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Influence of climate warming on Hálslón Reservoir sediment filling

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Abstract Hálslón reservoir is the main reservoir of the Kárahnjúkar hydropower project in the eastern highlands of Iceland. Studies for the environmental impact assessment for the hydropower project showed that sediment will fill the reservoir in about 500 years based on the present sediment transport rate. The main source of the sediment is the Brúarjökull outlet glacier which is a part of the Vatnajökull ice cap. Recent studies of the influence of climate warming on glaciers in Iceland show that they will decrease significantly and, in some cases, completely disappear during the next few hundred years. In this study, a glacier melt model for the Brúarjökull outlet glacier is constructed to predict how fast the glacier will retreat in response to accepted climate warming scenarios. The results from the glacier model are then used as input to a sediment transport mass balance model for the Hálslón reservoir, which predicts the influence of the retreat of the glacier on the sedimentation in the reservoir. The modeling shows that, instead of the reservoir being completely full of sediment in 500 years, the Hálslón reservoir will at that time still have about 50–60% of its original volume as the sediment yield will decrease as a result of the decreasing glacier size.
Keywords Climate warming; glacier melting; sedimentation; sediment transport

Introduction

The Hálslón reservoir is located in the eastern highlands of Iceland and is the main reservoir for the Kárahnjúkar hydropower project, being developed by Landsvirkjun. It will be the largest hydropower plant in Iceland, yielding 690 MW, and will be operational in 2007. The power plant harnesses water from two glacial rivers emerging from two separate outlet glaciers of the Vatnajökull ice cap, Eyjabakkajökull and Brúarjökull, at an elevation of slightly more than 600 m above sea level (asl) (Björnsson and Pálsson 1991b). The Hálslón reservoir is formed by damming the Jökulsá á Dal river at Kárahnjúkar, where it flows through a narrow gorge, about 25 km downstream of Brúarjökull outlet glacier. The total volume of the reservoir is 2400 million m^3 and has an area of 57 km^2. The total catchment area at the Kárahnjúkar dam is about 1800 km^2, whereof 1400 km^2 are covered by the Brúarjökull outlet glacier. The layout of the project is shown in Figure 1.

In the Environmental Impact Assessment (EIA) (Landsvirkjun 2001) for the hydropower project, it was projected, based on the current sediment transport in the Jökulsá á Dal river, that the Hálslón reservoir would be full of sediment in 500 years. The EIA study did, however, not take into account the possible effect of climate warming on the sediment yield from the drainage area. Recent studies of the effect of climate warming on glaciers in Iceland show that the glaciers are likely to retreat rapidly in the future. As an example, the most studied glacier, the Hofsjökull ice cap, is predicted to disappear in about 200 years.

In this paper, an estimate is made of the sediment filling rate of the Hálslón reservoir, taking into account the retreat of the Brúarjökull outlet glacier with respect to a defined

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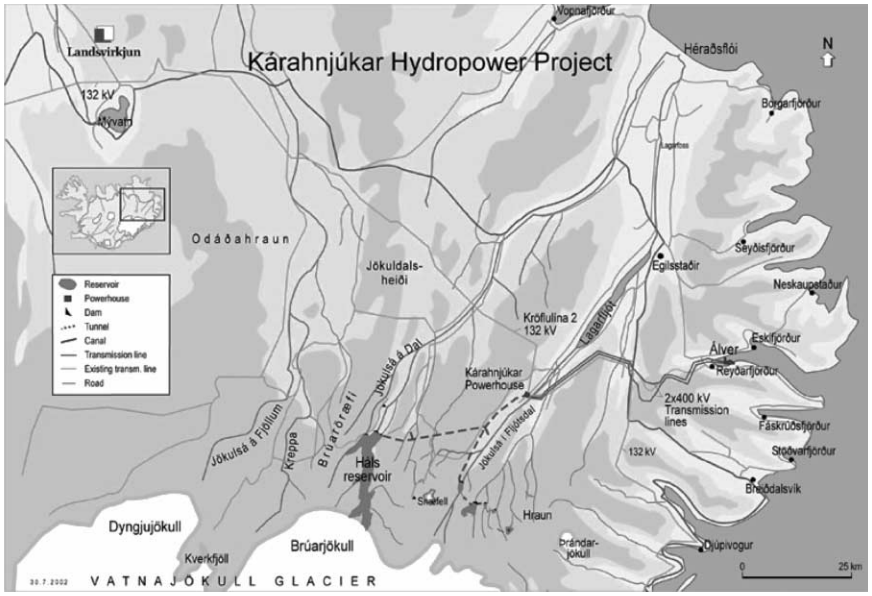

Figure 1 The layout of the Kárahnjúkar Hydropower project (Source: Landsvirkjun)

climate warming scenario. First, a simple melt model is developed to predict the response of the glacier to climate warming. Then, a sediment transport model is developed to predict the inflow of sediment into the Hálslón reservoir taking the results from the melt model into account and from that an estimate for the sediment filling rate are put forth.

