We   suggest   we   alter   this   to   just   "river   flow"   and   delete   "represents".   So

30

Groundwater flow through the entire aquifer thickness, sourced both from local precipitation and glacier meltwater, is approximately 9.8% (3.6 – 21%) the magnitude of annual flow in the river

And then add in a sentence indicating that local precipitation remains the largest source of recharge to the aquifer, before the discussion of the extent of river water / groundwater interaction

These have been implemented in full with glacial meltwater being referred to and clarification throughout that that the groundwater flow is not all glacier meltwater.

4. *Clarify aquifer width. Explain the assumption of 1 km width – this is a strong assumption that controls your ultimate groundwater discharge estimate. Can you explain it – is it b/c it is the approximate width of the watershed, and you assume the groundwater-shed is similar? When you report your groundwater discharge result, you should be careful to note the uncertainty due to assuming this width.*

Yes the width is based on the hydrological boundary which was mapped on the ground with dGPS. The large uncertainties attributed to the flow at depth 9.8% (3.6 – 21%) reflects this uncertainty, although we believe to have reduced some of the uncertainty in the shallower groundwater system4.5% (2.6-5.8%)

Refer to Reviewer 1 – we have clarified the groundwater catchment. Uncertainties in groundwater flow are calculated from uncertainty in aquifer thickness and permeability which are likely to be much greater than potential uncertainties in aquifer width. Therefore we have left the indicative width as 1 km and included uncertainties in depth and permeability

Other minor comments:

- p. 1, Line 21-23: These two sentences are confusing. I think the first sentence sets up the reader toexpect that groundwater is mainly fed by local precip. The second line could be edited to betteremphasize that glacial meltwater is even more important than precip inputs at certain places. Part of the confusion for me in the second line is that it was not evident that the river water is all meltwater, and so I did not realize that "groundwater / meltwater exchange" is actually groundwater /river water exchange, where river water is meltwater. - would "groundwater-meltwater" be better than "groundwater/meltwater"?

As discussion above – yes we will clarify this and refer to glacier meltwater rather than meltwater. We will also change to groundwater / river exchanges here and throughout where we are discussing direct exchanges between the meltwater river and the groundwater

Thanks or pointing this out. We have reworded and made it much clearer that precipitation is more important for the overall aquifer.

- p.1, Line 25: be explicit that "meltwater" here is "glacier meltwater"

Thanks – will do

Done

- p. 2, Lines 8-20. I have a few other suggestions for your lit review. Also examining a direct link between meltwater and groundwater, Saberi et al. 2019 used a watershed model to show that groundwater discharge increases by 20% with meltwater contributions in a glacierized watershed in Ecuador. Harrington et al. 2018 found that 100% of winter streamflow originates from gw (rock glacier spring discharge) in the Canadian Rockies. Baraer et al. 2015 is a nice summary paper about groundwater contributions to discharge in multiple glacierized watersheds in Peru. Also, you cite Hood et al. 2006, but you did not mention catchments in the Canadian Rockies.

Thanks for the references – we will read and consider them

Included Saberi at al 2019 in our discussion which adds weight to our findings that groundwater flow can lead to an under estimation of glacier melt.

5   We've added Harrington to our examples of rock glacier groundwater flow – adding a Canadian example to that o the Alpine one given

Barear et al has been added as a good example of where groundwater contributes much of winter discharge

Thanks also for the detailed comments below which will help considerably tightening the manuscript

10   Answers to two more significant ones

- p. 4, Line 12: comment on use of Jacob time-drawdown method for unconfined aquifer? (If not in main text, then in supplementary info?)

Yes will put in the supplementary material. And generally applies well if the drawdown is low compared to the saturated thickness of the aquifer

15   In the end we have clarified in the main text that we have modified for unconfined conditions and also used Theis recovery and added added a reference demonstrating that these methods are appropriate for unconfined conditions

-p. 7, Line 13: M1 is also very close to river. Any idea why it did not show up in 2nd pattern?

Yes – this puzzled us too. We believe that the reason is probably because there is a small locally sourced channel close to the

20   piezometer – giving the local precipitation a stronger control on groundwater levels

We have also implemented in full the other editorial suggestions – see marked up document

Groundwater ~~/~~ - glacier meltwater interaction in proglacial aquifers

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Abstract.

Groundwater plays a significant role in glacial hydrology and can buffer changes to the timing and magnitude of ~~meltwater~~ flows in meltwater rivers. However, proglacial aquifer characteristics or groundwater dynamics in glacial catchments are rarely studied directly. We provide direct evidence of proglacial groundwater storage, and quantify multi-year groundwater-meltwater dynamics, through detailed aquifer characterisation and intensive ~~and~~ high resolution monitoring of the proglacial system of a rapidly retreating glacier, Virkisjökull, in SE Iceland. Proglacial unconsolidated glaciofluvial sediments comprise a highly permeable aquifer (25 – 40 m d^{-1}) in which groundwater flow in the shallowest 20—40 m of the aquifer is equivalent to 4.5% (2.6 - 5.8%) of mean ~~annual meltwater~~ river flow, and 9.7% (5.8 - 12.3%) of winter flow. Estimated annual ~~G~~groundwater flow through the entire aquifer thickness~~, represents~~ is ~~9.8~~10% (4 – 22%)~~3.6 – 21%~~ ~~of~~ the magnitude of annual ~~meltwater~~ river flow. Groundwater in the aquifer is actively recharged by glacier meltwater and local precipitation~~.~~, both rainfall and snowmelt, and strongly influenced by individual precipitation events. Local precipitation represents the highest proportion of recharge across the aquifer. However, ~~S~~significant glacial meltwater influence on groundwater within the aquifer occurs in a 50–500 m river zone within which there are complex groundwater / ~~meltwater~~ river exchanges. Stable isotopes, groundwater dynamics and temperature data demonstrate active recharge from river losses, especially in the summer melt season, with more than 25% and often >50% of groundwater in the near-river~~is part of the~~ aquifer zone sourced from glacier meltwater. ~~Such p~~Proglacial aquifers such as these are common globally, and future changes in glacier coverage and precipitation are likely to increase the significance of groundwater storage within them. The scale of proglacial groundwater flow and storage has important implications for measuring meltwater flux, for predicting future river flows, and for providing strategic water supplies in de-glaciating catchments.

1 Introduction

A major challenge in modern hydrology is predicting changes in freshwater flows and storage resulting from glacier retreat in response to climate change (Jiménez Cisneros et al., 2014). Most glaciers worldwide have been in retreat since the mid-19th century, with the loss of global glacier ice accelerating during the 21st century (Zemp et al., 2015). This change has the potential to affect over one billion people who live in catchments where glacier melt contributes to river flow (Kundzewicz et al., 2008). Glacial retreat is expected to increase meltwater river flows until the mid-late 21st century (Jiménez Cisneros et al., 2014; Lutz et al., 2014). Longer term, as glacier ice loss continues, meltwater flows will decrease (Jiménez Cisneros et al., 2014). This lessening of the role of glaciers in regulating flows will change the nature of glacier-fed rivers and the importance of other water sources in glacier catchments: rainfall, snowmelt and groundwater. Predicted impacts include changes to: the frequency and magnitude of flooding (Jiménez Cisneros et al., 2014); hydroelectric power production (Laghari, 2013); drinking water and irrigation (Kundzewicz et al., 2008); ecosystem functioning of catchments (Brown et al., 2007); and groundwater recharge (Taylor et al., 2013).

The role of groundwater storage in the hydrology of deglaciating catchments is recognized, but to date there has been little direct hydrogeological investigation of groundwater-meltwater interactions (Levy et al., 2015, Vincent et al., 2018) with calls for more (Heckmann et al. 2016, Vincent et al, 2018). Indirect studies, inferred from river flow, indicate groundwater in Himalayan glacial catchments may be a significant source of delayed discharge to rivers (Andermann et al., 2012). Modelling of Himalayan catchments suggests that increased glacial melt this century will increase groundwater recharge from glacier runoff and the groundwater baseflow component in river flow (Immerzeel et al., 2013). Glacier Mmeltwater rivers in Alaska can potentially lose half their annual flow to groundwater (Liljedahl et al., 2017). Groundwater can comprise 15–75% of winter river flows in glacial catchments in the European Alps, Canadian Rockies, Peruvian Andes and Iceland (Malard et al., 1999; Hood et al., 2006; Bury et al., 2011; Hood et al., 2006; Malard et al., 1999; McKenzie et al., 2014; Baraer et al. 2015; MacDonald et al., 2016). Direct experimental studies of groundwater in glacial environments are rare (Vincent et al. 2018): e.g. subglacial groundwater behaviour (Sigurðsson, 1990; Boulton et al., 2001; Boulton et al., 2007a, 2007b); groundwater flow in relict rock glaciers (Winkler et al., 2016; Harrington et al., 2018); and the behaviour of shallow (<3 m) groundwater in glacial outwash plains in Iceland (Robinson et al., 2008; Robinson, et al., 2009a; Robinson, et al., 2009b). The latter Icelandic studies demonstrated meltwater recharge to proglacial aquifers and linked retreating glaciers with declining groundwater levels (Levy et al., 2015).

