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Veðurstofa
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Application of the program HydroOffice 2010 on river discharge data in Iceland

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Summary:

Rennslisraðir 16 mismunandi vatnsfalla voru greindar með tilliti til þess hvernig dró úr vatnsrennsli frá rennslistoppum að lágstöðu. Við greininguna var vatnafræðiforritið HydroOffice notað. Einkenni aðfallsferlanna voru borin saman við ýmsa staðfræðilega þætti svo sem vatnasvið, úrkomu, berggrunn og höggun. Frumniðurstöður benda til þess að aðferðin sé hentug til að greina rennsliseiginleika mismunandi vatnsfalla út frá umhverfisaðstæðum. Hún gæti því verið liður í að greina vatnsformfræðilega eiginleika vatnshlota samkvæmt lögum um stjórn vatnamála. Forritið er einfalt í notkun og tiltölulega fljótlegt að greina aðfallsferla í öllum þeim vatnsföllum sem mælingar ná til. Áður en það er gert þyrfti að þróa betur tölfræðilegar aðferðir við greiningu á aðfallsferlunum sjálfum.

Keywords: HydroOffice, master recession curves, discharge	**Managing director's signature:** Jórunn Harðardóttir
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Introduction

Extensive information on the characteristics of watersheds and their hydrological regime is included within the nature of river hydrographs. Hydrological regime is one of the main hydromorphological quality elements supporting biological elements in classification of ecological status within the Water Framework Directive (WFD) (European Parliament, Council of the European Union, 2000). The present-day hydrometric network in Iceland includes over 150 river gauges with continuous discharge series. For all those gauges hydrographs exist; hence there is an extensive database available for studies of the hydrological regime concerning quantity and dynamics of water flow. Many tools have been developed to quantify the different information incorporated in hydrographs and one such is the HydroOffice software package (Gregor & Malík, 2010a). Due to the possibility of using hydrograph parameters for quality element classification of surface waters, the Icelandic Meteorological Office decided to evaluate the use of this software package. Although the work was not funded directly through contracts with the Environmental Agency this report is included in the final submission of data/reports for 2013 as it is highly relevant for future work concerning WFD.

In this report the RC-tool of HydroOffice (2010), (Gregor & Malík, 2010a) was used to create master recession curves (MRC) based on discharge series from 16 rivers in Iceland. During the study different methods in the software were tested for the creation of the master recession curves. Furthermore, the capacity to draw conclusions from these master recession curves was evaluated because by studying the features of the curve, conclusions on the geological characteristics of the region can be drawn.

The 16 rivers from which data was analyzed are shown in table 1. The location of the rivers is shown in figure 1.

Table 1. Catchment surface area and period of discharge.

River (no. of water level gauge)	Period of discharge data	A (km^2)
Hvalá, Ófeigsfjörður (vhm 198)	12.8.1956–31.8.2011	178
Dynjandisá, Dynjandi (vhm 19)	12.8.1956–28.2.2012	43
Þverá, Nauteyri (vhm 38)	1.1.1948–31.8.2011	43
Kelduá, Kiðafellstunga (vhm 205)	30.8.2005–1.10.2011	262
Fellsá, Sturluflöt (vhm 206)	16,8.2006–1.9.2009	125
Vatnsdalsá, Forsæludal (vhm 45)	1.9.2005–30.9.2011	487
Fnjóská ofan Árbugsár (vhm 200)	1.9.2005–25.7.2012	1132
Bægisá, Öxnadal (vhm 92)	1.9.2005–19.9.2009	37
Brúará, Dynjandi (vhm 43)	29,9,1961–6.6.2012	596
Skaftá, Skaftárdalur (vhm 70)	1.9.1951–6.5.2012	1469
Tungufljót, Biskupstungum (vhm 68)	1.9.2005–6.6.2012	198
Ytri Rangá, Árbæjarfoss (vhm 59)	27.8.1965–25.4.2011	572
Jökulsá á Fjöllum, Grímsstaðir (vhm 102)	27.8.1965–25.7.2012	5178
Ormarsá á Sléttu (vhm 121)	1.9.2005–25.7.2012	167
Ása Eldvatn, Eystri Ásar (vhm 328)	1.9.2003–31.8.2010	1516
Hólmsá, Gunnarshólmi (vhm 185)	1.6.1972–31.8.2011	221

