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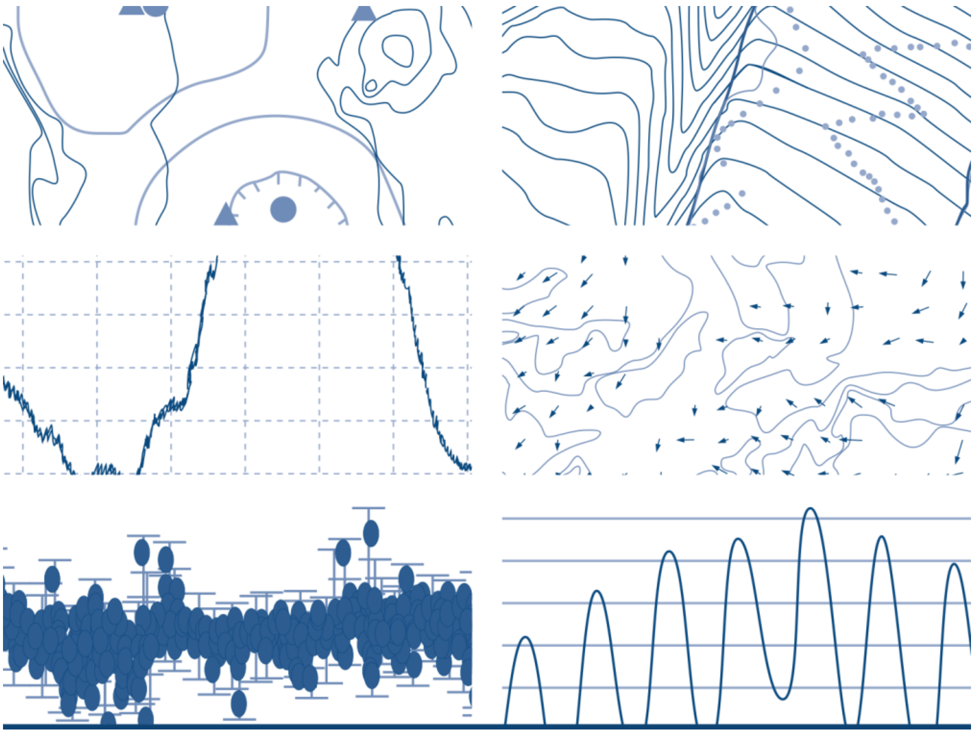

Improving groundwater representation and the parameterization of glacial melting and evapotranspiration in applications of the WaSiM hydrological model within Iceland

Bergur Einarsson
Sveinbjörn Jónsson

Report

VÍ 2010-017

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VÍ 2010-017
ISSN 1670-8261

Veðurstofa Íslands

Keypage

Report no.:	Date.:	ISSN:	Public ☒ Restricted ☐
VÍ 2010-017	December 2010	1670-8261	**Provision:**

Report title / including subtitle	**Number of copies:**
Improving groundwater representation and the parameterization of glacial melting and evapotranspiration in applications of the WaSiM hydrological model within Iceland	20
	Pages: 29
Authors:	**Managing director**
Bergur Einarsson and Sveinbjörn Jónsson	Jórunn Harðardóttir
	Project manager:
	Jórunn Harðardóttir
Project phase:	**Project number:**
Final Report	4331

Report contracted for:

National Energy Authority / The project "Loftslagsbreytingar og áhrif þeirra á orkukerfi og samgöngur" (LOKS) / The Climate and Energy Systems project (CES)

Prepared in cooperation with:

Summary:

The WaSiM model is used for hydrological modelling at the Icelandic Meteorological Office. The model application has been improved from former use by: i) improving the representation of groundwater by activating the model's groundwater module; ii) improving the representation of seasonal changes in the Hamon evapotranspiration scheme; and iii) by applying glacier melt parameters calibrated by mass balance measurements instead of river discharge data. Trial studies were done for two watersheds: Austari-Jökulsá, vhm 144, and Sandá í Þistilfirði, vhm 26. Comparable or better results are obtained with more physically realistic modelling.

Keywords:	**Managing director's signature:**
Hydrological modelling, groundwater modelling, evapotranspiration modelling, the hydrological model WaSiM, the CES project, Austari-Jökulsá, vhm 144, Sandá í Þistilfirði, vhm 26.	Jórunn Harðardóttir
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	Reviewed by:
	Philippe Crochet, SG

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1 Abstract

The WaSiM model is used for hydrological modelling at the Icelandic Meteorological Office. The model application has been improved from former use by: i) improving the representation of groundwater by activating the model's groundwater module; ii) improving the representation of seasonal changes in the Hamon evapotranspiration scheme; and iii) by applying glacier melt parameters calibrated by mass balance measurements instead of river discharge data. Trial studies were done for two watersheds: Austari-Jökulsá, vhm 144, and Sandá í Þistilfirði, vhm 26. Comparable or better results are obtained with more physically realistic modelling. Coefficients such as recession constants for direct runoff and interflow are now within expected range. Groundwater flow is important in Iceland because of young porous postglacial lava fields and high hydraulic conductivity through tectonical faults and fissure swarms and the activation of the groundwater module is therefore the largest improvement. Two different methods were used to obtain data required for the groundwater module. Simple estimation based on geological maps was used for Sandá í Þistilfirði, vhm 26, while values for Austari-Jökulsá, vhm 144, were based on a thorough hydrogeological study. Meteorological data from PSU/NCAR MM5 numerical weather model were used as input for the hydrological modelling but comparison to interpolated data from meteorological observation stations indicates that the MM5 temperature data might by biased towards to high temperatures during winter time. Temperatures data used for Sandá í Þistilfirði, vhm 26, were therefore shifted before being used as input for the hydrological modelling.

2 Introduction

Increased concentration of greenhouse gases in the atmosphere is predicted to lead to changed climate (IPCC, 2007). These changes will affect the hydrological regime as it is to large extent dependent on climatically controlled factors. The expected changes in the hydrological regime need to be estimated as it will be necessary to adapt to these changes. Increased temperature has been shown to cause changes in the storage of snow, in the magnitude of snowmelt floods and their timing along with changes in evaporation and major changes in glacier melting and thereby in the discharge of glacier-fed rivers. These changes will affect the hydropower industry, transportation and numbers of other sectors (Bergström *et al.*, 2007).

The consequences of climate change for the Nordic energy sector, in particular for the utilization of renewable energy sources, have been investigated in several collaborative Nordic research projects, of which the most recent is Climate and Energy Systems, (CES, 2007–2011), financed by The Nordic Energy Research and the Nordic energy sector (Snorrason & Harðardóttir, 2008). An Icelandic research project "Loftslagsbreytingar og áhrif þeirra á orkukerfi og samgöngur", (LOKS, 2008–2011) with a similar focus is working in parallel with the Nordic project.

The focus of one of the working groups in the CES project is on hydropower and hydrological modelling. One of the tasks of the Icelandic part of that workgroup was to improve the application of the hydrological model WaSiM in Iceland by: i) improving the representation of groundwater by activating the model's groundwater module; ii) improving the representation of seasonal changes in the Hamon evapotranspiration scheme; and iii) by applying glacier melt parameters calibrated by mass balance measurements instead of river discharge data. The National Energy Authority has supported this work with contracts on hydrological modelling and groundwater research. The model was then used to make a future projection of runoff for two watersheds in Iceland for the period of 2021–2050 (Einarsson & Jónsson, 2010).

The WaSiM model (Jasper *et al.*, 2002; Jasper & Kaufmann, 2003) was first set up and calibrated in Iceland during the joint Nordic research project, CE (Climate and Energy) (Fenger, 2007), and the Icelandic sister project VO (Veðurfar og Orka) (Jóhannesson *et al.*, 2007). The model has been used to make a runoff map for Iceland for the period 1961–1990 and a future projection of runoff for the decades 2071–2100 (Jónsdóttir, 2008).

During the CES project the model version was upgraded from 6.4, which was used in the CE project, to 8.5 as numerous improvements have been made on model internal calculation (wasim.ch, n.d.). In addition, several modifications have been made. First of all, the groundwater module of the model, not used previously, was activated. Then, a recalculation of seasonal coefficients in the evapotranspiration scheme was considered and finally, a change in the methodology for calibrating glacier melting parameters was introduced.

The activation of the groundwater module is by far the largest model update. Large areas of Iceland are covered with postglacial lava fields. These young lava fields are porous and with high hydraulic conductivity (Rist, 1956). Underground flow through tectonical faults and fissure swarms is also important in some locations (Rist, 1990). These phenomena are most common in the active volcanic zone of Iceland which reaches from Reykjanes in the south-west to the north-east as shown in Figure 1.