Climate warming scenario

Several climate warming scenarios have been proposed, both global and regional. In this study, climate warming scenarios according to Jóhannesson *et al.* (1995, 2004), which has been extensively studied, will be used. This climate warming scenario specifies both an increase in temperature and changes in precipitation amounts. The climate warming scenario prescribes a yearly mean warming of 0.3°C per decade, varying from a winter maximum of +0.35°C per decade to a summer minimum of +0.25°C per decade. With respect to precipitation, the scenario expects a relative precipitation increase of 5% per degree of warming, independent of the season, which corresponds to 0.15% increase per year.

Model of response of Brúarjökull outlet glacier to climate warming

At the present time there are limited model results available for climate warming response of the northern part of the Vatnajökull ice cap. Research work is under way for modeling the southern part of the Vatnajökull ice cap (Aðalgeirsdóttir *et al.* 2004) and in Flowers *et al.* (2005) the sensitivity of Vatnajökull ice cap hydrology to climate warming over the next 200 years is investigated.

The Hofsjökull ice cap, which is located in central Iceland, has been more extensively studied. Jóhannesson (1997) presents results for the response to climate warming for two outlet glaciers, the Blöndujökull/Kvíslajökull outlet glacier and the Illviðrajökull outlet glacier, of the Hofsjökull ice cap in central Iceland. These outlet glaciers are about 10–20% each of the total Hofsjökull ice cap. The response is based on a degree-day glacier mass-balance model coupled to a dynamic glacier model for temperate glaciers. In this study, a simple melt model of the Brúarjökull outlet glacier is developed by applying to the Brúarjökull outlet glacier the results from the modeling by Jóhannesson (1997) of the Hofsjökull outlet glaciers.

Present shape of Brúarjökull outlet glacier

The Brúarjökull outlet glacier is one of the largest outlet glaciers of the Vatnajökull ice cap with a surface area of nearly 1700 km^2, a volume of about 770 km^3 (Björnsson and Pálsson 1991c) and over 50 km long margin. The main runoff from the glacier is the Jökulsá á Dal glacial river. The snout of the glacier is at an elevation of slightly more than 600 m asl so it will extend into the Hálslón reservoir as it has a spillway crest at an elevation of 625 m asl. The glacier margin is constantly moving as the glacier surges several kilometers roughly every 80 years during a remarkably short period of time (on the order of few months) in an event called glacial advance and then retreats again during the ensuing decades (Björnsson *et al.* 2003).

The present shape and size of the Brúarjökull outlet glacier is obtained from maps by Björnsson and Pálsson (1991a, b, c) which show the glacier surface, ice and water divides and the sub-glacial surface. The maps show that the outlet glacier flows in a relatively flat valley so for the modeling in this study the glacier will be approximated by a triangular shape shown in Figure 2, conserving the measured volume. Simplifying the shape of the glacier in this way is considered to be reasonable as the uncertainty in other variables is similar. The initial length of the outlet glacier is 60 km, the maximum thickness is 900 m, and the average width 28.5 km, yielding a total initial volume of 769 km^3.

Brúarjökull outlet glacier response model

The model of the response of the Brúarjökull outlet glacier to climate warming is constructed by applying the runoff increase for the Hofsjökull ice cap study (Jóhannesson 1997) to the Brúarjökull outlet glacier. It is noted that the Brúarjökull outlet glacier in itself is about two times the size of the whole of the Hofsjökull ice cap and it is also a part of the Vatnajökull ice cap, which is about 5 times the size of Brúarjökull, but even though the sizes are different it is expected that the increase in specific runoff will be similar. The result from Jóhannesson (1997) shows that the outlet glaciers will decrease by about 40% in the next century, and the ice cap will essentially disappear during the next 200 years.