In this study, we directly investigate the 3D aquifer properties of a proglacial floodplain (referred to here as *sandur*) of the Virkisjökull glacier in SE Iceland, to 15 m depth, using geophysics, drilling and hydraulic conductivity testing; and provide continuous time series data for groundwater, river stage/flow and precipitation over three years, with campaign sampling for stable isotopes. We explore the relationships between groundwater, glacier meltwater flows and precipitation, revealing, seasonal and spatial hydrological patterns.

Iceland provides an ideal observatory for studying groundwater in deglaciating catchments. Ice melt from glaciers, which cover ~11% of Iceland, provides an estimated third of total river runoff (Björnson & Pálsson, 2008), but glacier retreat across Iceland (Sigurðsson et al, 2007) is forecast to produce significant changes in glacial catchment hydrology (Aðalgeirsdóttir et al., 2011). The British Geological Survey (BGS), in collaboration with Veðurstofa Íslands (the Icelandic Meteorological Office), have studied the Virkisjökull catchment since 2009, monitoring rapid glacier retreat (Bradwell et al., 2013), retreat mechanisms (Phillips et al., 2013; Phillips et al., 2014), and researching glacial meltwater hydrology (MacDonald et al., 2016; Flett et al., 2017; Mackay et al., 2018).

1.1 Study site

Virkisjökull is an outlet glacier of the Vatnajökull ice cap in SE Iceland (Figure 1), within the Virkisá river basin, which has a catchment area of ~32.5 km^2 to the confluence with the Svinafellsá river (MacDonald et al., 2016). Virkisjökull drains ice steeply southwestwards from an elevation of >1800 m asl on the ice cap summit to <150 m asl at its terminus, with an average gradient of approximately 0.25. It has a high mass balance gradient, with net annual accumulation of more than 7 m w.e. a^{-1} (metres of water equivalent per annum) at the ice cap summit (Guðmundsson, 2000) and net annual ice melt of more than 8 m w.e. a^{-1} in the main ablation zone (Flett, 2016). The equilibrium line altitude on Virkisjökull is approximately 1150 m asl (MacDonald et al., 2016). The glacier has been retreating since 1990 (Hannesdóttir et al., 2015), with a marked acceleration in retreat rates since 2005 (Bradwell et al., 2013), during which time the glacier terminus has retreated by ~1 km and there has been extensive surface lowering.

The Virkisá river emerges from a small, shallow proglacial lake that has formed during the recent rapid deglaciation, and flows initially for 1 km over bedrock, flanked by moraines, and then for 4 km across the Virkisjökull sandur to the Svinafellsá river (Figure 1). The river drains glacial meltwater and virtually all precipitation falling on Virkisjökull glacier, adjacent hillslopes and proglacial moraines. It occupies a single channel across the upper sandur, separating into a number of distinct channels across the lower sandur (Figure 1). The mean summer river flow over three years of continuous monitoring (2011–2014) ranged from 5.3–7.9 m^3 s^{-1}; and significant river flow occurred in winter (mean 1.6–2.4 m^3 s^{-1}). Isotopic studies (MacDonald et al., 2016), validated by numerical modelling (Mackay et al., 2018), demonstrate that summer river flows are governed by glacier ice melt, and that winter flows are a combination of glacier meltwater, local precipitation and groundwater flow. The Virkisjökull sandur falls from 100 to 50 m asl with a surface gradient of 0.017 (Figure 1). Over much of the sandur where river channels are actively migrating, there is little vegetation cover and no soil development. In more stable areas thin soils and more developed vegetation cover occur (Figure 1). The groundwater catchment on the sandur associated with outflow from Virkisjökull has been estimated by using the surface water catchment identified from Lidar and dGPS (Figure 1).

The proglacial area has a maritime climate with cool summers (mean summer air temperature 8–12 °C) and mild winters (1 °C). Air temperature in the Virkisá basin is controlled mainly by altitude, with an average annual lapse rate of -5 °C km^{-1} (Flett, 2016; Mackay et al., 2018). Mean annual precipitation southwest of the Vatnajökull ice cap, including the Virkisjökull sandur, is ~1800 mm; precipitation on the eastern side of the ice cap averages 3000 mm a^{-1}, and can exceed 7000 mm a^{-1} on

the ice cap summit (Guðmundsson, 2000). The proglacial area receives ~150 precipitation days per year, estimated from interpretation of three years of daily photographs (MacDonald et al., 2016), which also show that snow cover, even in winter, rarely lasts for more than a week before melting. Potential evapotranspiration over the sandur was estimated at ~450 mm a^{-1} by Einarsson (1972) and actual evapotranspiration at 100–414 mm a^{-1} by Jónsdóttir (2008).

5

2 Methodology

2.1 Aquifer characterisation

Eight boreholes were drilled into the sandur to 9–15 m depth during July and August 2012, in three transects approximately
10   perpendicular to the river along a 3 km longitudinal reach in the upper, middle and lower study catchment (Figure 1a). Sediment samples collected during drilling were lithologically logged. The boreholes were installed as piezometers in September 2012, with 88 mm diameter uPVC plain casing to at least 5–12 m depth and a 3–6 m length of 0.5 mm slotted well screen below this (Table S1). A further two boreholes were drilled into volcanic bedrock, to 5.5 and 13.75 m depth, between the glacier terminus and the upper edge of the sandur (Figure 1a). Three methods were used to establish the physical aquifer properties of the
15   sandur: (1) infiltration tests to 0.15 m depth at 20 locations, using a Guelph permeameter, and saturated hydraulic conductivity calculated by the Laplace method (Reynolds et al., 1983) (Table S2); (2) particle size analysis on 42 sandur sediment samples to 0.5 m depth, at 22 locations, and hydraulic conductivity estimated using a modified Hazen formula suitable for heterogeneous glacial deposits (MacDonald et al., 2012; Williams et al. 2019) (Table S3); and (3) constant rate pumping tests of between 3.5 and 6 hours in each sandur piezometer, at rates of 0.5–1.8 l s^{-1}, and transmissivity estimated by the Jacob time-
20   drawdown and Theis Recovery methods corrected for unconfined conditions (Kruseman and de Ridder, 1994)(Table S1).
To measure aquifer thickness and depth to bedrock, two Tromino® passive seismic surveys were undertaken transversely across the Virkisjökull sandur, and a third longitudinally down the Svinafellsandur aquifer 4.5 km to the west, using a single broad-band three-component seismometer with one vertical and two horizontal components. Measurements were recorded for 15 minutes at 50–100 m lateral intervals and data processed to derive depth to bedrock assuming typical shear wave velocities
25   of 400–600 m s^{-1} for Icelandic glacial sands and gravels (Bessason and Kaynia, 2002; Castellaro et al., 2005). These data were interpreted with a previous seismic reflection survey in the area to infer sediment thickness and potential layering (Guðmundsson, 2002).

2.2 Groundwater, surface hydrology and precipitation monitoring and sampling

30   Monitoring of groundwater levels and temperature in sandur piezometers, at 15 minutes intervals, was undertaken from August 2012–May 2015 (34 months) using In-Situ Inc. Rugged Troll 100 non-vented pressure transducers at 7–8.4 m depth. Two In-

Situ Rugged Barometer Trolls measured air pressure and temperature. River stage and discharge data are available for August 2012-May 2015 from an automatic stream gauge at Virkisá bridge (Figure 1) with two water-level sensors, checked using daily photographs and continuous flow measurements from a radar mounted beneath a bridge (MacDonald et al. 2016). From April 2013–March 2015 river stage and temperature were additionally monitored continuously every 15 minutes adjacent to

5   piezometer U1 by an In-Situ Inc. Rugged Troll 100 pressure transducer (Figure 1). Rainfall data and temperature for the proglacial area were measured at the closest of the three Automatic Weather Stations installed by BGS in the catchment (AWS1; 156 m asl). These weather stations were not equipped to measure snowfall, but daily photographs enabled periods of snowfall to be estimated. Long term weather data from the Fagurhólsmýri weather station operated by the Icelandic Meteorological Office (IMO) approximately 12 km south of the study site, and national scale gridded products (Nawri et al.