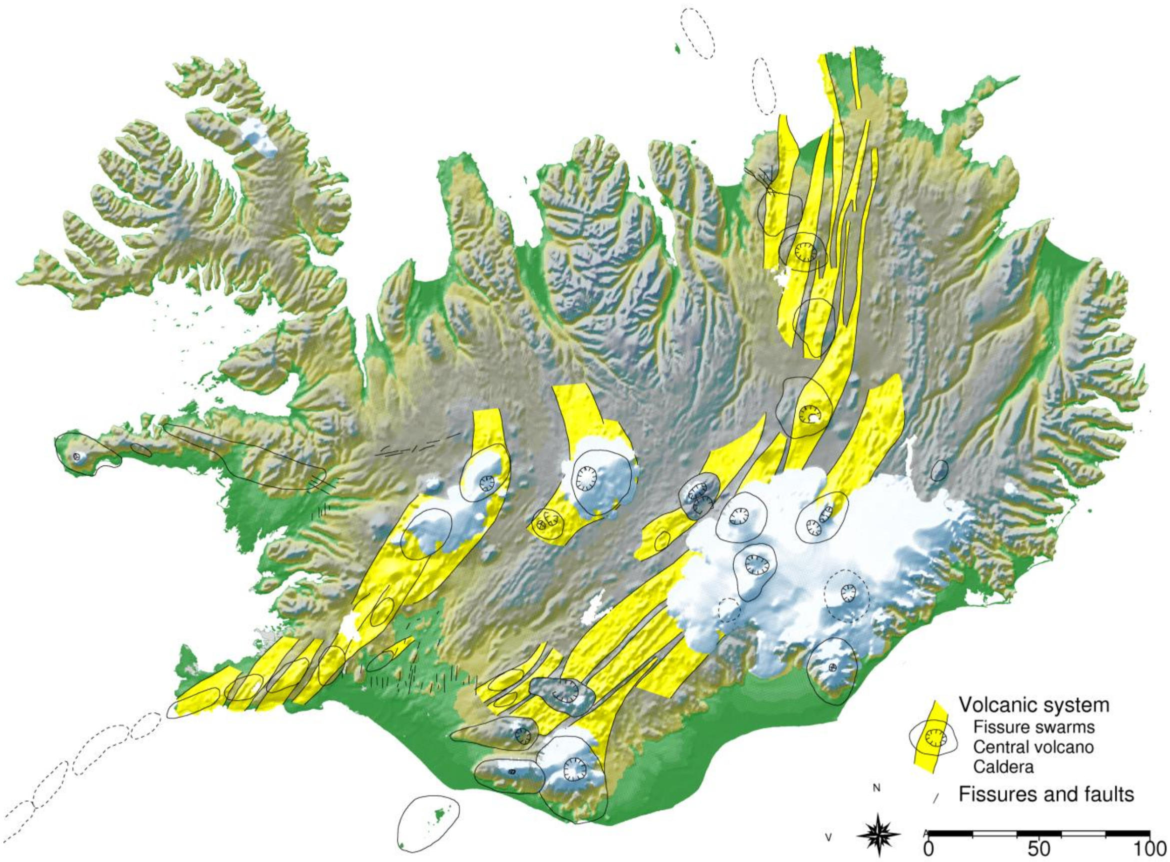

Figure 1. Volcanic zones of Iceland, shown in yellow (Einarsson & Sæmundsson, 1987).

The high hydraulic conductivity of both the lava fields and the fissure swarms make groundwater flow an important part of the runoff from many areas. In total, approximately 20% of runoff in Iceland originates from groundwater (Hjartarson, 1994a).

In the above mentioned previous simulation of runoff map for Iceland for the period 1961–1990, groundwater was omitted. Effects of groundwater flowing across watershed boundaries were simulated by scaling the precipitation for each watershed. On watersheds where part of the precipitated water leaves the watershed as groundwater, precipitation was scaled down, but on watersheds where groundwater flow from other watersheds emerges as spring flow, precipitation was scaled up. To account for the damping and smoothing effects of groundwater, recession constants for direct surface runoff and interflow were increased to many times the normal values. These approximations are simple and give satisfactory results for total runoff, but for many other parameters such as snow storage, maximum winter snow and thereby total amount of spring melt, these approximations are not acceptable in areas with considerable groundwater flow. As shown in Figure 2 the annual number of days per year with snow covered ground are suspiciously low in the area of the volcanic zones in the south-western and the north-eastern part of the country due to the precipitation scaling.

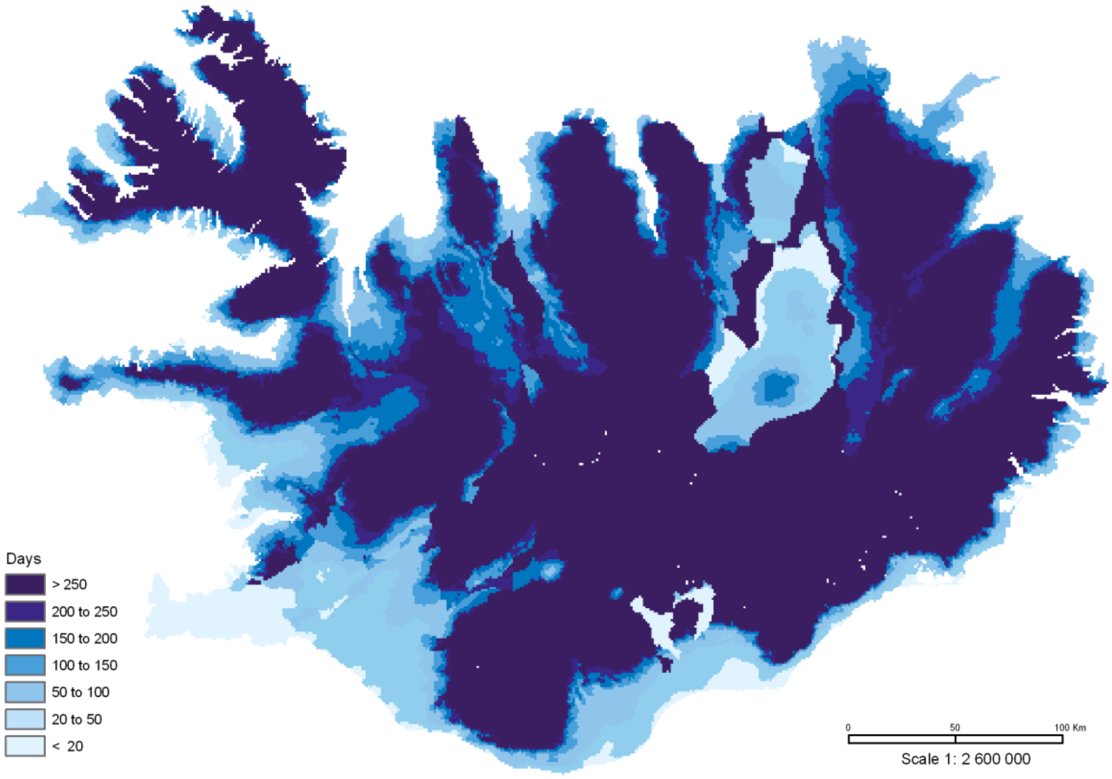

Figure 2. Mean annual number of days per year with snow covered ground for 1961–1990 (Jónsdóttir, 2008).

On watersheds where groundwater plays an important role, the above approximation leads to model parameters describing surface runoff and interflow that are very different from those that can be deduced from the unit hydrograph for these watersheds. This implies that physical description of some processes is compromised for better overall calibration performance. This is a drawback for future scenario modelling for example because bias correction and scaling defined for present conditions may not be valid for future conditions and a proper modelling of physical processes is preferable.

Above mentioned improvements of model application and their resulting improvement on results for two watersheds, Sandá í Þistilfirði, vhm 26, and Austari-Jökulsá, vhm 144, are reported below. The watersheds have different hydrological properties and climate characteristics. Sandá í Þistilfirði is located close to the coast in the north-eastern part of Iceland while Austari-Jökulsá is located in the northern part of the central highland and has a 10% glacier coverage. The location of each watershed (and the two subcatchments of vhm 144, vhm 269 and vhm 167) is shown on Figure 3.