The model assumes that the melting rate increase will be similar to what the Hofsjökull ice cap will experience. This melting rate corresponds to an increase of annual melting per surface area of $\beta_R = 16.5$ mm/a (water equivalent). This might actually be a conservative estimate as there is more tephra on the surface of Brúarjökull outlet glacier compared to the

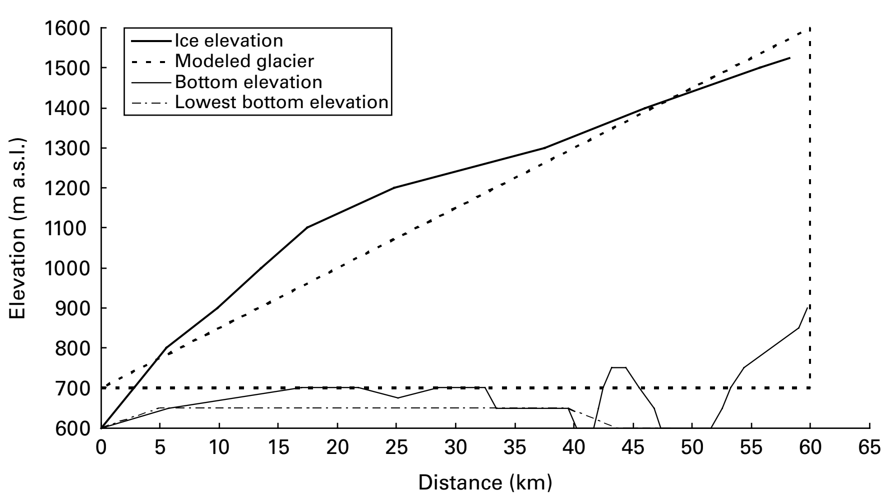

Figure 2 Longitudinal section of the glacier surface and the subglacial surface. The thick dotted line indicates the approximate triangular shape used in the calculations

Hofsjökull ice cap. Hence, the runoff per unit area in the year $t = k$ is

$$R^k = k\beta_R \tag{1}$$

where, as always in this paper, the superscript k is an index denoting a time step. The model for the melting of the Brúarjökull outlet glacier is based on modeling the glacier as a three-dimensional triangular wedge, $V^k = \frac{1}{2}L^k h^k b$ at time $t = k$, where L^k is the base length of the wedge, h^k the height and b the width, as is shown in Figure 3. Assuming that the glacier is presently near a steady state condition, the volume of runoff in year $t = k$ due to increased melting is

$$\Delta V^k = R^k A^k \tag{2}$$

where A^k is the horizontal projection of the glacier surface

$$A^k = bL^k. \tag{3}$$

The melting is assumed to be of depth r at the downstream end of the glacier and decreasing linearly to a depth of $\alpha_R r$ at the upstream end, where α_R is taken to be 0.2 which corresponds roughly to the modeling in Johannesson (1997). This simple melt model is demonstrated in Figure 3. Based on this, the melting of a volume ΔV_k requires the value of r^k, defined as the melting depth at the glacier edge at time $t = k$, to be

$$r^k = \frac{1}{2}\left[\frac{h^k}{\alpha_R}(\alpha_R + 1) - \sqrt{\frac{(h^k)^2}{\alpha_R^2}(\alpha_R + 1)^2 - \frac{8h^k}{\alpha_R b L^k}\Delta V^k}\right] \tag{4}$$

Then the height and length of the wedge at time $t = k + 1$ are, respectively,

$$h^{k+1} = h^k - \alpha_R r^k; \quad L^{k+1} = L^k - r^k \frac{L^k}{h^k}. \tag{5}$$

This simple model approximates the real glacial melting process where the melting takes place below the equilibrium line and glacier flow yields the thinning upstream of the equilibrium line. The model does not take into account the influence of glacier surges as it is assumed that the glacier edge will, on average, follow a mean receding path and the surges will only make the edge fluctuate around the mean.

Model result

The model results are shown in Figure 4. The maximum increase in runoff occurs in the year 173, 1.77 m/yr, based on the current area of the glacier, which is 96% of present runoff. As Figure 4 shows, the influence of the warming climate starts out slowly. It is noted that this process may have started several decades ago for Brúarjökull outlet glacier. In the year 100 about 17% of the volume has melted. Then the retreat speed reached a relatively fast rate and in the year 300 only about 14% of the glacier volume is left and about 20% of the area. At that point the runoff with respect to the original area is decreasing fast as the reduction in the area of the glacier is influencing the melting. Based on this model it can be concluded that the glacier will more or less disappear in 350–400 years.