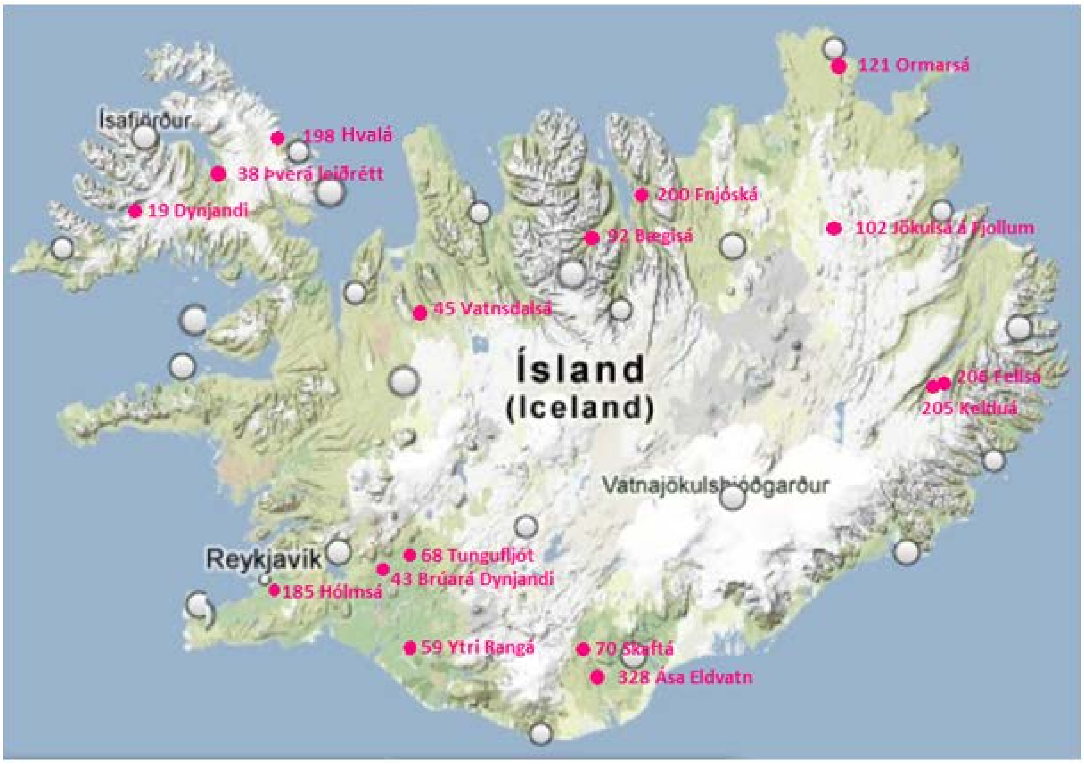

Figure 1. Locations of the rivers studied in this report (I.W. Lugten, 2013 edited from Google Maps).

Chapter 2 of this report gives a short introduction on the hydrogeological characteristics of Iceland. The background of the HydroOffice (2010) is explained in chapter 3, including discussion on the input and the methods used. The MRCs are evaluated in chapter 4, whereas the results of the different methods for analyzing the MRCs in the HydroOffice tool are discussed in chapter 5. Subsequently, the results of the created MRCs in HydroOffice are portrayed in chapter 6. The pros and cons of the tool in HydroOffice are discussed in chapter 7, whereas conclusions and recommendations for further usage of the tool are given in chapter 8.

The work introduced in this report was carried out as a part of Irene W. Lugten's internship at the Icelandic Meteorological Office supervised by Davíð Egilson. Philippe Crochet provided precipitation data for the watersheds. The final version of the report enhanced greatly by reviews of David Finger.

2 Hydrogeological characteristics of Iceland

The map in figure 2 shows the mean annual precipitation in Iceland between 1971 and 2000. The precipitation in the south-east of the country is relatively high and the precipitation in the north of Iceland is relatively low.