10   2017), were used to check the plausibility of weather data measured on site.

Hierarchical cluster analysis of groundwater level data was carried out on the entire dataset. Data were treated using the Standardized Groundwater level Index (Bloomfield and Marchant, 2013), which indicated the optimal number of clusters is four. Groundwater flow was estimated assuming a mean aquifer width of 1 km, aquifer thickness at the river gauge from the passive seismic interpretation, average measured groundwater level gradient of 0.016 and hydraulic conductivity from median

15   of all measured values (n = 64). Uncertainty was calculated from the interquartile range of measured K and uncertainty in aquifer thickness interpretation. The hydraulic conductivity of the deeper, unmeasured, sandur aquifer layer were estimated using the formula of MacDonald et al. (2012) taking into account a change in sediment state from very loose, to loose and firm which is likely to over-estimate the reduction in pore space due to loading (Schmidt and McDonald, 1979). The total volume of groundwater stored in the aquifer was estimated using a conservative estimate of average aquifer porosity of 15% (Parrieux

20   & Nicoud, 1990).

2.3 Groundwater isotopic sampling and analysis

Physico-chemical analysis and modelling were based on samples of groundwater from piezometers and springs collected during three summer campaigns in September 2012, 2013 and 2014 and three winter (pre-melt) campaigns in January 2013, April 2013 and May 2014. Groundwater sampling from piezometers was carried out after piezometers were purginged by low-

25   flow pumping until stable readings were obtained for field-measured parameters. Field measurements of specific electrical conductance (SEC), temperature and bicarbonate alkalinity by titration pH (Table S4), and of dissolved oxygen and redox potential (Eh), were made at the time of sampling. Samples for stable isotopes $\delta^{18}O$ and δ^2H were collected unfiltered in glass or Nalgene™ polyethelyne bottles and analyzed at BGS laboratories by isotope ratio measurement on a VG-Micromass Optima mass spectrometer. Data are quoted in permil (‰) with respect to Vienna Standard Mean Ocean Water (VSMOW)

30   (IAEA/WMO, 2016); measurement precision was ±0.1‰ for $\delta^{18}O$ and ±1.0‰ for δ^2H.   Local precipitation stable isotope composition and a local meteoric line were estimated from International Atomic Energy Agency station data for Reykjavik (IAEA/WMO, 2016), supported by estimates for southeast Iceland (Arnason, 1977) and for south Iceland (Sveinbjörnsdóttir et al., 1995), as described in MacDonald et al. (2016). The isotopic composition of meltwater in the Virkisá river as it enters

the sandur was established by ~~nine summer (melt) or winter (pre-melt)~~ sampling campaigns from September 2011–December 2014 (MacDonald et. al., 2016).

The high topographic gradient of the catchment, with large climatic differences between the upland glacial accumulation area (>1800 m asl) and the lowland temperate proglacial area (<150 m asl), results in two easily distinguished isotopic compositions: ~~for~~ (1) glacier meltwater~~,~~; and (2)~~for~~ precipitation across the proglacial area. A binary mixing model for δ^2H was applied to investigate the relative contributions of local precipitation and of river water (which is dominated by ~~glacial~~ glacier melt) to sandur groundwater, based on a two-component mixing equation. The end members applied for δ^2H composition were -76.1‰ for river water (Table S4) and -58.5‰ for average annual local precipitation (MacDonald et al., 2016). The fraction of local precipitation in sandur groundwater (FGW) was calculated using the formula $FGW = (\delta^2H_R - \delta^2H_P)$ / $(\delta^2H_{GW} - \delta^2H_{HR})$, where δ^2H_R is the composition of river water; δ^2H_P is the composition of local precipitation; and δ^2H_{GW} is the composition of sampled groundwater. Since most river recharge to the aquifer occurs during the summer months when river flow is high and dominated by glacier melt, the impact of the small evolution in stable isotope composition down river observed in winter due to groundwater baseflow (MacDonald et. al. 2016) is insignificant, ~~—~~particularly when compared to the large difference between river flow and local precipitation isotopic composition.

3 Results

3.1 Sandur structure and aquifer properties

The groundwater study catchment covers 6 km^2 and encompasses the sandur, adjacent hillslopes and moraines, and river outflow from the proglacial lake (Figure 1). Geophysical evidence from the passive seismic and previous seismic reflection survey indicates that (Figure 2, Figure S1) depth to bedrock increases from approximately 60–100 m in the upper sandur to 100–150 m in the lower sandur. The shallow aquifer material comprises loosely consolidated, moderately to poorly sorted, dominantly medium- to coarse-grained glaciofluvial sand, gravel and cobbles (Figure 2). All the sediment is of volcanic origin and has been transported and deposited by the Virkisá river. The deeper deposits are not exposed, but nearby seismic interpretation confirms that the material is generally uniform to >50 m, reflecting the similar sediment derivation and deposition mechanisms (Guðmundsson, 2002). Although not directly observed in the seismic data there is a possibility that at greater depth (>-50 m) there exists more consolidated Pleistocene aged sediments which have been ~~compaction~~ compacted by ice loading during earlier glaciations (Guðmundsson, 2002). Observations of bedrock from nearby exposures and two boreholes drilled in bedrock reveal relatively massive and poorly fractured volcanic rock.

The sandur aquifer is highly permeable to at least 15 m depth, with a median hydraulic conductivity of 35 m d^{-1} (IQ range 25–40 m d^{-1}) (Figure 2a, Tables S2, S3). Transmissivity of the upper 15 m is 100–2500 m^2 d^{-1} with median value of 600 m^2 d^{-1} consistent with hydraulic conductivity measurements (Table ~~S4~~S1). The permeability of the deeper sandur aquifer was not directly measured. However given the grain size distribution is the same as the shallow aquifer, and assuming the worst case of compaction due to burial and ice loading (Shmidt and McDonald, 1979), median hydraulic conductivity may have reduced

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to 15 m d^{-1} or at a worst case 6 m d^{-1} (MacDonald et al., 2012).   By contrast, the underlying bedrock has ~~very~~ low transmissivity, less than the lower limit from the experimental methods employed ~~below that which could be measured using a constant rate test~~ (transmissivity < 0.25 m^2 d^{-1}). The sandur aquifer is unconfined. Depth to groundwater ranges from 0 to 4.4 m below ground level and maximum measured seasonal groundwater level fluctuations are 1.0–3.6 m. From 1 km down-sandur from its upper edge, there is extensive groundwater discharge at the ground surface via perennial and ephemeral springs (Figure 2). A conservative estimate of the volume of groundwater stored in the full thickness of the aquifer is 51 ±15 million m^3, approximately 1 – 2 % of estimated ice volume in the glacier (Mackay et al. 2018).

3.2 Groundwater dynamics

Groundwater level elevation falls from upper to lower sandur, with a gradient of 0.018 across the upper and 0.013 across the lower sandur (Figure 2). In the upper sandur, closest to the glacier, groundwater levels adjacent to the glacial meltwater channel are on average 1 m below river stage for most or all of the year (Figure 3a, b), leading to a strong piezometric gradient away from the river to groundwater. Across the middle sandur, groundwater levels close to the river vary from 0.5 m below to 0.5 m above adjacent river stage, leading to complex ~~meltwater~~river/groundwater interactions. Here, piezometric gradients are generally from river to aquifer in the summer melt season, when river flows are highest; and from aquifer to river in winter, driven by high winter precipitation and associated recharge. From 2 km down-sandur, groundwater levels are above adjacent river stage for much of the year, creating a piezometric gradient that drives visible groundwater discharge through seeps and springs to the river (Figure 2d) and ephemeral and perennial springs (Figure 2e).

Hierarchical cluster analysis of groundwater level data indicates two patterns of groundwater level fluctuation (Figure 3c): one driven primarily by local precipitation; and the second driven partly by precipitation but also strongly influenced by river stage, especially in summer (Figure 3d). Groundwater levels showing the first pattern (in piezometers U2, M1, M2, M3 and L3) fluctuate dominantly in response to individual precipitation events and longer term precipitation patterns. The magnitude of groundwater level fluctuations typically increases with distance from the river. Rainfall is higher than its long term average throughout most of the winter and lower in summer, and this is generally reflected in the groundwater level fluctuations (Figure 3d). Groundwater levels showing the second pattern (in piezometers U1, L1 and L2) fluctuate in response to river stage as well as local precipitation, at seasonal (Figure 3d) and also at event timescales (Figure 3a). River stage is typically higher than its long term average during peak summer melt, and groundwater levels in this group also remain close to or higher than their long term average throughout the summer (Figure 3d). The strongest response to river stage at a seasonal timescale is in piezometer L1, where groundwater levels during the 2013 summer melt season remained consistently higher than throughout the three winters from 2012–2014 (Figure 3d). The strongest response at an event timescale is in piezometer U1, where groundwater levels show consistent diurnal fluctuations during the summer melt season that coincide with diurnal melt-controlled fluctuations in river stage (Figure 3a).