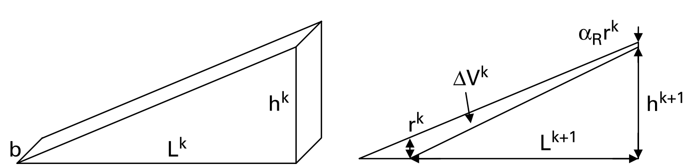

Figure 3 Schematic of the melting process in the melt model for the Brúarjökull glacier

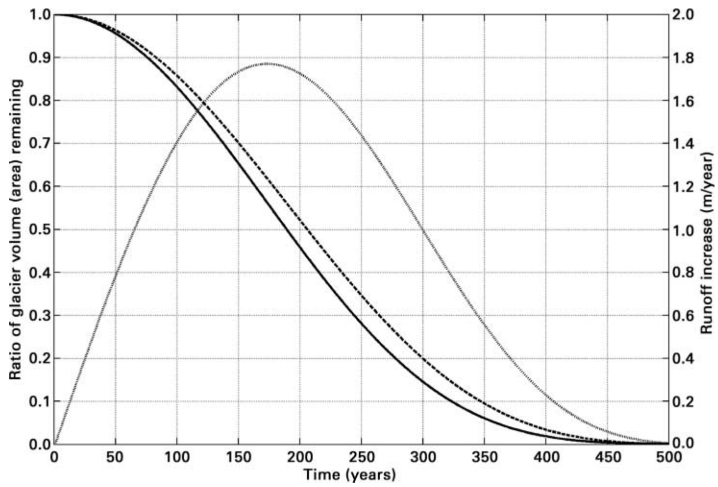

Figure 4 Brúarjökull glacial melting as predicted by the glacier melt model. The glacier volume is shown with the black line, the glacier area with the broken line and the runoff increase (right axis) with the dotted line

The results from the melt model are used as an input to the sediment transport model discussed in the following section.

Model of Hálslón sedimentation

Current reservoir filling rate

In VST (2001b), which is part of the EIA for the Kárahnjúkar hydroelectric project, the sediment filling rate was estimated according to the current rate of sediment transport to the Hálslón reservoir without taking into account potential changes in the size of the Brúarjökull outlet glacier due to climate warming. The estimate is based on sedimentation modeling of the reservoir (VST 2001b) and the result is shown in Figure 5. The sedimentation modeling shows that 93% of the sediment will be trapped in the reservoir. This means for the current size of the glacier and associated sediment load that the reservoir will be full of sediment in about 500 years. It is assumed the density of the sediment is 1.4 tons/m^3.

Sediment yield

The suspended sediment has been measured in Jökulsá á Dal by the National Energy Authority since 1963. The measurements show that the load is about 6.7 million tons per year (Pálsson *et al.* 2000; VST 2003). The bed load was measured during three summers, 2000–2003, and based on these measurements, the bed load is estimated to be in the range of 0.4–1.0 million tons which is 6–13% of the total load. In the modeling in this study the value of 1.0 million tons per year will be used in order to use a conservative estimate for the bed load. Hence, the total sediment transport in Jökulsá á Dal river is estimated to be about 7.7 million tons per year.

The sediment yield from the glaciated and non-glaciated parts of the drainage areas for the Hálslón reservoir is very different. In Tómasson (1990) the yield from the non-glaciated areas is estimated to be 20–50 tons/km^2/yr. In this study the higher number is adopted, yielding a total load from the non-glaciated area of about 20 000 tons/yr as the size of the non-glaciated area is 405 km^2 at the present time. The size of the glaciated area that contributes to the Hálslón reservoir is 1700 km^2, so based on the total sediment transport, less the yield from the non-glaciated areas, the yield from the glaciated areas is about 4500 tons/km^2/yr or nearly 100 times the yield from the non-glaciated areas. Hence, when