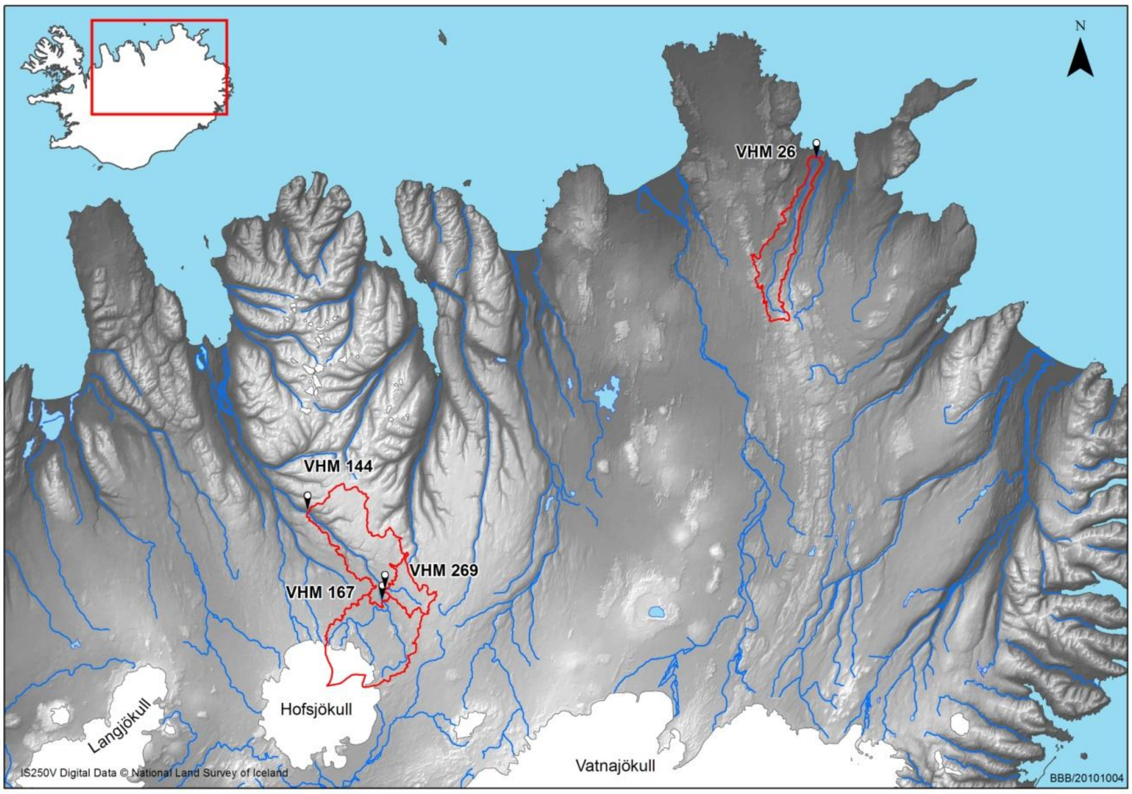

Figure 3. Location of the partly glacier covered watershed Austari-Jökulsá, vhm 144 (and its subcatchments vhm 167 and vhm 269), and the non-glacier covered watershed Sandá í Þistilfirði, vhm 26.

3 Methods

3.1 General methodology

WaSiM is a physically-based distributed hydrological model that has been used in recent years in Iceland and has proven reliable for modelling of mountainous areas with considerable snow accumulation (Kunstmann *et al*., 2006).

The model offers various methods to calculate the different elements of the hydrological cycle depending on the availability of input data. For calculating evapotranspiration, the simple temperature-based Hamon approach was adopted. For calculating snowmelt, a temperature-wind index method was used where the effects on melting, of increased convectional thermal transport with increased wind speed are accounted for. Extended melt approach was used to account for melting on glaciers where the effects of radiation are added to a classic degree-day model. For infiltration, a methodology of Peschke, based on the approach of Green and Ampt, was used. To calculate the fluxes within the unsaturated soil zone, the Richards equation was used. The groundwater table was modelled in both the unsaturated zone module and the groundwater module. The coupling between both modules was done by a net boundary flux between the unsaturated zone and the groundwater (Schulla & Jasper, 2007).

Information on land use, soil type, elevation and other general properties of the watershed are given in static distributed grids while a number of parameters describing specific processes are adjusted to the properties of each watershed by comparison of modelled and measured discharge series.

In this study, the methodology used previously by Jónsdóttir (2008) is followed. Eleven parameters describing the unsaturated zone, snow accumulation, snow melt and groundwater flow were adjusted to fit each watershed. In addition, three parameters were adjusted for glacier covered areas. For the unsaturated zone, the following five parameters were adjusted: (1) storage coefficient of direct runoff k_d; (2) storage coefficient of interflow k_i; (3) drainage density d; (4) the fraction of surface runoff from snowmelt; and (5) the recession constant k_{rec} for the decreasing saturated hydraulic conductivity with increasing depth. For the groundwater flow, adjusted parameters (6–7) are the hydraulic conductivity in the X and Y direction. The hydraulic conductivity is adjusted in distributed grids unlike other parameters that have one value for each sub-basin and are defined in the control file of the model. The four snow model parameters that were adjusted were (8) temperature threshold for rain/snow $T_{R/S}$, (9) temperature threshold for snow melt T_0, (10) degree-day factor without wind consideration c_1, and (11) degree-day-factor with wind consideration c_2. The additional three parameters that were calibrated for the glacier-covered watershed describes specific storage coefficients for (12–14): ice, snow, and firn. Model parameters were adjusted manually until simulated and observed discharge series were in agreement.

The Nash-Sutcliffe coefficient R^2 and R^2_{log} were used to measure how well the simulated runoff fits the observed runoff. Both coefficients R^2 and R^2_{log} range for 1 to $-\infty$, where a perfect fit corresponds to 1. The coefficient R^2 emphasizes the fit of high flows and floods while R^2_{log} puts greater weight on how well low flows are simulated (Jónsdóttir, 2008).

For a more detailed model description see Schulla & Jasper (2007).

3.2 Improvements in model application

3.2.1 Activation of groundwater module

Two watersheds were selected for experimenting the activation of the groundwater module. Groundwater plays an important part in the hydrology of both watersheds, but the groundwater settings are relatively simple with regards to anisotropy, influx of groundwater from other watersheds and other similar factors. Extensive groundwater researches have been made for one of the two watersheds while groundwater parameters were estimated from geological settings for the other one. The more researched watershed is the one of Austari-Jökulsá and estimations on hydraulic conductivity, porosity and hydraulic conductivity through tectonical fissures are available in Sigurðsson (2004). The other watershed is Sandá í Þistilfirði where hydrological properties were estimated from tables of hydrological properties of geological formation (Hjartarson, 1994b) and a geological map by Jóhannesson and Sæmundsson (1998).

During the implementation of the groundwater module two internal errors in WaSiM were encountered. Both errors caused artificial creation of water as certain cells started to act as an inexhaustible source of water. One of the error emerged when it was initially tried to describe the hydrological properties of a watershed using two aquifers, an upper shallow one describing the hydrological properties of the soil and sediments, and a lower deeper aquifer describing the properties of the bedrock. When running WaSiM with this setup, water emerged from the upper aquifer when the lower one was not full, even though the upper aquifer was empty. When this was clear, the author of WaSiM, Dr. Jörg Schulla, was contacted and this bug was fixed. It did also appear that using a setup with two aquifers was not recommended as it has not been thoroughly tested so far.

Although the use of a setup with two aquifers had been abandoned and that the bug had been fixed, the water balance for our partly glacier covered watershed was still unrealistic. As before, more water was flowing from the watershed than could be expected by rain, incoming groundwater flow, and snow and ice melt. The source of this excess water was traced to the glacier. Under normal circumstances the groundwater level is calculated in two modules in WaSiM: i) in the module for the unsaturated zone where the groundwater level is estimated from infiltration and the release of groundwater as spring flow, and ii) in the groundwater module where the groundwater level is estimated by the horizontal flow of groundwater between cells. These estimations are then harmonized with iteration. When examining the origin of excess water released from the glacier it was observed that the groundwater module was running beneath the glacier, but the unsaturated zone module was not. According to the documentation of the model and its author, Dr. Jörg Schulla, this is an error because the model is not designed to run the groundwater module, or the unsaturated zone module beneath glacier.

For the cells where only the groundwater module was run, the calculation of the elevation of the groundwater table became wrong and these cells began to function as cells with a fixed pressure head. That is the groundwater level in cells beneath the glacier will always be the same regardless of what flows out from them and they will function as an endless source of excess water. This bug has still not been fixed but can be avoided by setting the hydraulic conductivity for the aquifer under the glacier manually to zero. By this procedure the groundwater module under the glacier is disabled.

3.2.2 Better representation of seasonal fluctuation in potential evapotranspiration

WaSiM offers various methods to calculate the potential evapotranspiration and in this work Hamon approach was used. The potential evapotranspiration using Hamon approach is given by Schulla & Jasper (2007):

$$ETP = 0.1651 \cdot f_i \cdot h_d / 12 \cdot \frac{216.7 \cdot e_s}{T + 273.3}$$

with: f_i emperical factor, monthly values

h_d day length [h]

e_s saturation vapor pressure at temperature T [hPa]

T temperature [°C]

Saturation vapour pressure at the given temperature is calculated by the Magnus-formula. Day length is calculated based on geographical location and sun declination for each given day. To describe different evapotranspiration between seasons, monthly correction factor are used. In former work with WaSiM in Iceland these monthly factors had been estimated by comparing measured water balance for few small watersheds during the summer months to calculated water balance (Jónsdóttir & Einarsson, 2006). Only summer months were used because snow storage can affect monthly water balances for other times of the year. The correction factor for the summer months was then used for all months of the year. This approach resulted in too high correction factors for other seasons than summer giving too high estimation of evapotranspiration. This was especially problematic during the winter months because winter evapotranspiration was highly overestimated, evaporating unrealistically large amounts of the winter snow away leaving too little snow available for spring melt and generation of spring floods. To improve the estimation of monthly correction factors f_i, potential evapotranspiration calculated with uncorrected Hamon approach was compared to potential evapotranspiration calculated by using Penman approach (Philippe Crochet, personal communication), using a nearby meteorological station for which the estimation of evapotranspiration by Penman approach was available (Einarsson 1972). Resulting parameters are given in Table 1 for Hveravellir, showing clear seasonal variation with much lower values in winter than during summer time. These parameters have been used to correct Hamon evapotranspiration.