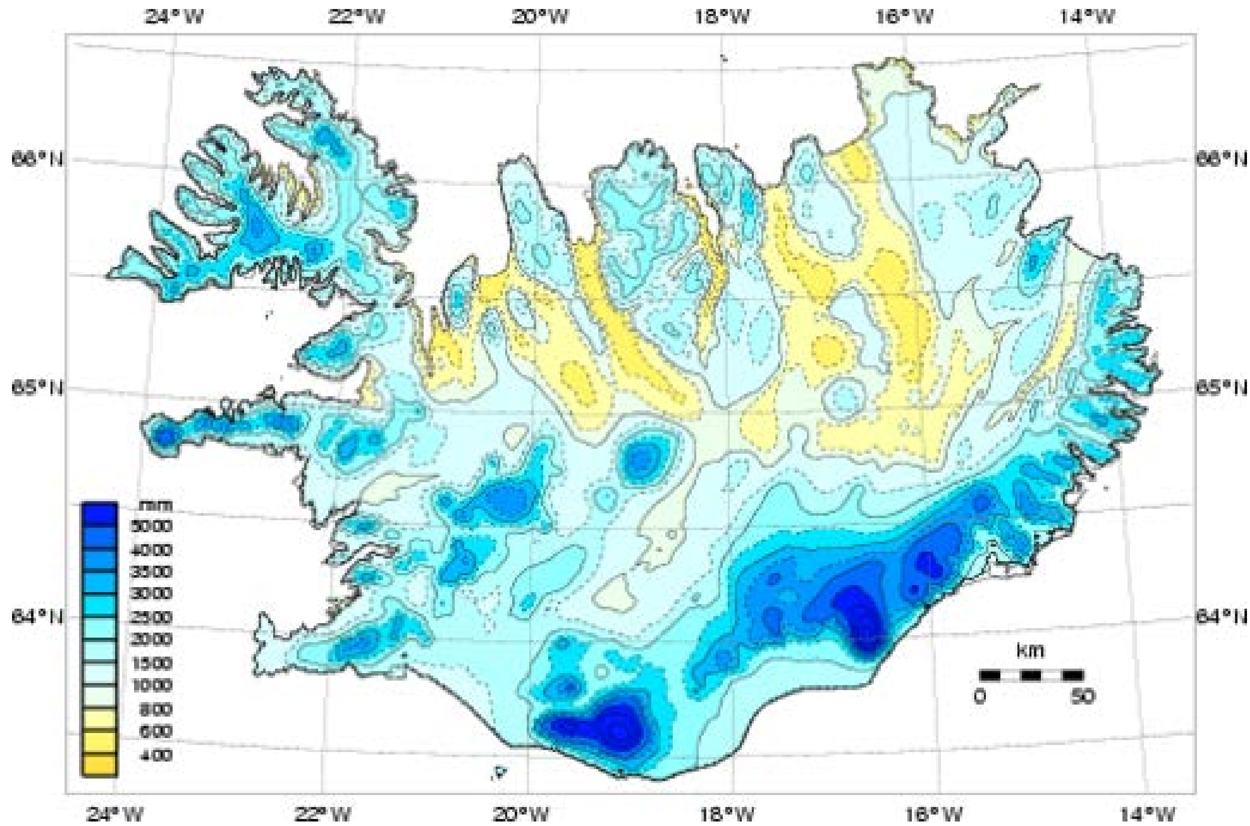

Figure 2. Precipitation in Iceland 1971–2000 (Crochet et al., 2007, Jóhannesson et al, 2007).

According to the hydrological simulation the average runoff in Iceland was 1460 mm/year during the water years 1961–1990 (Jónsdóttir, 2008). This is equivalent to about 4770 m^3/s runoff of the country as a whole. Figure 3 shows the runoff on Iceland per region and per season. The mean runoff from the glaciers is clearly visible in the figure as the borders of the glaciers have the highest runoff values in the country. Furthermore, it illustrates that the south-eastern part of Iceland has the highest runoff values. To the north of the Vatnajökull is an area with relatively low runoff as most of the water flowing from the region is groundwater due to the extremely porous nature of the new bedrock and is hence not represented in the runoff map. The differences in runoff throughout Iceland are most pronounced in summer. In the summer there is a large variation in runoff within the country, as the meltwater from the glaciers and the snowpack contributes significantly to the runoff while in the other parts of Iceland the runoff in summer is relatively low.