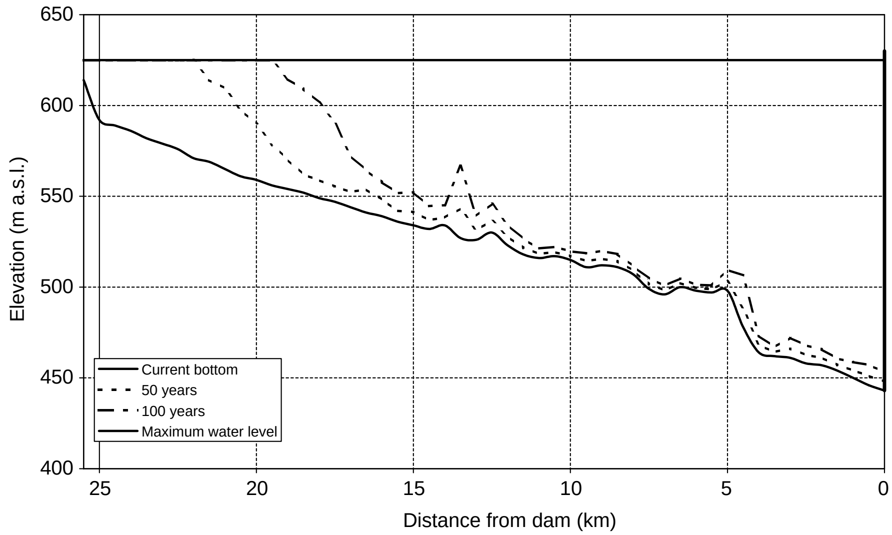

Figure 5 Predicted sedimentation in the Hálslón reservoir for the first 100 years based on current sediment transport (VST 2001b)

the glacier retreats the non-glaciated areas will increase and the total sediment load from the drainage area will therefore decrease.

Sedimentation upstream of the Hálslón reservoir

Estimation of the sedimentation upstream of the reservoir, in the areas vacated by the retreating glacier, is developed from maps of the subglacial surface (Björnsson and Pálsson 1991a). The valley of the outlet glacier is about 10 km wide between the 700 m asl contour lines. The lowest point of the valley is about 1–3 km wide at 650 m asl for most of the 45 km distance. Upstream of that, close to the ice divide, the maps indicate that the valley deepens below 600 m asl over an area of several square km. The longitudinal profile of the subglacial surface of the valley is shown in Figure 2. The river that will form upstream of the reservoir as the outlet glacier retreats will have to develop a sufficient slope in order to be able to transport the sediment into the reservoir. The slope will be dependent on the discharge, the sediment load and the sediment size. The conditions upstream of the reservoir will probably develop similar to the conditions at the present time for the Jökulsá á Dal river for the downstream-most 20 km of the current water course as it discharges into the Héraðsflói bay. Presently, for that river reach, the river slope is slightly less than 2 m/km (VST 2001a). The D_{50} for the bed material is about 10 mm and D_{10} is about 0.3 mm (Harðardóttir 2001). About 10% of the suspended sediment is coarser than 0.3 mm (VST 2001b) and about 90% of the bed load (VST 2003) at Hjardarhagi measuring station. The bed load is about 6% of the total load so it is reasonable that all of it is deposited in the river reach upstream of Héraðsflói bay as well as at least 10% of the suspended material (coarser than 0.3 mm). Therefore, it is estimated that about 15–25% of the sediment transport will be deposited, building up a slope of 1–2 m/km upstream of the reservoir.

Increased sediment yield due to increased precipitation

The increased precipitation, predicted by the climate warming scenarios, will influence the sediment transport from the non-glaciated areas as it is dependent on discharge. If the sediment yield is assumed to follow a relationship of the form $Q_{NG} = \alpha Q^{\beta}$, the sediment yield from non-glaciated areas, Q_{NG}, due to increased precipitation is, for year k, calculated as

$$Q_{NG} = \alpha Q^{\beta}(1 + k\gamma)^{\beta} \tag{6}$$

where α and β are constants derived from the measured sediment transport, Q the discharge, Q_{NG} the sediment load and γ is the discharge increase which, according to the above stated climate warming scenarios, is 0.0015. Increased precipitation will not influence the sediment yield from the glacier itself as it is only related to the area of the glacier.

Sedimentation model of Hálslón reservoir

The sediment model is a mass balance model, keeping track of the sediment sources and sinks in time as they are influenced by the effects of the retreat of the Brúarjökull outlet glacier due to climate warming.