Table 1. Monthly correction factors, f_i for Hamon-Evapotranspiration at Hveravellir.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
f_i	0.10	0.60	0.95	1.15	1.70	1.30	1.14	0.97	0.80	0.40	0.20	0.10

3.2.3 Calibration of glacier melt parameters

Increased glacier runoff is one of the main changes that are expected in river runoff with changed climate. It is therefore important that glacier runoff is modelled and parameterized with sound physical basis. Glacier melt parameters that were previously calibrated with river runoff data are now calibrated with mass-balance data. Glacier runoff in WaSiM is modelled by the same formulation as in Regines Hock's *Meltmod* (Hock, 1998; Schulla and Jasper, 2007). The method applied in this study is an extended degree-day melt approach including the effects of radiation:

$$M = \begin{cases} \frac{1}{n} \quad MF + \alpha_{snow/firn/ice} \cdot I_0 \cdot \frac{G_S}{I_S} \quad \cdot \quad T - T_0 & : T > T_0 \\ 0 & : T \leq T_0 \end{cases}$$

with:

M	melt [mm/time step]
n	number of time step per day [time step day^{-1}]
MF	melt factor with identical values for snow, firn and ice [$\text{mm}\cdot°\text{C}^{-1}\cdot\text{day}^{-1}$]
α	empirical coefficients for snow and firn (identical) and for ice [$\text{mm}\cdot\text{Wh}^{-1}\cdot\text{m}^{2}\cdot°\text{C}^{-1}\cdot\text{day}^{-1}$]
I_0	potential direct incoming shortwave radiation for each grid cell [$\text{Wh}\cdot\text{m}^{-2}$]
I_S	potential direct incoming shortwave radiation for location of a meteorological station [$\text{Wh}\cdot\text{m}^{-2}$]
G_S	observed radiation at the location of the meteorological station [$\text{Wh}\cdot\text{m}^{-2}$]
T	air temperature in a standard elevation of 2 m [°C]
T_0	threshold temperature for melt [°C]

Regines Hock's *Meltmod* method using an extended degree-day melt approach including the effects of radiation has been applied on Hofsjökull glacier and calibrated based on mass balance measurements for the years 1988–2004 (Þorsteinsson & Einarsson, 2006). Parameters for the glacier module in WaSiM found in former calibration for the watershed of Austari-Jökulsá differ substantially from those found for Hofsjökull by *Meltmod* although the glacier covered part of the watershed of Austari-Jökulsá is a part of Hofsjökull. The melting parameters are much better reflected in the mass balance measurements that are used to calibrate *Meltmod* than in the discharge measurements that are used to calibrate WaSiM. The reason is probably that faulty parameterization of other hydrological processes in WaSiM might be compensated by the calibration of the glacier melt parameters. It was therefore decided not to calibrate the glacier melt parameters in WaSiM, but to adopt the result from the calibration of *Meltmod* instead. Comparison on melt parameters is shown in Table 2. Retention of water in the glacier: snow, firn and ice, is described by a set of parallel single linear reservoirs each described by a recession constant (Schulla & Jasper, 2007). As these recession constants do not affect ablation they are still calibrated based on discharge measurements.

The *Meltmod* calculation is based on temperature data from the meteorological station at Hveravellir which is located outside the watershed to the west of Hofsjökull glacier, while the WaSiM calculation are based on temperature data on the watershed and estimated from the MM5 meteorological model as described below. This is a drawback for the direct transfer of coefficients between studies as any differences in input data will affect these coefficients. See further discussion in chapter 6.

Table 2. Comparison of glacier melt parameters from Meltmod for Hofsjökull and from WaSiM for Austari Jökulsá.

Parameter	**Former WaSiM calibrations**	**Meltmod calibration**
MF [$\text{mm}\cdot°\text{C}^{-1}\cdot\text{day}^{-1}$]	8.0	3.7
Radiation coefficient for ice α_{ice} [$\text{mm}\cdot\text{Wh}^{-1}\cdot\text{m}^{2}\cdot°\text{C}^{-1}\cdot\text{day}^{-1}$]	0.0007	0.0012
Radiation coefficient for snow α_{snow} [$\text{mm}\cdot\text{Wh}^{-1}\cdot\text{m}^{2}\cdot°\text{C}^{-1}\cdot\text{day}^{-1}$]	0.0003	0.0006

4 Data

4.1 Discharge data

Discharge series from two watersheds are used in this study. These are the watershed corresponding to water-level gauge vhm 144 by Skatastaðir in the river Austari-Jökulsá and the watershed corresponding to gauge vhm 26 by Sandárfoss in the river Sandá í Þistilfirði. Discharge rating curves, relating water level to discharge, are available for both of these water-level gauges. Discharge series are therefore available for both gauges from the time of their setup to date. The gauge in Austari-Jökulsá, vhm 144, was built in 1970 while the one in Sandá í Þistilfirði, vhm 26, was built in 1965 (Icelandic Meteorological Office, 2010a; Icelandic Meteorological Office, 2010b). Those discharge series are not fully complete both because of instrument breakdown and ice interference. These data gaps in discharge are usually interpolated by estimation for most common use of these data, but all interpolated data are filtered out in this study.

The watershed of Austari-Jökulsá, vhm 144, was selected for studying because of its extensive glacier cover (10%). The area of the watershed is 1024 km^2 and it has had an average annual discharge of about 39 m^3/s for the last 37 years (Icelandic Meteorological Office, 2010a). The watershed is situated in the central highland and is highly elevated for an Icelandic watershed, the elevation profile of the watershed is shown on Figure 4. Apart from the glacier, the most important part of the watershed in terms of the hydrology is a large relatively flat heathen area. The spring floods are the most pronounced part of the mean annual hydrological variation, but the late summer glacier-peak is also pronounced.

Sandá í Þistilfirði, vhm 26, has a smaller watershed of only 268 km^2 and was selected as a typical direct runoff river. The watershed is at a lower elevation than the watershed of Austari-Jökulsá, vhm 144, and it is closer to the ocean. The elevation distribution of the watershed is shown on Figure 4. As for the watershed of Austari-Jökulsá and most watersheds in Iceland (Rist, 1990), the spring flood peak is most pronounced in the annual hydrological variation. The mean 33 year discharge average for Sandá í Þistilfirði is about 13.5 m^3/s (Icelandic Meteorological Office, 2010b).

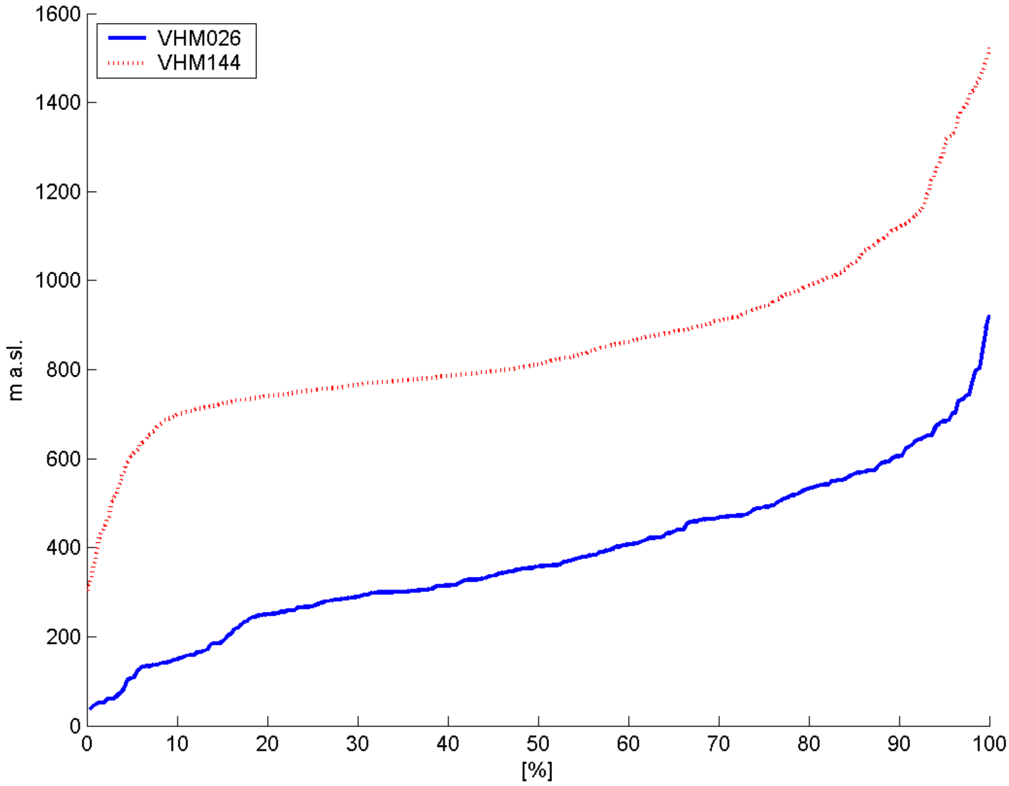

Figure 4. Elevation distribution for Sandá í Þistilfirði (vhm 26, blue curve) and Austari-Jökulsá (vhm 144, red broken curve).