Piezometers U1 and U2 (20 m and 90 m from the river, respectively) illustrate the relative impacts of summer glacier meltwater flows and large winter precipitation events on groundwater level–river stage gradients (Figure 3). In summer, low precipitation

and large glacier meltwater flows cause groundwater levels in U1 to rise above U2, creating a piezometric gradient away from the river (Figure 3a). During individual winter rain storms, groundwater levels in U2 rise higher than in U1, creating a piezometric gradient towards the river (Figure 3b) and driving baseflow to the river further downstream in the middle sandur.

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Mean estimated annual groundwater flow through the shallow part of the aquifer calculated using Darcy's equation (20—40 m thick) is 0.19 m^3 s^{-1} (IQ range 0.093–0.30 m^3 s^{-1}), equivalent to 4.5% (2.7—5.8%) of mean annual river flow and 9.7% (5.8 —12%) of mean winter river flow. The relatively small seasonal variation in groundwater levels means there is no significant seasonal variation in estimated groundwater flow across the aquifer. Overall groundwater flow through the total depth of the

10 sandur aquifer is estimated as 0.42 m^3 s^{-1} (0.12—1.1 m^3 s^{-1}) equivalent to 9.8% (3.6—22%) of mean annual river flow and 21% (7.7—46%) of mean winter river flow.

3.3   Stable isotopes and temperature

Stable isotope composition (δ^2H and δ^{18}O) in groundwater from piezometers and springs was compared to that of ~~river water~~glacier meltwater and local rainfall (Figure 4, Table S4). Previous studies have demonstrated that glacial meltwater and

15 local rainfall on the proglacial area are easily distinguished using δ^2H and δ^{18}O due to the high elevation of the accumulation area (MacDonald et al. 2016). Across individual piezometers, springs and the river, variability between sampling campaigns was much less than variability between sites (Table S4). In particular-, the river samples (taken as the river enters the sandur and therefore largely glacier meltwater) exhibited little seasonal variability -76.1 ± 2.6 δ^2H (n = 19). Therefore, mean values ~~were taken~~ from across the campaigns were used for analysis. Groundwater stable isotope compositions vary considerably

20 across the sandur, spanning the range of compositions expected from glacier meltwater and local precipitation (Figure 4). Piezometers (U1, L1, L2) identified from their hydrographs as most influenced by the river have isotopic compositions similar to river water, while piezometers whose hydrographs are influenced more by precipitation have a much wider range of isotopic~~s~~ composition, with U2 and M3 similar to local rainfall, and M2, M1 and L3 a mixture between local rainfall and river water. The springs showed a wide variety of compositions.

25 A binary mixing model developed for δ^2H indicates the relative proportion of precipitation and glacier meltwater in groundwater (Figure 4b, 4c) and demonstrates a clear relationship with distance from the meltwater river. Within a zone extending up to 50 m from the river in the upper sandur, 130 m in the central sandur and 500 m in the lower sandur, groundwater in piezometers generally comprises more than 50% ~~river~~ glacier meltwate~~water~~r. Shallower groundwater from springs within this river zone is more influenced by local precipitation, but still comprises more than 25% glacier meltwater. Beyond this

30 zone, groundwater from both piezometers and springs consistently comprises less than 25% river water (Figure 4c). Since the binary mixing model uses glacier meltwater as its endpoint it is likely to be conservative in the proportion of river-groundwater interactions as it does not account for evolution of the river water stable isotope composition downstream due to groundwater baseflow. Selected hydrochemical tracers and water temperature also help distinguish these two zones (Table S4). Specific

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electrical conductance (SEC) and bicarbonate (HCO_3) are significantly lower in those piezometers strongly influenced by the river than those where precipitation influence is dominant (Figure S1). River water temperature is relatively constant year-round at an average of 1.7°C, and mean annual groundwater temperature is lowest in piezometers close to the river, and highest in those furthest from the river (Table S4).

5

4   Discussion

This study in Iceland shows that proglacial floodplains can form thick, highly permeable aquifers. By directly quantifying aquifer parameters and groundwater–glacier meltwater interaction we have provided evidence of the significance of groundwater in proglacial hydrology. This has important implications for measuring glacial meltwater flux, for predicting
10 future river flows and ecological impacts, and for water supplies in de-glaciating catchments. Similar thick proglacial glaciofluvial aquifers with high permeability and storage occur in other active glacial environments: e.g. elsewhere in Iceland (Robinson et al., 2008); the European Alps (Parrieux & Nicoud, 1990); and the Peruvian Andes (McKenzie et al., 2014), and with rapid deglaciation occurring globally proglacial aquifers are developing in many other locations increasing the importance of characterising groundwater (Vincent et al. 2018).

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4.1 Groundwater flow

Our study shows that significant watermeltwater can flow through a glacierized catchment as groundwater, despite groundwater representing only a small proportion of the volume of water stored in glacial ice in the catchment. Reliable measurements of glacier meltwater are important for calibrating cryospheric-hydrological models (Bliss et al., 2014; Lutz et
20 al., 2014; Mackay et al., 2018).   The estimated volume of groundwater flow through the shallowest 20—40 m of the Virkisjökull proglacial aquifer is significant, 0.19 m^3 s^{-1}, equivalent to approximately 4.5% of mean annual river flow or 9.7% of mean winter river flow, with estimates 9.8% and 21% respectively if flow through the full thickness of the aquifer is considered. Other studies in Iceland have proposed that a similarly large proportion of meltwater (0.5—1 m w.e. a^{-1}) can flow through the groundwater system, either from sub-glacial or proglacial recharge (Sigurdsson, 1990; Hemmings et al., 2016);
25 meltwater river losses to groundwater of up to 50% have also been reported (Liljedahl et al., 2017). Measuring river flow in catchments with active glaciers is notoriously difficult, given the harsh conditions, the actively changing river beds, and the wide ranges in flows and sediment load. Therefore mMeasurements are therefore subject to high uncertainty. Here, we demonstrate that groundwater adds another source of uncertainty. Measurements of river flows that rely solely on river stage in the proglacial area are likely to underestimate total annual meltwater flows, with much higher relative errors at low flows.
30 Similar potential underestimation in glacier melt estimations due to groundwater flow have recently been reported in South America (Saberi et al., 2019).

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4.2 Meltwater / groundwater interaction

Groundwater-glacier meltwater interactions are controlled by relative differences in water levels between the river and the proglacial aquifer, and vary both spatially, down the catchment, and seasonally. There is year-round active recharge of river
5   water to the aquifer in the upper catchment, complex interaction in the middle of the sandur, and extensive groundwater baseflow to the river and springs across the lower catchment. Distinct patterns of groundwater ~~/~~ - glacier meltwater dynamics are observed in groundwater level fluctuations and in groundwater stable isotopic composition, temperature and chemistry. In a zone extending up to 50–500 m from the ~~meltwater~~ river, the influence of the river on groundwater overshadows that of local precipitation. Here, recharge of glacier meltwater to the aquifer from river losses has a significant impact on the physical,
10 chemical and stable isotopic characteristics of groundwater in the proglacial aquifer. The aquifer provides additional water storage, and groundwater discharges back to the river further downstream through a large number of springs and seeps (Figures 1 and 4). This is consistent with other studies in ~~glacierized~~ glacier dominated catchments, which inferred groundwater baseflow to rivers of 15–75% (Malard et al., 1999; Hood et al., 2006; Bury et al., 2011; ~~Hood et al., 2006~~; ~~Malard et al., 1999;~~ McKenzie et al., 2014; MacDonald et al., 2016; ~~McKenzie et al., 2014~~).

15 However, away from the river the aquifer is recharged dominantly from local precipitation. Active precipitation recharge to the aquifer is evident from groundwater stable isotopic composition and groundwater level response to precipitation, and reflects high annual precipitation (rainfall and snow), high aquifer permeability, and low evapotranspiration linked to limited soil development and vegetation cover. Recharge is likely to occur not only from direct precipitation on the sandur surface, but from ephemeral streams draining from hillslopes and groundwater seepage from surrounding moraines. Groundwater
20 discharge via springs and baseflow in the lower catchment supports surface water flows and local ecosystems and comprises groundwater derived mainly from local precipitation Figure 4).