The initial conditions for the sediment originating from the Brúarjökull glacier is set equal to the current sediment transport, which is slightly less than 7.7 million tons per year. It is assumed that the sediment yield from the glacier is proportional to the area of the glacier area as calculated by the glacier melt model. This assumption is based on results from Gurnell *et al.* (1996) that show that the specific sediment yield from Icelandic glaciers is independent of the glacier size. The yield is dependent though on various factors such as underlying rock type and subglacial deposits, rates of glacier movement, character of the glacier drainage system and the topography of the basin. These factors will remain similar as the glacier retreats, yielding approximately constant sediment yield per unit area of glacier. This assumption also requires that the sediment transport from the glacier is controlled by the specific yield and will therefore not increase due to increased melt water flow. The yield from the deglaciated area will decrease over a period of time from the glaciated yield to the non-glaciated yield. It is assumed that this transition will take 50 years and follow a sinusoidal curve.

The initial conditions for the sediment originating from non-glaciated areas of the Hálslón reservoir drainage area is set equal to the yield of the area, or 50 tons/km^2/yr, yielding a total of 20 250 tons/yr. With time the non-glaciated area will increase as the glacier retreats. In addition, the sediment transport from the non-glaciated areas will also increase due to increased precipitation (0.15% per year) due to the climate warming as previously described. It will be assumed, somewhat arbitrarily, that the precipitation increase will cease after 200 years when the precipitation will be 35% more than today.

The largest sink for the sediment is the Hálslón reservoir. It is assumed that the reservoir will trap 93% of the sediment, which is the same ratio as was calculated for current conditions. The rest of the sediment either leaves the reservoir with spillwater or through the headrace tunnel.

The other sink for the sediment is the area upstream of the reservoir that becomes ice-free when the glacier retreats. The sediment model assumes that the equilibrium slope upstream of the reservoir will be 1.5 m/km. Hence, for the areas where the subglacial surface slope is less the model deposits 20% of the sediment load, as previously discussed, to build a slope of 1.5 m/km.

The total sedimentation in the year T is therefore

$$Q_{HD}^{T} = \sum_{k=1}^{T} Q_{HD}^{k} \tag{7}$$

where Q_{HD}^{k} is the sediment deposited in Hálslón reservoir (tons/yr) in year k and is calculated by considering the following sediment budget for year k:

$$Q_{G}^{k} + Q_{NG}^{k} + Q_{G2NG}^{k} = Q_{HD}^{k} + Q_{DU}^{k} + Q_{HT}^{k} \tag{8}$$

where Q_{NG} is defined in Equation (6). The sediment from the glaciated portion of the drainage area, Q_G, is defined as

$$Q_G^k = A_G^k Y_G \quad (9)$$

where A_G is the area of the glacier and Y_G the yield from glaciated areas as previously discussed. The sediment transport from the deglaciated areas, Q_{G2NG}, is defined as

$$Q_{G2NG}^k = \sum_{t=0}^{k} \left(A_G^k - A_G^{k-1}\right) \cdot \begin{cases} Y_{NG}; & t \leq k - T_t \\ Y_{NG} \sin \dfrac{t-(k-T_t)}{T_t}\dfrac{\pi}{2} + & \\ Y_G\left(1 - \sin \dfrac{t-(k-T_t)}{T_t}\dfrac{\pi}{2}\right); & t > k - T_t \end{cases} \quad (10)$$

where T_t is the transition time for the yield to decrease from glacier yield to non-glacier yield, chosen to be 50 years as previously described. The sediment deposited upstream of the Hálslón reservoir in the area vacated by the glacier, Q_{DU}, is defined as

$$Q_{DU}^k = \min\left[\max\left(0, \rho_s V_{DU} - \sum_{t=1}^{k-1} Q_{DU}^t\right), \alpha_1 Q_G^{k-1}\right] \quad (11)$$

where α_1 is the portion of the transport that settles (20% as previously explained), ρ_s the density of the sediment, taken as 1.4 tons/m^3 and

$$V_{DU} = \begin{cases} 0; & R \leq R_0 \\ 1/2(R - R_0)^2 SB; & R_0 < R \leq R_{\max} \\ 1/2(R_{\max} - R_0)^2 SB; & R > R_{\max} \end{cases} \quad (12)$$

where R is the retreat distance at time $t = k$, S the bed slope, B the width of the area where sediment is deposited ($B = 2$ km), $R_{\max} = 45$ km and $R_0 = 5$ km.