4.2 Meteorological data

Information about precipitation, temperature, wind and incoming shortwave solar radiation are needed as input for the hydrological modelling. For this study, data from the meteorological PSU/NCAR MM5 numerical weather model were used (Grell *et al.*, 1994; Rögnvaldsson *et al.*, 2007). These data were calculated on an 8x8 km grid and exported into grids usable for input into WaSiM. The data are further interpolated onto a 1x1 grid within WaSiM.

During the calibration of Sandá í Þistilfirði, snow melt was observed to start unreasonably too early independently of parameterization, and most of the winter snow pack was melted already in January leaving no snow to be melted during April as observed. This led to suspicion about the quality of the simulated temperature data for this watershed. For this reason, it was decided to compare the MM5 temperature to a gridded temperature data set estimated by Crochet and Jóhannesson (2011), from the manual observation network. These gridded temperature data are calculated with a tension-spline interpolation after correction for elevation, using a 1-km Digital Terrain Model and a constant lapse-rate of -6.5°C/km. The result of this comparison showed that the MM5 temperature data were systematically higher than observed as shown in Table 3 and on Figure 5. This is in agreement with an earlier comparison of MM5 temperature data with spatial interpolated observed temperatures. In Jóhannesson *et al.* (2007), the MM5 temperature was found to be 0.9°C warmer on the average for the period 1961–1990.

Table 3. Mean monthly temperature for Sandá í Þistilfirði (vhm 26), 1961–2005.

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Win**	**Sum**	**Year**
Mean MM5 [C°]	-3.2	-3.1	-3.2	-1.6	1.8	5.8	8	7.5	4.3	1.2	-1.7	-3.1	-3.1	7.1	1.1
Mean obs. [C°]	-4.3	-4.1	-3.8	-1.6	1.8	5.4	7.4	7.1	3.9	0.5	-2.5	-4.1	-4.1	6.6	0.5
Difference	1.1	1.0	0.6	0.0	0.0	0.4	0.6	0.4	0.4	0.7	0.8	1.0	1.0	0.5	0.6

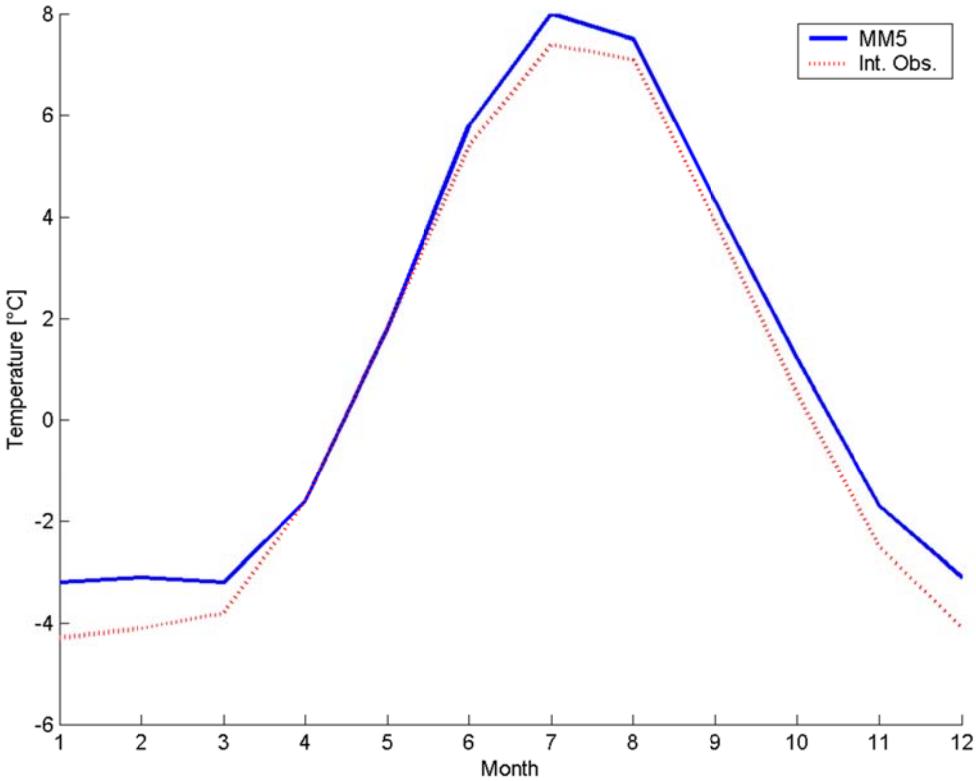

Figure 5. Comparison of mean yearly temperature 1961–2005 for Sandá í Þistilfirði (vhm 26); an interpolation of manual observation is shown with a broken red curve and MM5 temperature is shown in blue.

Due to this systematic difference the MM5 temperatures data were corrected to fit the mean monthly gridded values, see Table 3.

No suspicion about the quality of the MM5 temperature data arose when calibrating the Austari-Jökulsá watershed; but when comparing the MM5 temperatures to the interpolated ones, a similar difference was observed. The MM5 temperatures were also systematically higher than observations for the winter months as shown in Table 4 and Figure 6.

The high elevation gradient for the lowest areas of the Austari-Jökulsá watershed (see Figure 4) reduces the effect of this temperature bias. The difference is most pronounced for the cold winter months November to March when melting only takes place in warm events and then generally only on the lower part of the watershed. As the elevation gradient for the lower part is high the temperature bias in the MM5 data will only cause the addition of a narrow elevation band with small area reaching above the melt threshold. Added unrealistic melt will therefore be small. The effects on runoff are therefore much less pronounced than for

Sandá í Þistilfirði and were therefore not noticed during the calibration. This bias in the modelled temperature data should nevertheless have been corrected, but due to time constraints and since this was not noticed until after the calibration of the watershed this was not done.

Table 4. Mean monthly temperature for Austari-Jökulsá (vhm 144), 1961–2005.

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Win**	**Sum**	**Year**
Mean MM5 [C°]	-5.9	-5.7	-5.7	-3.7	-0.8	2.6	5.3	4.8	1.5	-1.5	-4.4	-5.7	-5.7	4.3	-1.5
Mean obs. [C°]	-7.2	-6.8	-6.4	-3.7	0	3.8	5.7	5.1	1.6	-2.2	-5.4	-7.0	-7.0	4.9	-1.8
Difference	1.3	1.1	0.7	0.0	-0.8	-1.2	-0.4	-0.3	-0.1	0.7	1.0	1.3	1.3	-0.6	0.3

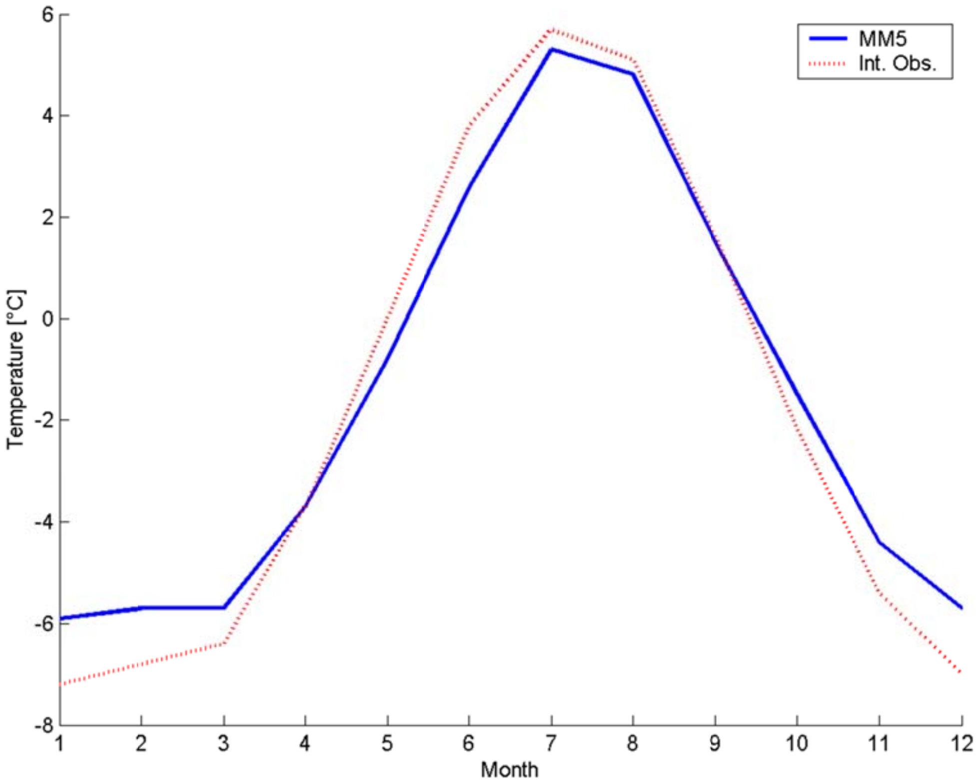

Figure 6. Comparison of mean yearly temperature 1961–2005 for Austari-Jökulsá, (vhm 144); an interpolation of manual observation is shown with a broken red curve and MM5 temperature is shown in blue.