Looking forward, as the glacier continues to melt, the proglacial aquifer will continue to have a buffering effect on river flow. High river flows will recharge the aquifer, whether caused by glacier icemelt, snowmelt or winter storms, as occurs in relic glacial outwash aquifers now in now-temperate areas (e.g. MacDonald et al., 2014), and will sustain springs, baseflow and
25 surface ecosystems further down the catchment. Local precipitation falling on the aquifer is likely to continue to be a major source of aquifer recharge and contribution to river baseflow in addition to the groundwater discharging from other glacial deposits emerging within the landscape (MacDonald et al., 2016).   In upland areas in northern Europe where glaciofluvial deposits from past glaciations are present, detailed studies have demonstrated that groundwater often comprises more than 50% of flow to river headwaters (Soulsby et al. 2005; Blumstock et al., 2015; Scheliga et al. 2017). Therefore, as glaciers
30 continue to melt, groundwater baseflow is likely to become an increasingly important proportion of river flow in deglaciating catchments.

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4.3 Proglacial aquifers as strategic water resources

This study has demonstrated that the Virkisjökull sandur is a highly productive aquifer with regular recharge. Similar thick proglacial glaciofluvial aquifers occur throughout the world, and are increasing in extent as glaciers recede, and are likely to also have the potential to sustain high quality reliable water supplies. In formerly glaciated areas, these aquifers are often targeted for public water supply (e.g. Ó Dochartaigh et al. 2015) because of their ability to sustain high yielding boreholes, their connectivity with rivers that provides additional recharge, and the generally high chemical quality of the groundwater compared to surface water. If projected glacier losses and increased precipitation in glacierized catchments are realized (Jiménez Cisneros et al., 2014), proglacial aquifers, recharged by local precipitation, represent a potentially significant store of high quality water in regions around the world that currently rely on glacier melt for water supply.

Conclusions

Three years of investigations of groundwater and ~~glacier~~ meltwater at Virkisjökull, SE Iceland, have enabled the aquifer parameters of the proglacial floodplain to be reliably characterised, and seasonal groundwater-~~glacier~~ meltwater dynamics to be quantified. The key findings from the research are:

1. Direct measurements of aquifer characteristics show consistently high permeability (35 m d^{-1} n=64, IQR 25 – 40 m d^{-1}), and volume of groundwater storage (50 ±15 million m^3). The proglacial floodplain therefore forms a highly productive aquifer.

2. Significant ~~meltwater~~ water flows as groundwater through the shallowest 20—40 m of the proglacial floodplain ~~as groundwater~~ (0.19 m^3 s^{-1}; IQR range 0.09—0.29 30 m^3 s^{-1}), equivalent to 4.5% of mean annual meltwater flow and 9.7% of mean winter flow. If the full thickness of the aquifer is considered then groundwater flows of 0.42 m^3 s^{-1} (IQ range 0.12—1.1 m^3 s^{-1}) equivalent to 9.8% (3.6—22%) of mean annual river flow and 21% (7.7—46%) of mean winter river flow are possible.

3. Groundwater is recharged both from the glacial meltwater river ~~water~~ and local precipitation falling on the aquifer, or draining from nearby hillslopes. Glacier ~~M~~meltwater is particularly important in a zone from 50–500 m from the river where glacier meltwater comprises > 25% and often ~~can form~~ >50% of ~~the~~ recharge.

4. There are complex but consistent river/groundwater interactions: in the upper sandur, closest to the glacier, the river loses to groundwater much of the year; in the middle sandur the river loses to the groundwater in the summer melt and gains from groundwater in the winter low flows; in the lower sandur groundwater provides baseflow to the river through springs and baseflow seeps.

Proglacial aquifers are common worldwide and increasing in extent with deglaciation. These findings, therefore, have wider implications for measuring glacier meltwater flux, for predicting future river flows, and for water supplies in de-glaciating catchments.

Effectively understanding and characterizing groundwater flows and storage in catchments with glaciers, and incorporating this in hydrological models, will strengthen our ability to predict and manage the hydrological and environmental impacts of accelerating glacier retreat.

Data availability

Water chemistry, groundwater level, river stage and precipitation data are available freely from the National Geoscience Data Centre and from the authors on request.

Author contribution

BEOD managed the field sampling campaign and installation of piezometers and wrote early drafts of the manuscript. AMM oversaw the research and analysis and wrote the final draft of the paper. PW, MR, BEOD, JE, AB, AM and LJ undertook fieldwork and analysis of individual components of the research and WGD provide interpretation of the stable isotopes. All commented on final draft of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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(a)

UPPER SANDUR

LOWER SANDUR

U2 U1

M3

M2
M1

L3

L2

L1

Legend:
- Piezometer- sandur
- Piezometer- bedrock
- River flow gauging
- River stage monitoring
- Glacier extent (approx. 2015)
- Proglacial lake (approx. 2015)
- Automated Weather Station 1
- River channel (active 2015)
- River channel (inactive 2015)
- Catchment boundary
- Flood bund
- Road

0   0.5   1
km
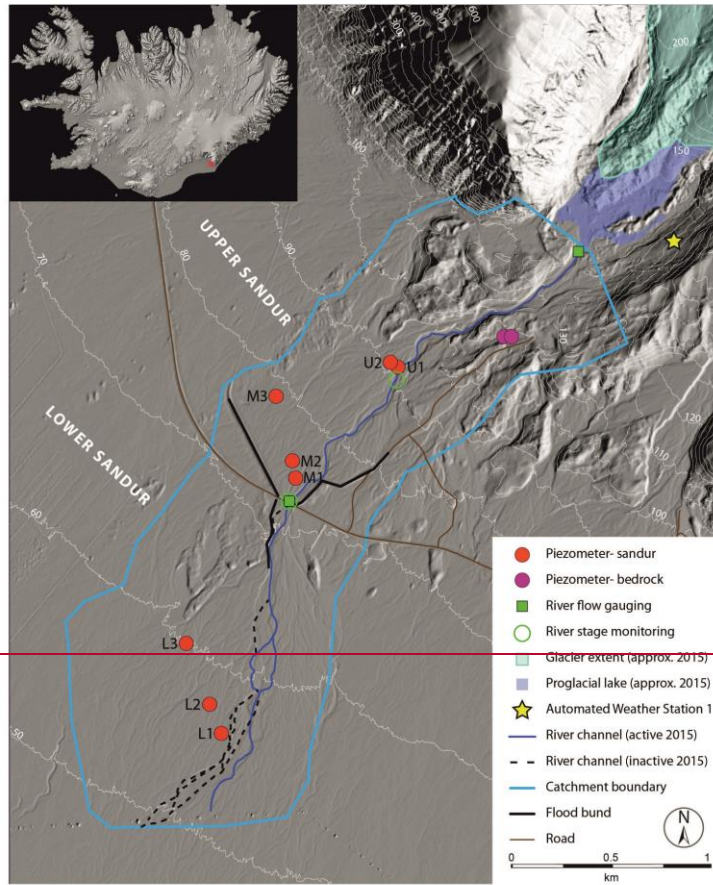
(b)