The amount of sediment, Q_{HT}, that is transported through the reservoir with spillwater and discharge to the hydropower plant is calculated as

$$Q_{HT} = \frac{1 - \alpha_2}{\alpha_2} Q_{HD} \quad (13)$$

where $\alpha_2 = 0.93$.

Then, by using Equations (8)–(13), Q_{HD}^k is calculated as

$$Q_{HD}^k = \alpha_2\left(A_G^k Y_G + A_{NG}^k Y_{NG}(1 + \min(k, 200)\gamma)^\beta + Q_{G2NG}^k - Q_{DU}^k\right) \quad (14)$$

and the total deposition in the Hálslón reservoir at time $k = T$ is then found by Equation (7).

Sediment model results

The results of the model calculation of the sediment transport and the sedimentation for the Hálslón reservoir for the next 500 years is shown in Figure 6. The total sediment transport to the reservoir is dominated by the area of the glacier as shown with the solid line in the figure. Part of that sediment will deposit upstream of the reservoir as the broken black line shows. The subglacial surface slopes more than 1.5 m/km for the first 5 km but then the subglacial surface is almost flat with a width of 2 km. At that point sedimentation upstream of the reservoir starts and the supply to the reservoir decreases. The sediment transport from the non-glaciated areas is also shown. It increases for the first half of the period as the non-glaciated areas increase with decreasing size of the glacier and with increasing

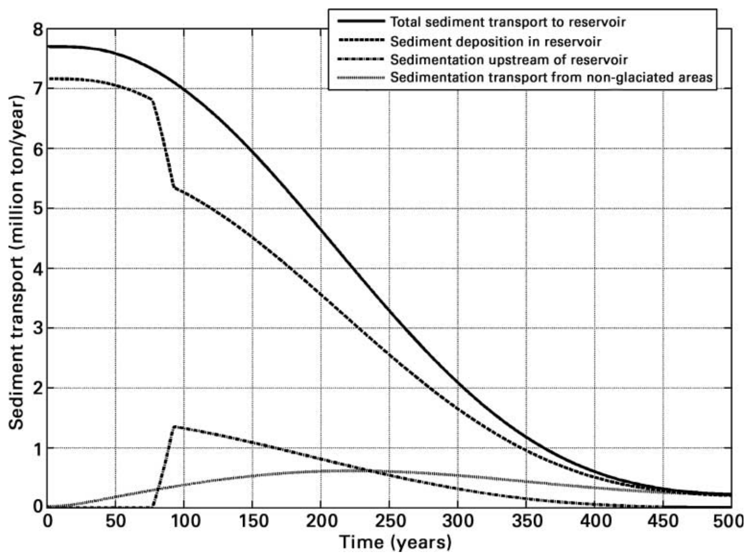

Figure 6 Sediment transport and sedimentation for the Hálslón reservoir as predicted by the sedimentation model

precipitation. Then it decreases again when smaller areas are vacated by the glacier and the precipitation increase ceases after 200 years.

The ratio of sediment filling in the Hálslón reservoir as a function of time is shown in Figure 7. The broken line shows the sedimentation in the reservoir as the ratio of the total volume based on the current sediment transport to the reservoir. The reduction in volume is linear and the reservoir will be full of sediment in about 500 years. The solid line shows the sedimentation in the reservoir when the retreat of the Brúarjökull glacier due to climate warming is taken into account. For the first 100 years the sedimentation will be similar to the rate based on the current sediment transport. By then the influence of climate warming has decreased the size of the Brúarjökull outlet glacier sufficiently to influence the sediment transport rate and the filling rate starts to deviate significantly from the current condition