4.3 Information for groundwater modelling

Data requirements for the use of the groundwater module are high. Spatial information about aquifers thickness and hydrological conductivities are needed. Hydrogeology for large areas of Iceland is unknown although hydrogeological maps have been made for areas important for hydropower production. Discrete hydrogeological studies have also been made for several areas (Sigurðsson, 2004; Sævardóttir, 2002a; Sævarsdóttir, 2002b). One of these areas is the watershed of Austari-Jökulsá í Skagafirði (Sigurðsson, 2004). Estimations from geological settings for hydraulic conductivity were therefore available for modelling of groundwater flow. As these estimates are coarse and not based on measurements (Sigurðsson, 2004) these values were only used as a starting value for further calibration. Though the values were calibrated, they are kept inside the range of expected values for the given type of geological formation.

Underground flow through tectonical faults and fissure swarms is important in some locations (Rist, 1990) as mentioned above, therefore the hydraulic conductivity can be highly anisotropic. For those areas, estimations of hydraulic conductivity are divided into two categories: hydraulic conductivity along the uninterrupted bedrock; and hydraulic conductivity along tectonical faults and fissure swarms. The later one is highly directional as the faults and fissure swarms are linear features directed according to the tectonics of the area (Sævarsdóttir, 2002b).

To account for such effects, it is possible to give two different conductivity values in WaSiM, one for each perpendicular horizontal direction in the calculation grid (Schulla & Jasper, 2007). By assuming that there is one main direction in the maximum fissure conductivity the fissure conductivity and rock conductivity can be combined into two bulk conductivity components. One parallel to the direction of maximum fissure conductivity and one perpendicular to direction of maximum fissure conductivity. Following the methodology of Sigurðsson (1985) assuming that fissure conductivity normal to maximum fissure conductivity is neglectable and rock conductivity is isotropic:

$$k_{bp} = k_r + k_f$$

$$k_{bn} = k_r$$

with:

- k_{bp} bulk hydraulic conductivity in direction parallel to maximum fissure conductivity [ms^{-1}]
- k_{bn} bulk hydraulic conductivity in direction normal to maximum fissure conductivity [ms^{-1}]
- k_f hydraulic conductivity along fissures [ms^{-1}]
- k_r hydraulic conductivity along the rock matrix [ms^{-1}]

For large areas of Iceland hydrogeological maps are not available, nor are any other hydrogeological surveys. This is the case for Sandá í Þistilfirði, vhm 26. Geological maps are therefore used along with information on the range of hydraulic conductivity of geological formation to estimate an initial hydraulic conductivity estimate. These values were then calibrated within the range of hydraulic conductivity of the geological formation in question. This method is coarser and does not include the effects of conductivity along fissures.

The thickness of aquifers will along with the hydraulic conductivity determine the transmissivity of the aquifer (Fetter, 2001). Estimation of the thickness of active groundwater flow needs therefore to be estimated. For coarse hydrological modelling these values have commonly been set to 50 or 100 m in Iceland (Sævardóttir, 2002b) or 30 m as done in former modelling work for Austari-Jökulsá. To be consistent with former work done in the area, the surmise of 30 m was kept unchanged. The quality of this estimate will affect the calibration of the hydraulic conductivity, but wrong estimate of the thickness of the active groundwater flow will be compensated by biased estimation of hydraulic conductivity as high or low transmissivity can be reached either by higher or lower hydraulic conductivity or larger or smaller thickness. To minimize this risk, estimations are kept inside the range of hydrological conductivities for the geological formation in questions as mentioned above but this process is inherently uncertain.

Estimation of aquifer thickness for Sandá í Þistilfirði was not available nor any felt data. The surmise of 30 m was used there as for Austari-Jökulsá. For both watersheds the final results of the calibration did not reach the limit of the range for expected hydraulic conductivity indicating that the estimation of 30 m thick aquifer is probably realistic.

5 Results

Comparisons of calculations for the two watersheds, Austari-Jökulsá, vhm 144, and Sandá í Þistilfirði, vhm 26, with and without the groundwater module activated, indicate that comparable or better results are obtained by using the groundwater module although it requires considerable more effort in preparation and calibration. The modelled time series extends from 1961–2005. As MM5 meteorological input data are only available from 1961 results from a spin up model run, based on meteorological data for 1961–1971, are used as initial condition for the 1961–2005 model run. Calibration and validation periods are different between the former calibration without the groundwater module and the new one with the groundwater module. In the former one the period of 1971–1990 is used for calibration (Jónsdóttir, 2008) while the period of 1971–1980 is used for calibration in the later one. The validation period used for all comparisons is 1990–2005. In the former calibration without the groundwater module active the former parameterization of the Hamon evapotranspiration scheme is used and the former glacier melt parameters are used for Austari-Jökulsá while both the evapotranspiration scheme and the glacier melt parameters have been updated in the calculation with the groundwater module active. The results therefore reflect a combination of these changes although the activation of the groundwater module is by far the largest model update.

On Figure 7 and Figure 8 modelled daily discharge, with and without the groundwater module active, is compared to measured discharge on scatter plots. Performance for low flow is improved for both watersheds while similar spread is observed for high flows for both modelling approach. Mean discharge seasonality, 1990–2005, modelled with the groundwater module active captures the measured mean discharge seasonality better than the one modelled without the groundwater module for both watersheds as shown on Figure 9 and Figure 10. Late summer is still captured better without the groundwater module active for Austari-Jökulsá. Modelled discharge values for days where no measurement is available are discarded in the calculation of mean modelled discharge seasonality. Data gaps are much more common during wintertime because of ice interferences. The averages for winter days are therefore not all based on values from each year.

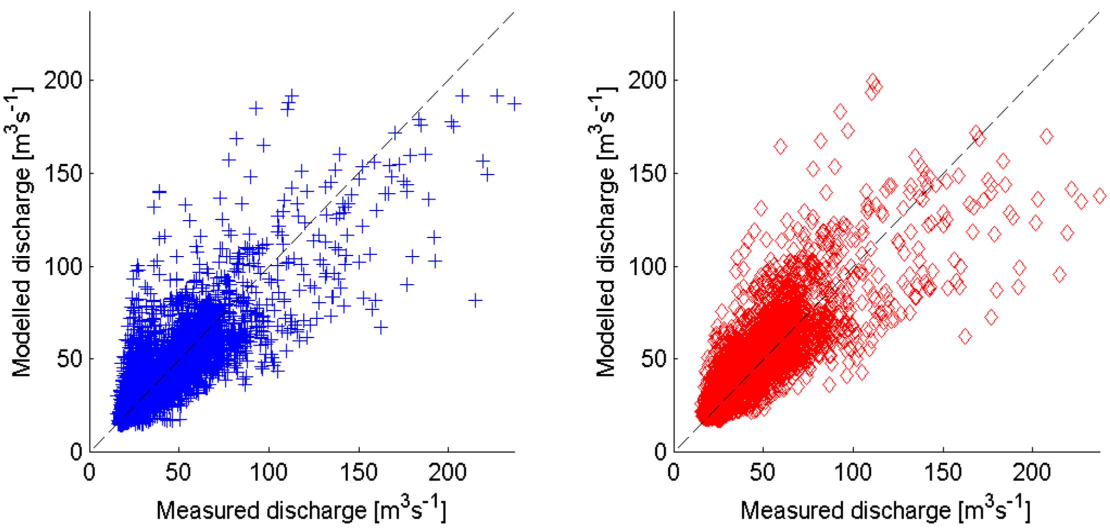

Figure 7. Scatter plots of the modelled and measured daily discharges for Austari-Jökulsá, vhm 144, 1990–2005. Former calibration without the groundwater module active to the left and new calibration with the groundwater module active to the right.

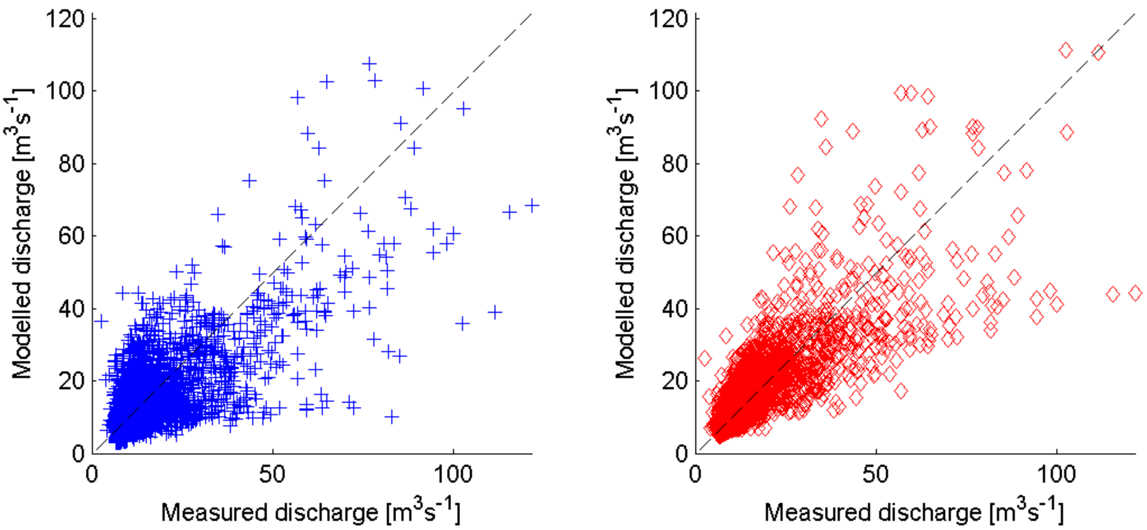

Figure 8. Scatter plots of the modelled and measured daily discharges for Sandá í Þistilfirði, vhm 26, 1990–2005. Former calibration without the groundwater module active to the left and new calibration with the groundwater module active to the right.