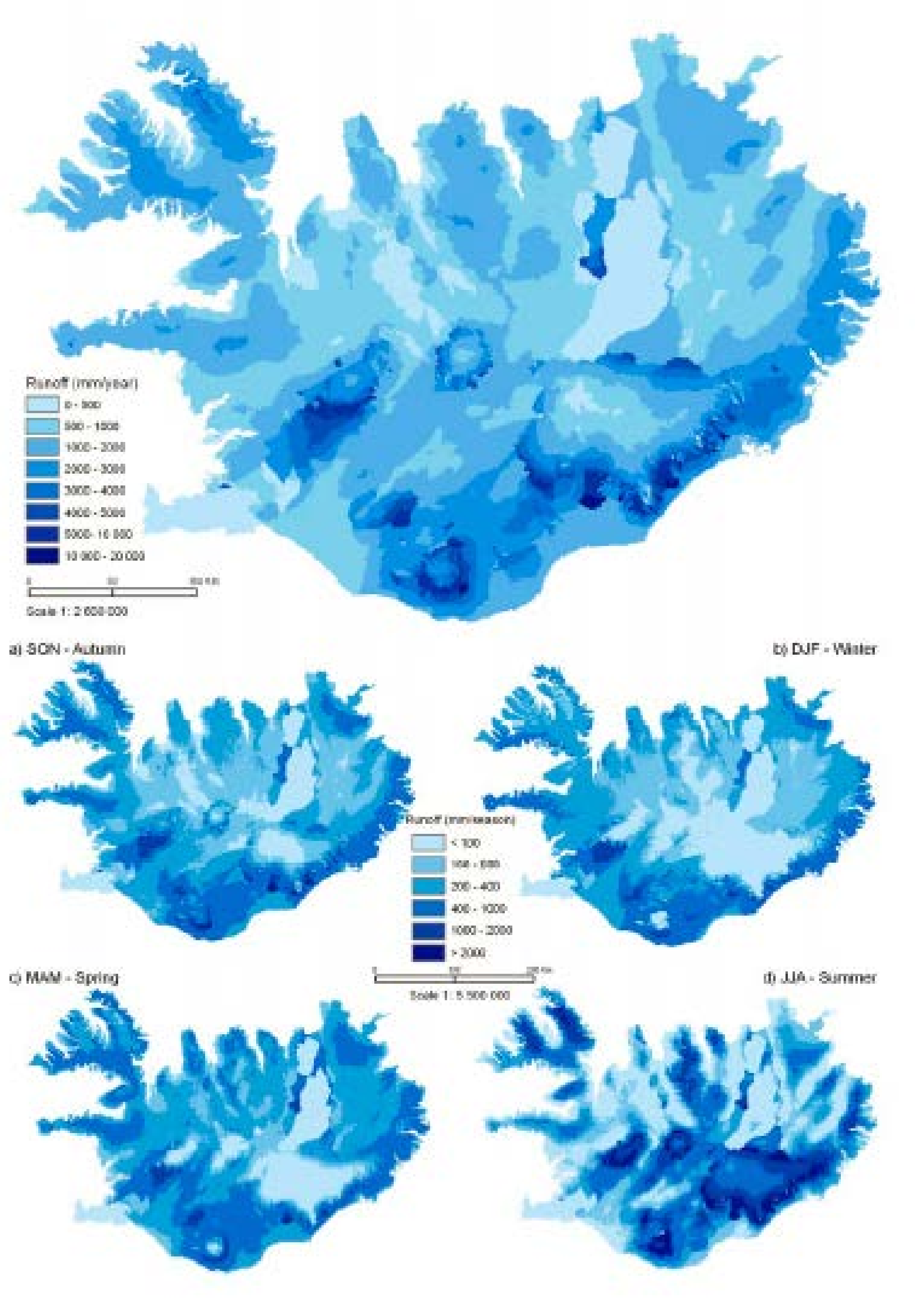

Figure 3. Average runoff in Iceland during the period 1961–1991 (Jóhannesson et al., 2007; Jónsdóttir, 2008).

In Iceland substantial parts of the water flows originates from the glaciers, which cover around 10% of the surface and constitute the headwaters of most major Icelandic rivers. Precipitation, glacier- and snow melt water infiltrate into the underlying soil and rocks and become groundwater. This groundwater emerges to the surface in lower parts of a catchment in spring areas at elevation level from 300–700 m a.s.l. (figure 4). The spring water enters into adjacent rivers forming the largest part of their baseflow.

It has been estimated that groundwater flow in Iceland amounts to about 1000 m^3/s, of which, the contribution from glaciers is around 200–300 m^3/s (Sigurðsson, 1992). The groundwater constitutes about 20% of the total runoff.