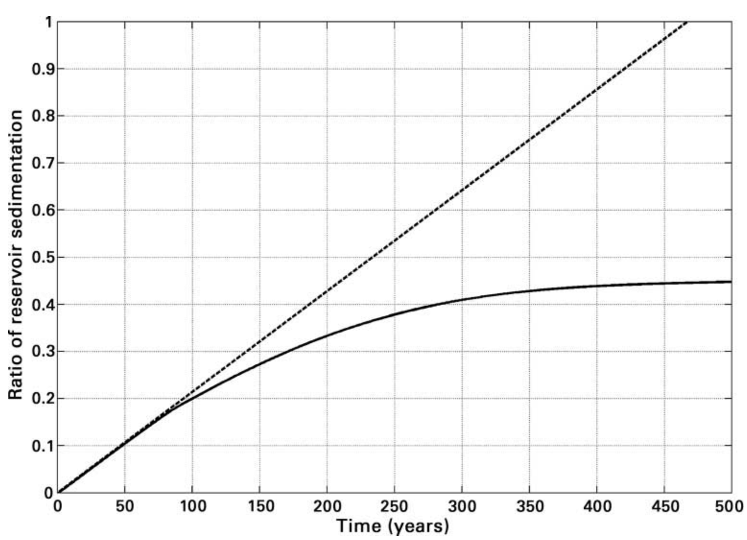

Figure 7 Hálslón reservoir sediment filling comparison with (solid line) and without (broken line) the influence of climate warming

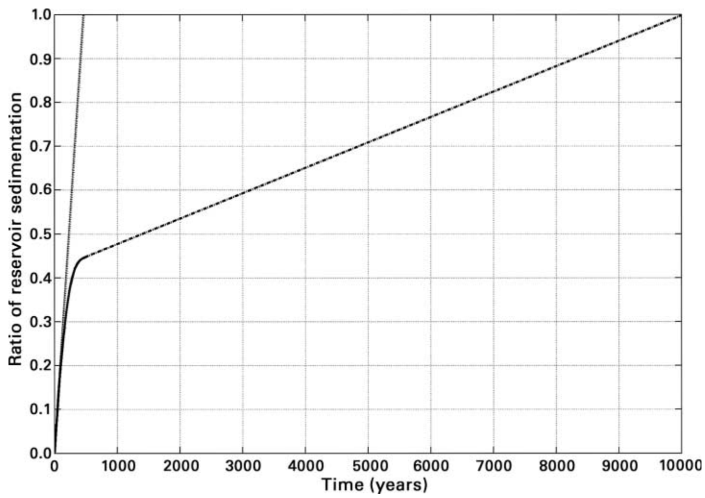

Figure 8 Extended prediction for sedimentation in the Hálslón reservoir when the Brúarjökull outlet glacier has melted. Note that Figure 7 shows an enlarged view for the first 500 years

curve and in about 250 years less than 40% of the volume will be lost to sedimentation as compared to 55% based on the current sediment transport rate. In 500 years it is predicted that the reservoir will only have lost about 40–50% of its volume when the glacier retreat is taken into account compared to being almost full based on current sediment transport rate.

This is a significant difference which means, for example, that it will be possible to run the Kárahnjúkar Hydropower Plant longer into the future than previously expected with a relatively large reservoir. In addition, the storage requirements for operating the power plant will decrease with decreasing size of the Brúarjökull outlet glacier as less of the precipitation will be stored as snow and ice during winter. That is, it can be expected that the winter discharge to the reservoir will be significantly larger as a proportion of the total yearly discharge and therefore the summer discharge proportionally smaller, decreasing the seasonal effect of the glacier that governs the size requirements of the reservoir. The effect of this is currently being studied.

The size of the Brúarjökull outlet glacier will be insignificant in 400 years as shown in Figure 4 if the climate warming scenario materializes. Hence, from that point on, the main source of the sediment yield into the Hálslón reservoir will be from the non-glaciated areas which by then will cover the whole watershed. The sediment load from non-glaciated areas will be about 210 000 tons/yr when the Brúarjökull outlet glacier has melted or about forty times smaller than at present time. The Hálslón reservoir will only be about 45% full of sediment in 500 years so it will take about 10 000 yr for the sediment transport to fill up the remaining volume as is shown in Figure 8. It is noted that predicting sedimentation so far into the future is, of course, very uncertain but based on the best available data this is the best estimate for how the sedimentation in the Hálslón reservoir will develop over the next several thousand years.

Conclusions

A simple melt model for the Brúarjökull outlet glacier is developed that predicts the response of the glacier to a climate warming scenario. The model shows that the glacier will almost disappear in about 350–400 years. Based on the glacier melt model, a sediment transport model is developed that predicts inflow of sediment to the Hálslón reservoir accounting for the retreat of the glacier. The model shows that the reservoir will be about 40–50% full of sediment in 500 years instead of being nearly full at that time as is predicted by using the present sediment transport rate to the reservoir. Furthermore, the model shows that it will take on the order of 10 000 yr to fill the remaining half after the glacier has disappeared.

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