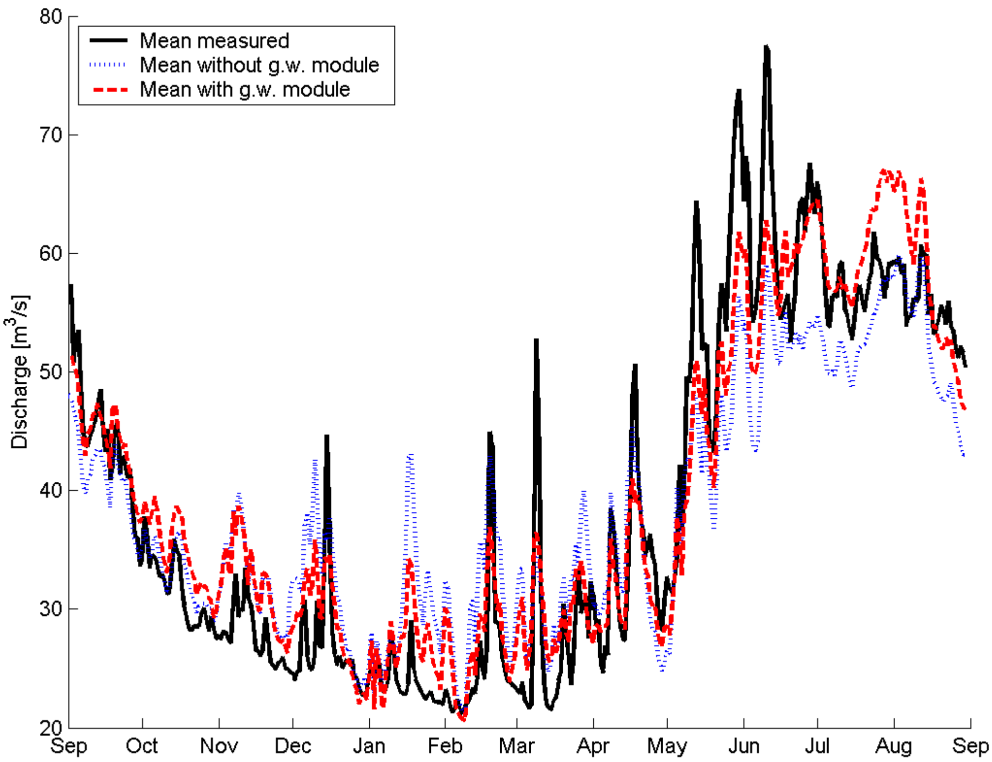

Figure 9. Mean discharge seasonality for Austari-Jökulsá, vhm 144, 1990–2005. Measured, modelled without the groundwater module active and with the groundwater module active. Data for all three curves are only from days with valid measured value.

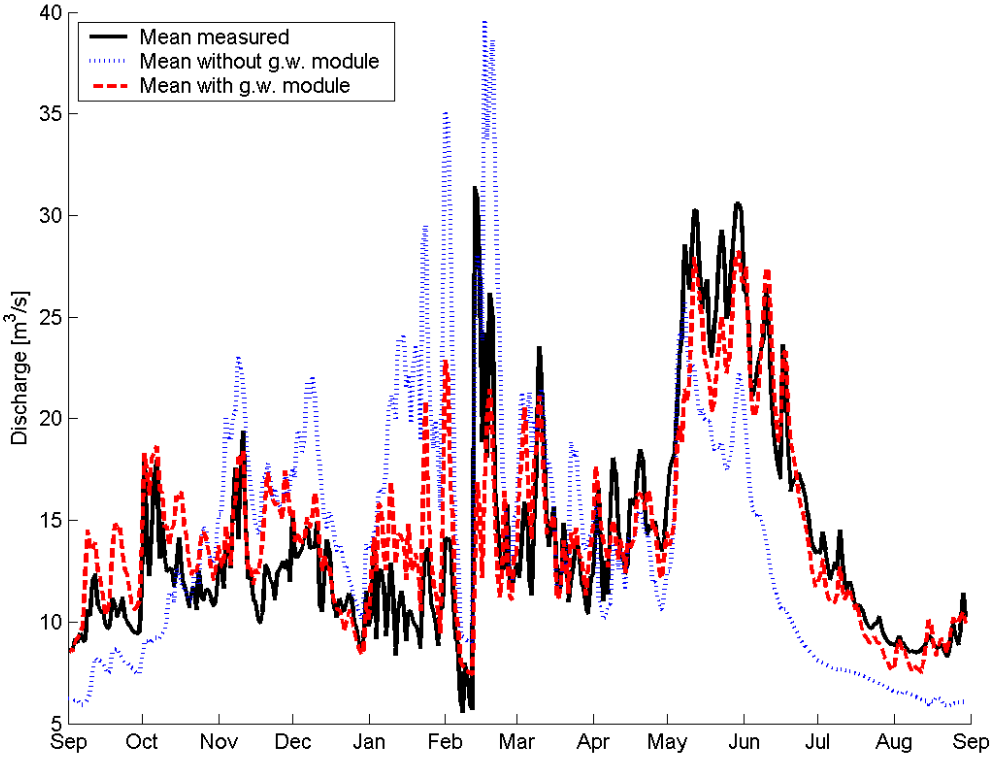

Figure 10. Mean discharge seasonality for Sandá í Þistilfirði, vhm 26, 1990–2005. Measured, modelled without the groundwater module active and with the groundwater module active. Data for all three curves are only from days with valid measured value.

For both watersheds, model performance was found to be improved according both to the Nash–Sutcliffe criterion calculated on daily stream flow and Nash-Sutcliffe criterion calculated on the logarithm transformed daily stream flow, i.e. performances were improved both for flood events and peaks and for low flows as shown in Table 5. The improvement for low flows is considerable larger and can also be noticed on Figure 7 and Figure 8. The representation of inter annual variability was also found to be improved by the activation of the groundwater module and other improvements as seen from values of root mean square error (RMSE) for annual values and lower spread on Figure 11 and Figure 12. There is, however, a systematic overestimation in the modelled yearly discharge for Austari-Jökulsá although the same number of years is still underestimated and overestimated. For Sandá í Þistilfirði, former systematic underestimation is corrected.

Table 5. Recession constants for the surface runoff (k_D) and interflow (k_I) estimated by two different methods and results without and with groundwater module. Nash-Sutcliffe coefficients (R^2) are also presented along with mean percentage error (MPE) and root mean square error (RMSE) for both daily and annual discharge values. Data are from the period 1990–2005.

	k_D (opti-mized) [hours]	**k_D (from hydro-graph) [hours]**	**k_I (opti-mized) [hours]**	**k_I (from hydro-graph) [hours]**	**R^2**	**R^2_{log}**	**MPE annual [%]**	**RMSE annual [m³/s]**	**MPE daily [%]**	**RMSE daily [m³/s]**
Austari-Jökulsá, vhm 144										
Without g.w. module	81	20–50	5000	120–240	0.65	0.66	2.3	4.0	7.9	14.1
With g.w. module	50	20–50	150	120–240	0.68	0.75	5.5	3.7	9.1	13.6
Sandá í Þistilfirði, vhm 26										
Without g.w. module	100	35–80	2000	150–350	0.47	0.18	-10.3	2.3	-1.4	8.5
With g.w. module	50	35–80	300	150–350	0.65	0.69	1.6	1.3	7.1	6.9

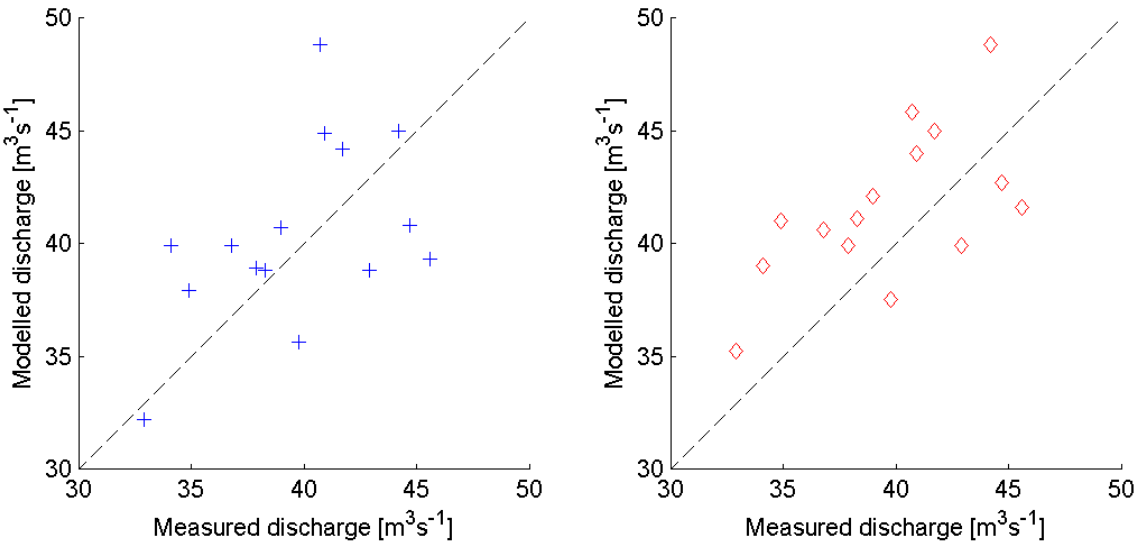

Figure 11. Scatter plots of the modelled and measured annual discharges for Austari-Jökulsá, vhm 144, 1990–2005. Former calibration without the groundwater module active to the left, and new calibration with the groundwater module active to the right.