(c)
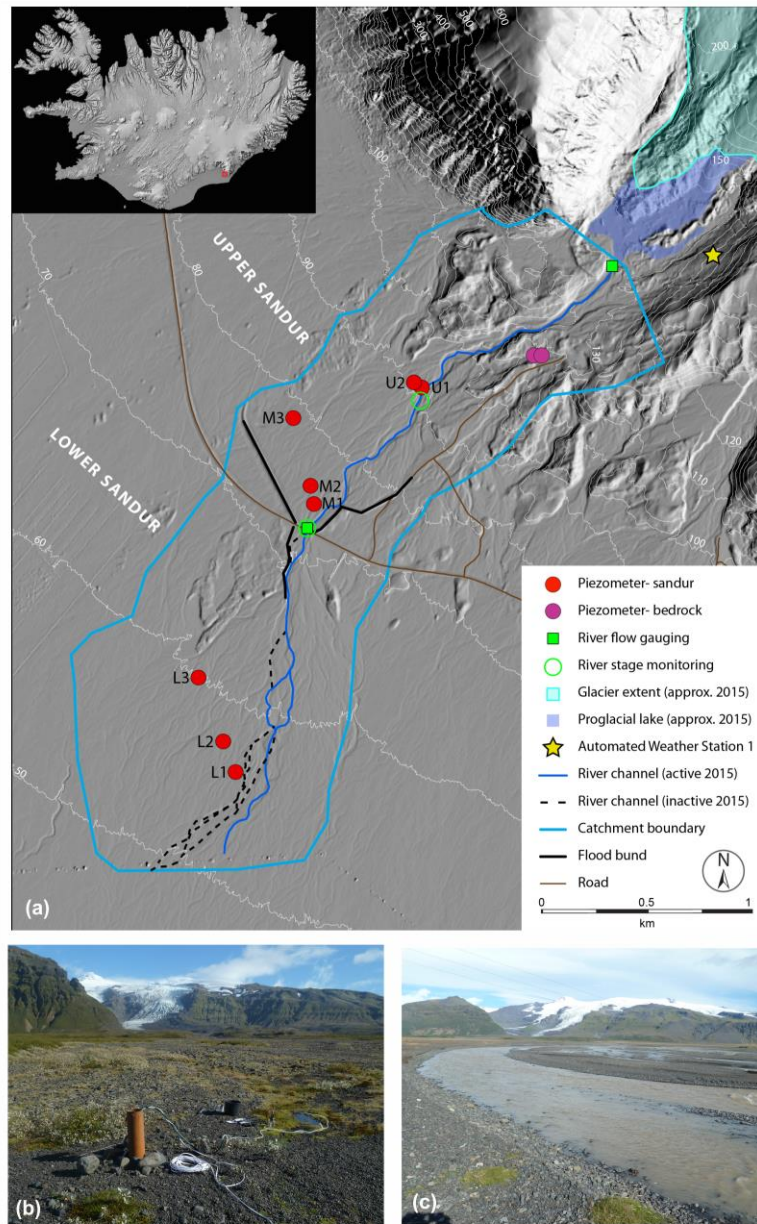
Figure 1: Virkisjökull study catchment. (a) Study area on Virkisjökull sandur, SE Iceland, encompassing 6 km² groundwater catchment originating at proglacial lake outlet. Hillshade model generated from LiDAR DEM © Veðurstofa Íslands, 2010. (b) Piezometer M1 on upper sandur near catchment edge, showing established sandur vegetation and in middle distance, area of moraines. (c) Virkisá river on lower sandur in summer melt season showing braided channels and active, unvegetated sandur surface. Piezometers in the sandur are in three transects: Upper (U1 – U2), Middle (M1 – M2) and Lower (L1 – L3).
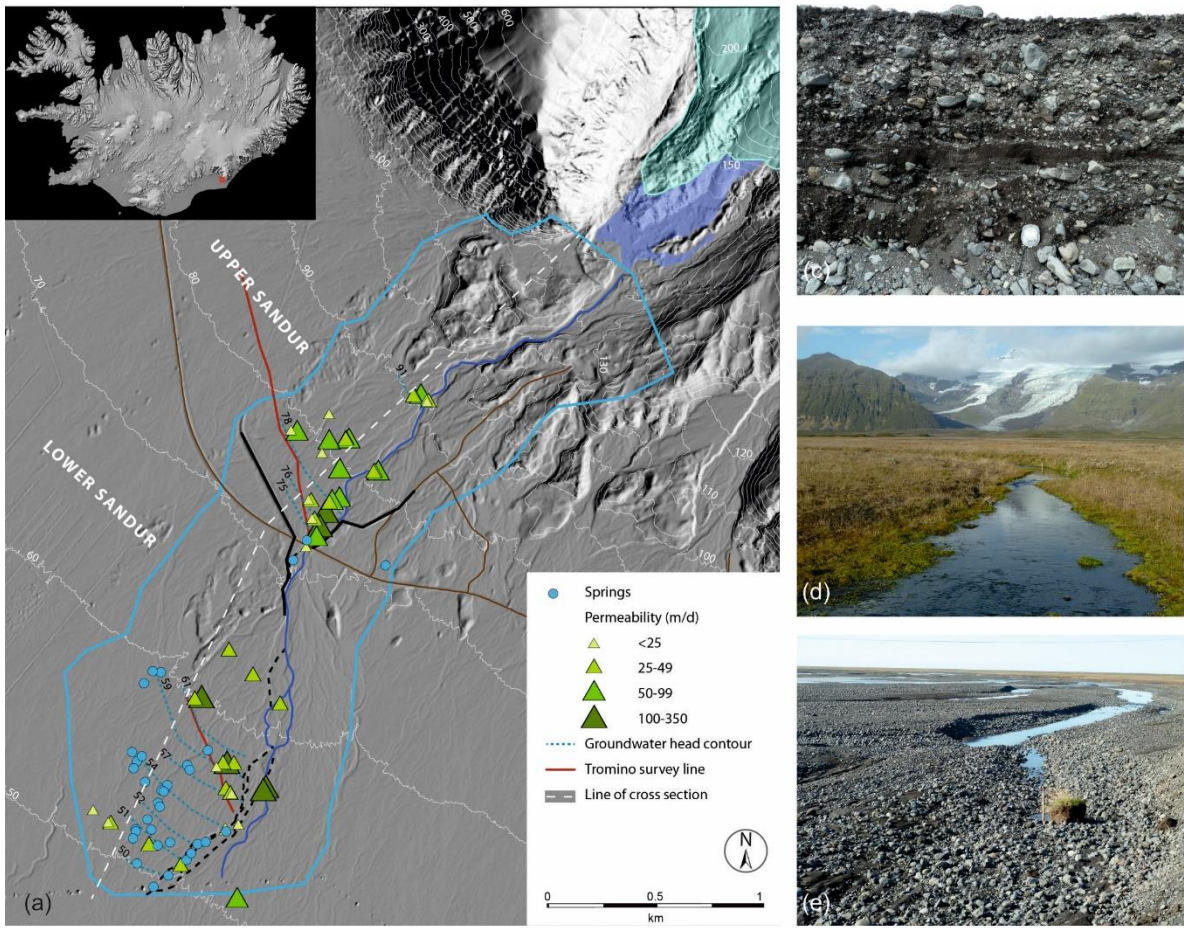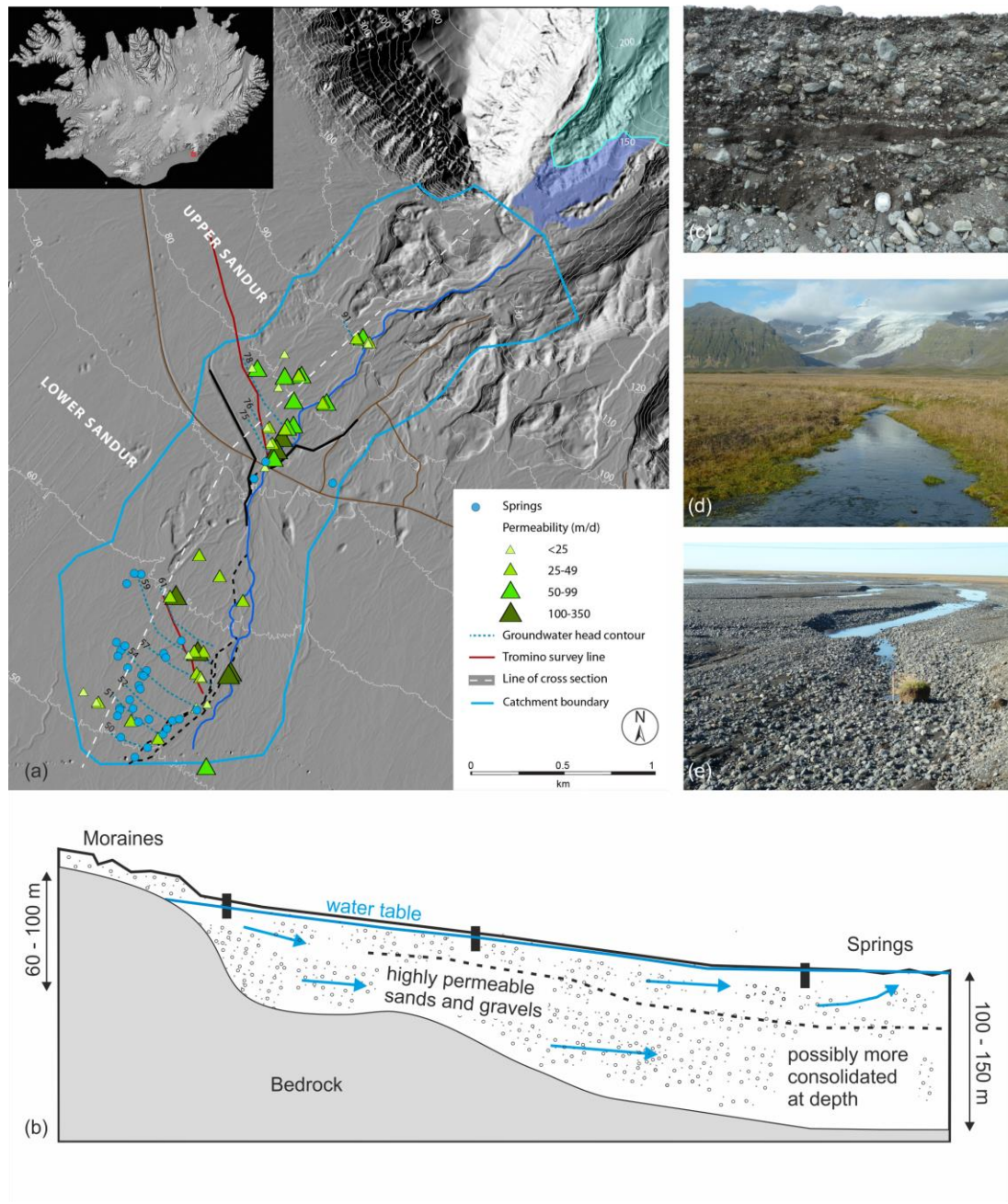
Figure 2: Geometry, geology and hydrogeology of the sandur aquifer. (a) Hydraulic conductivity and summer groundwater level contours. Other legend as Figure 1. Hillshade model generated from LiDAR DEM © Veðurstofa Íslands, 2010; (b) schematic cross section of hydrogeology, showing location of piezometer transects, spring discharge area and indicative groundwater flow lines; (c) geological section through river bank showing heterogeneous glaciofluvial