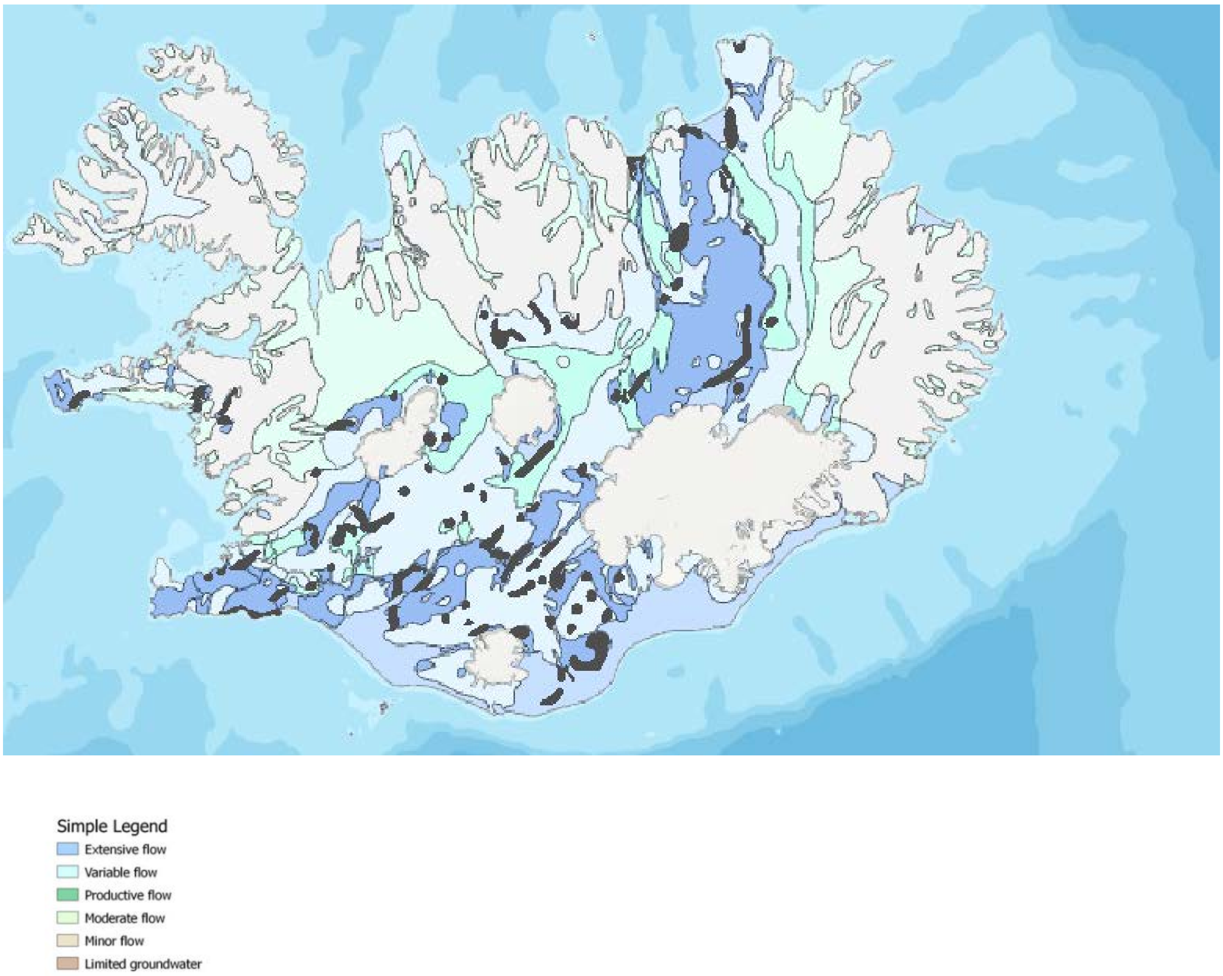

Figure 4. Groundwater bodies in Iceland and main groundwater spring areas (Egilson & Stefánsdóttir, 2014).

Groundwater and rivers in Iceland are used as freshwater supply for the inhabitants, the industries, and potentially for the production of electricity.