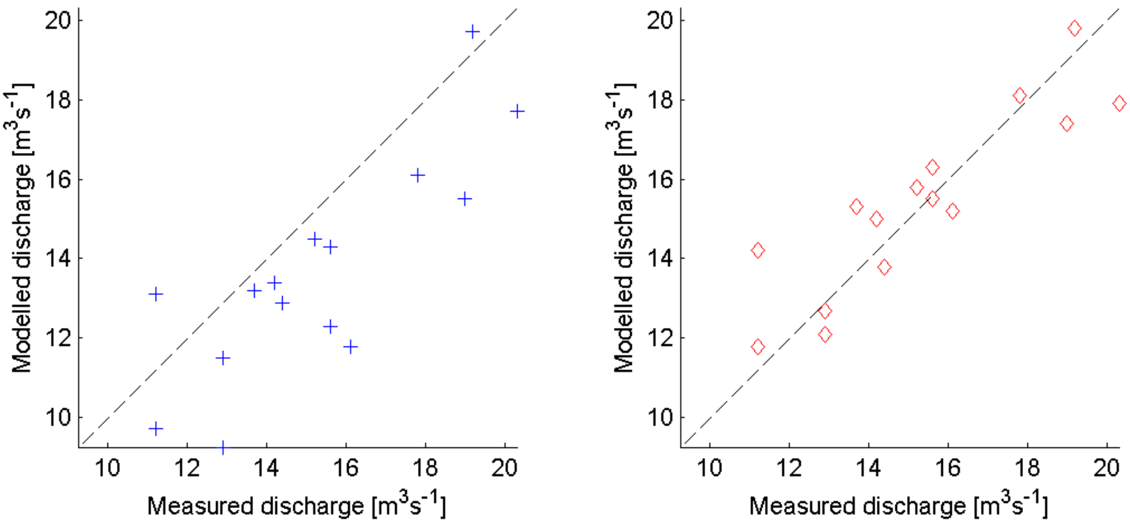

Figure 12. Scatter plots of the modelled and measured annual discharges for Sandá í Þistilfirði, vhm 26, 1990–2005. Former calibration without the groundwater module active to the left, and new calibration with the groundwater module active to the right.

6 Discussion

The model performance has been improved or matched by using a more physically based representation of natural processes such as the groundwater module, as shown in Table 5 and on Figure 7 to Figure 12. Comparison of final calibrated recession constants and recession constants estimated from hydrographs shows that there is much better consistency between recession constants optimized with the groundwater module active and the estimated ones than the ones that are optimized without the groundwater module and the estimated ones. This indicates that the modelling with the groundwater module active provides a better physical description of processes giving greater confidence in the use of the model for future prediction of discharge and other uses of the model.

The Hamon evapotranspiration scheme is a simple empirical formulation building on temperature as an indicator of evapotranspiration. There are other methods available in WaSiM such as Penman-Monteith and Wendling (Schulla & Jasper, 2007). Penman-Monteith should preferable be used as it is the most physically based. It has been tested before in Iceland, but it was abandoned at that time for practical reasons. A bug in the control file was recently discovered, explaining why Penman-Monteith had not been successful.

Evapotranspiration calculation by both Hamon and Penman-Monteith methods are dependent on temperature. The uncorrected temperature bias in the MM5 data for the Austari-Jökulsá will therefore introduce a bias in the evapotranspiration calculations.

Errors in temperature data will in fact affect number of processes in the modelling as abovementioned evapotranspiration calculations, calculations of snowmelt, rain snow thresholds, and glacier melt as discussed below. The shift in the MM5 temperature data should be corrected in further work for Austari-Jökulsá and other catchments as was done for Sandá í Þistilfirði. Generally speaking, it is highly important to have reliable meteorological data for hydrological modelling so as to minimize calibration errors introduced by biased data.

The difficulties met in calibrating Sandá í Þistilfirði that caused suspicion about the temperature data used as input, can be seen on the discharge seasonality modelled without the groundwater module active on Figure 10. Flow during winter time is overestimated because of unrealistic snow melt. The overestimated snow melt during winter time then causes too thin snow pack during spring time and highly underestimated spring flood.

Discharge from a glacier is physically a derived quantity from the melt and a number of other factors like water storage and retention in snow, firn and ice. Water level gauges are in addition normally not located by the glacier margin but far away from the glacier causing even larger attenuation of the glacier melt signal. Mass balance measurements are on the other hand a direct measurement of glacier melt and accumulation. The method of using mass balance data to calibrate the glacier melt parameters should therefore be preferred to the use of discharge data where mass balance data are available. The mass balance measurements do although only represent the melt parameters. Recession constants for linear reservoirs describing water storage and retention in: snow, firn and ice are needed to be calibrated by discharge.

In this study melt parameters were taken from a study on the mass balance of Hofsjökull glacier (Þorsteinsson & Einarsson, 2006) as described above. Temperature data from the weather station at Hveravellir located outside the watershed were used in that study. The inconsistency described above between temperature from the MM5 model and station measurements will affect the transferability of parameters between studies. For the summer, which is the main melting time, the MM5 data are colder than the station measurements leading to underestimation of glacier melting by about 10%. This is a fault that shall be corrected in further work by either shifting MM5 temperature data, using other temperature data or recalibrating the glacier melt parameters.

Although the above discussion indicates that glacier melt might be underestimated, the late summer discharge which is dominated by glacier melt is overestimated for Austari-Jökulsá when the model version based on the groundwater module active is used and when glacier melt parameters are calculated with mass balance measurements, see Figure 9. In the modelling with the groundwater module active, total annual glacier melt for 1990–2005 is increased by 4% compared to the modelling without the groundwater module active. In addition the firn recession constant is 30 h compared to 100 h before. The retardation in the firn is by far the largest retardation in the glacier, an order of magnitude larger than retardation in snow and two orders of magnitude larger than retardation in ice. The recession constant for the firn is therefore dominant in shaping the seasonal discharge from the glacier. The final value of the recession constant for firn as 30 h is low compared to recommended range which is 100–1000 h (Shulla & Jasper, 2007) and values found for other glaciers (Hock, 1998). The annual discharge peak from the glacier in late summer is therefore presumably unnaturally sharp for the modelling of Austari-Jökulsá with the groundwater module active, causing the modelled discharge to overshoot the measured one in late summer. Improved and more thorough calibration of glacier recession constant within the recommended range is hence needed.

As seen in Table 5 and on Figure 7 to Figure 12 there are still considerable possibilities for improving the modelling of measured discharge. The timing and magnitude of spring floods, which is the main hydrological event of the year, is too late and underestimated for Austari-Jökulsá on the average. The winter flow for Sandá í Þistilfirði is likewise overestimated during November, December, and January. Part of this difference can be assigned to inadequate calibration of model parameters. As mentioned above the calibration was done manually, but automatic or semi-automatic calibration is expected to be able to produce better results.

7 Conclusions

The application of the WaSiM hydrological model within Iceland has been improved in number of ways. Groundwater representation has been improved by the activation of the model's groundwater module. Calibration of glacier melt parameters has also been improved by using mass balance measurements instead of river discharge, and better estimates of monthly correction factors in the Hamon evapotranspiration scheme have been found. Although these improvements have been made, further improvements could be considered such as the adoption of a better evapotranspiration scheme, the use of better input meteorological data and the adoption of an automatic or semi-automatic calibration procedure.

8 Acknowledgments

This study was carried out as a part of the projects Climate and Energy Systems (CES), financed by The Nordic Energy Research and the Nordic energy sector, and "Loftslagsbreytingar og áhrif þeirra á orkukerfi og samgöngur" (LOKS) funded by Landsvirkjun (the National Power Company of Iceland), the National Energy Authority, The Icelandic Road Administration and the Icelandic Meteorological Office. We want to thank Dr. Jörg Schulla, one of the authors of the WaSiM model, for various assistance with application of the model. We are also grateful to Philippe Crochet and Tómas Jóhannesson for help during this study.

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