deposition; (d) perennial groundwater-fed stream on lower sandur, associated with extensive growth of mosses and other aquatic vegetation; (e) groundwater discharge to otherwise inactive river channel on lower sandur, flowing to active channel in distance.
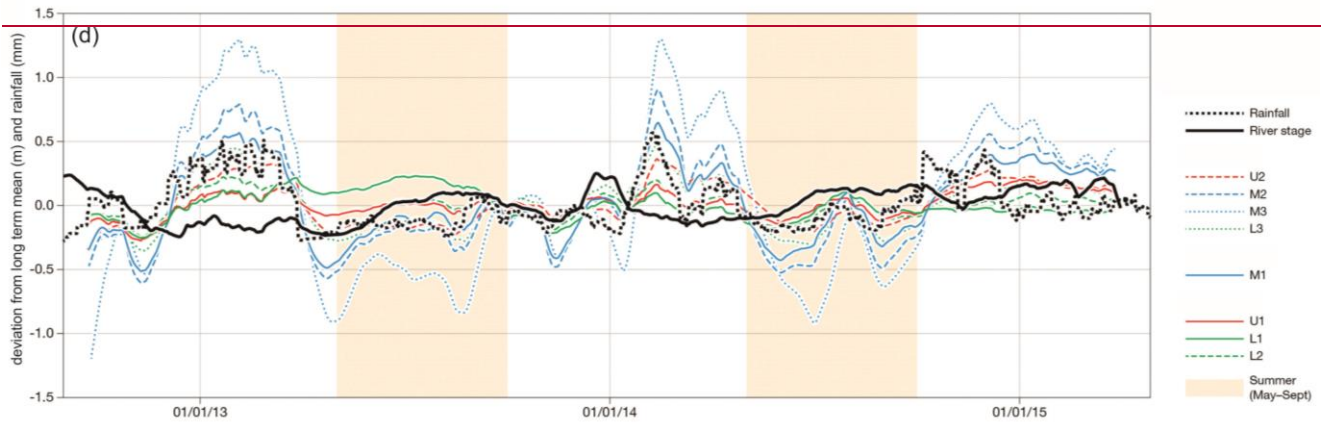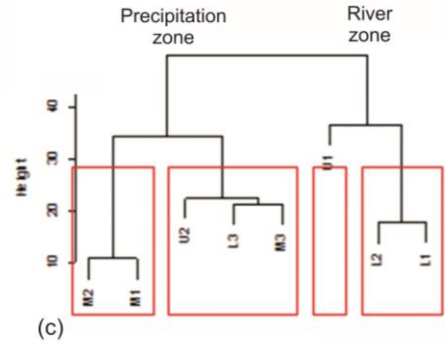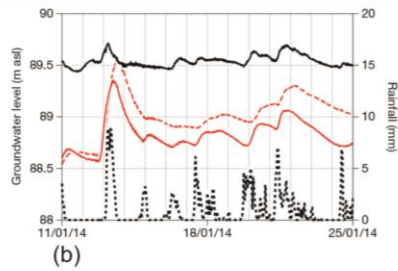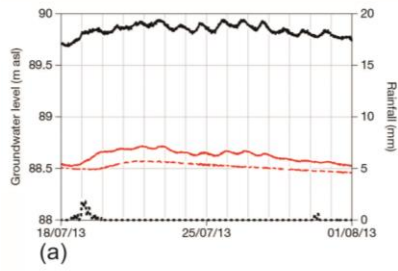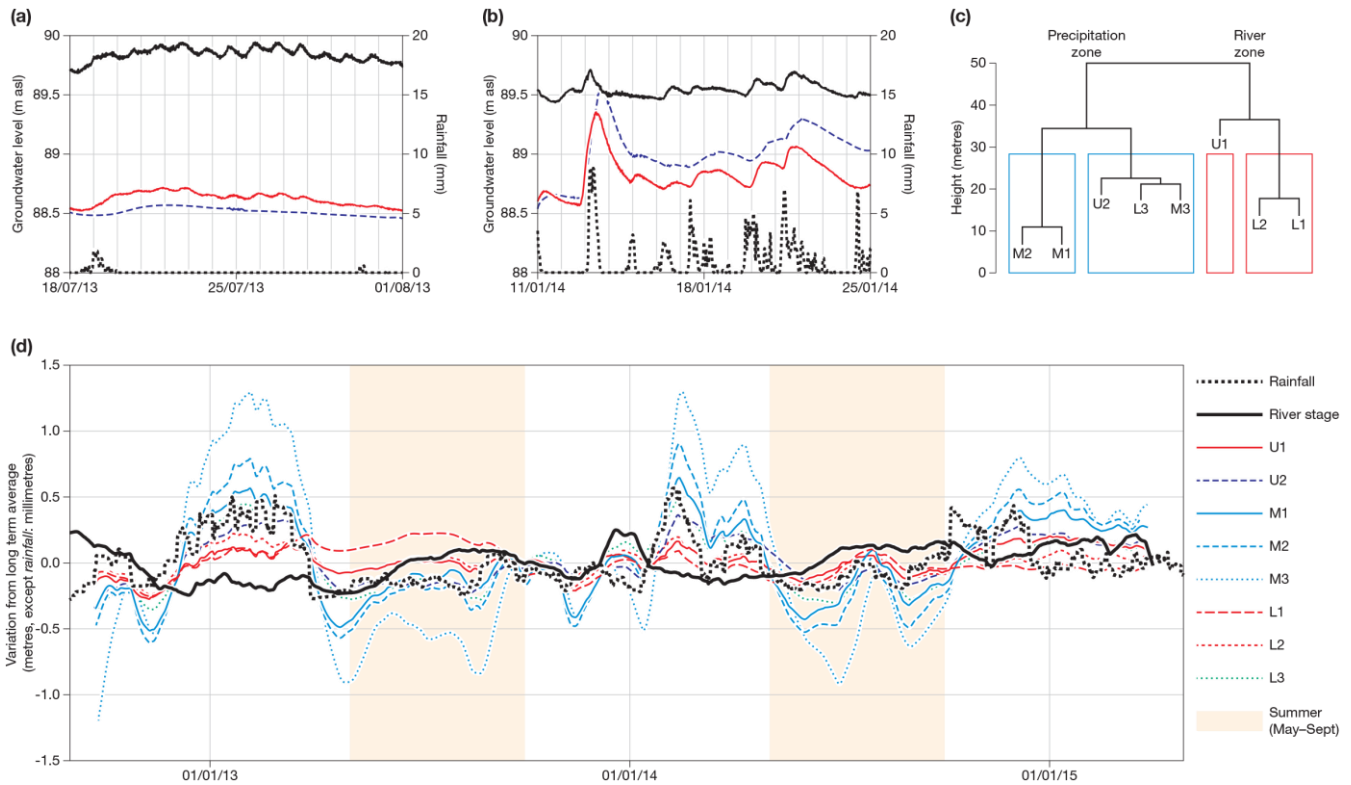
Figure 3. Groundwater levels, river stage and precipitation. (a) Groundwater levels in upper sandur during a 14-day dry period in summer (for legend see (d)). **(b)** Groundwater levels in upper sandur during a 14 day rainy period in winter (for legend see (d)). Piezometer U1 (solid) is 20 m from the river; piezometer U2 (dashed) is 90 m from the river. **(c)** Dendogram obtained by hierarchical cluster analysis of groundwater level data from sandur piezometers (piezometer locations in Figure 1). The highest level break shows two clusters representing piezometers where groundwater is influenced dominantly by local precipitation (U2, M1, M2, M3, L3) and piezometers where groundwater is influenced by the meltwater river (U1, L1, L2). ~~Red boxes~~Boxes show the four optimal sub-clusters indicated by data standardization. **(d)** Monthly running mean of river stage (m), hourly precipitation (mm) and groundwater level (m), as variation from long term average (LTA = 0).
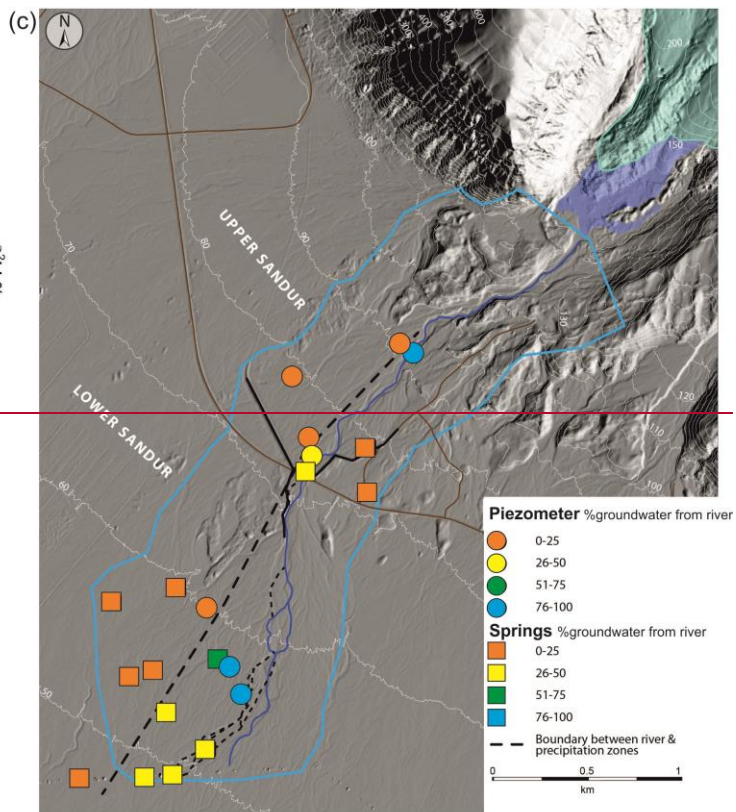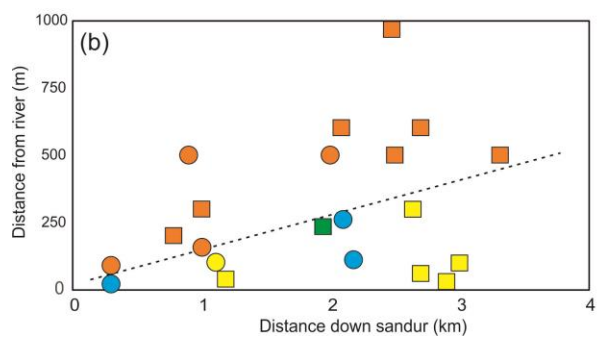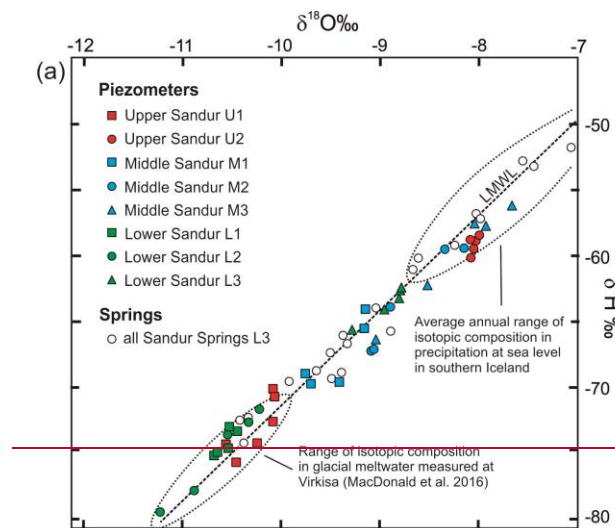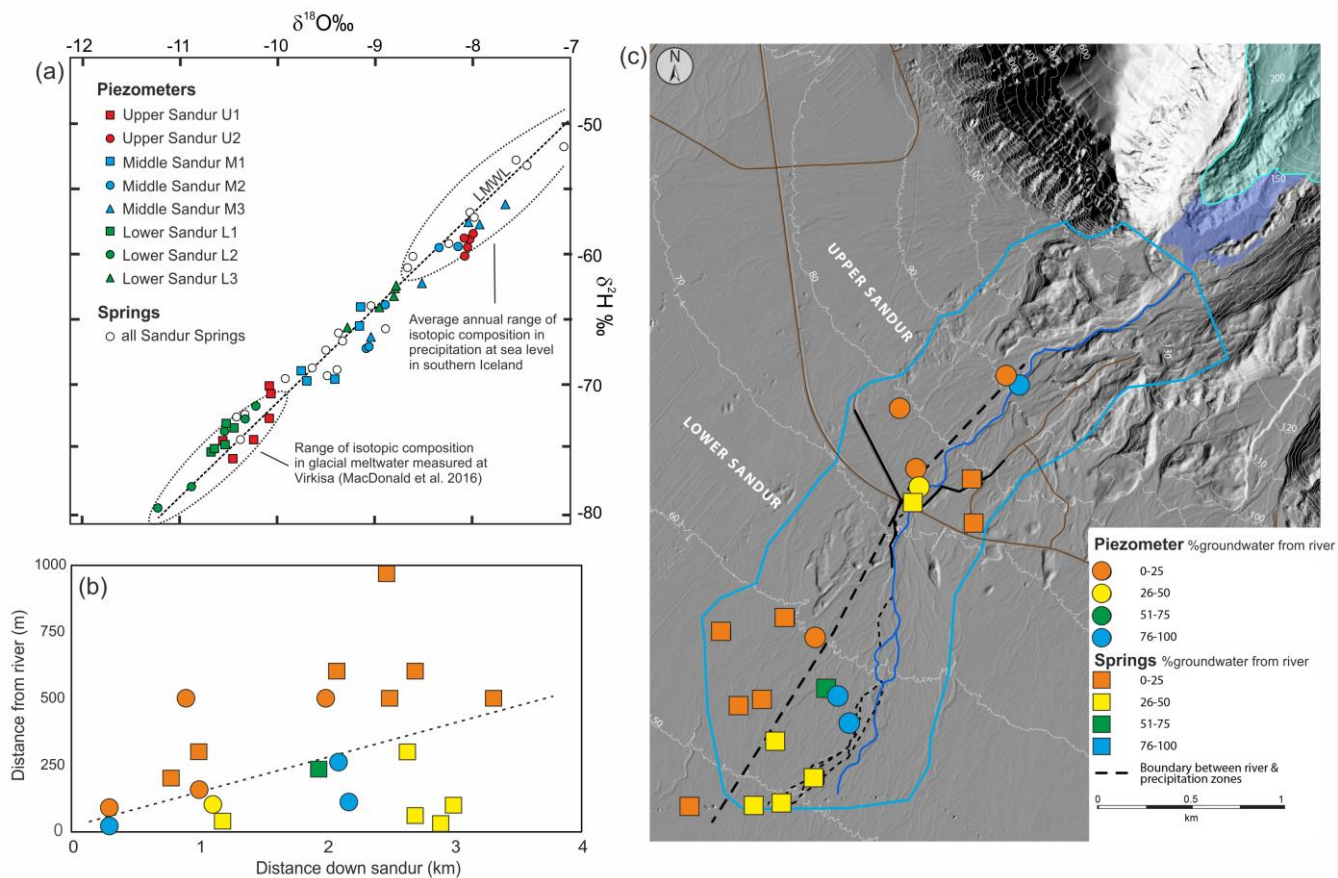
Figure 4. Stable isotope composition of waters and results of binary mixing model of δ^2H in groundwater. (a) Stable isotope composition of sandur groundwater in piezometers and springs. Individual piezometers labelled; piezometer locations in Figure 1. Also shown are ranges in stable isotope composition of precipitation and river water (MacDonald et al. 2016). Plotted on Local Meteoric Water Line (LMWL) calculated for Reykjavik. (b) Plot of mean proportion of groundwater recharged from the river using binary mixing of model of δ^2H by perpendicular distance from the river and down-sandur. (c) Map of mean proportion of groundwater estimated to be recharged from river using binary mixing model for δ^2H. Hillshade model generated from LiDAR DEM © Veðurstofa Íslands, 2010.