The hydrogeological characteristic of the bedrock that is covered by the glaciers varies greatly per region. In general, the young formations of the Late Quaternary to recent are highly permeable, and the older formations of the Tertiary and Early Quaternary are semi- to impermeable. Figure 5 shows the geological map of Iceland. The mid-Atlantic ridge crosses the island diagonally from south-west to north-east, so the bedrock formations are relatively young in this area where the country is drifting apart (figure 5) (Sigurðsson & Einarsson, 1988).

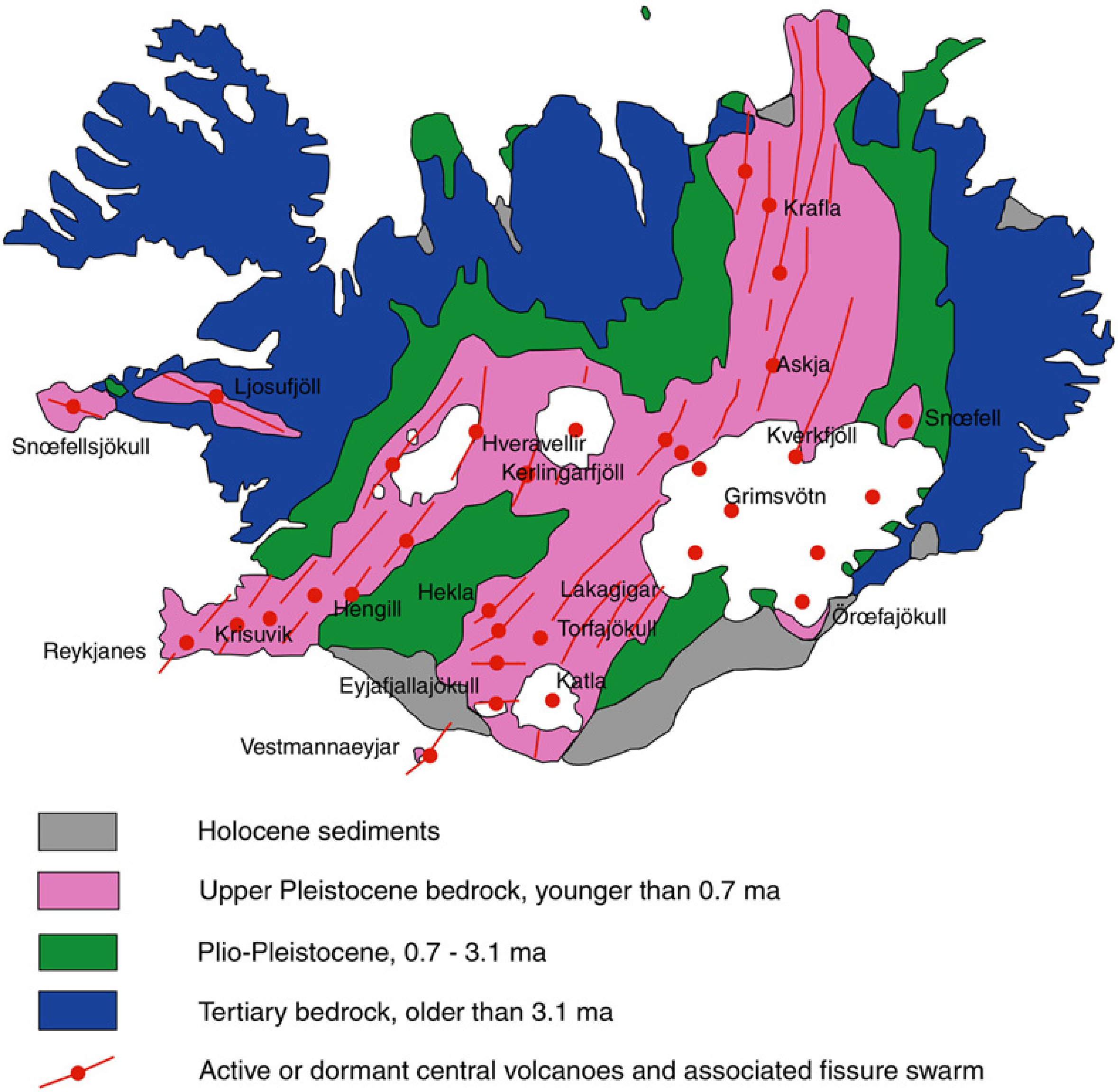

Figure 5. Simplified geological map of Iceland (Weisenberger, 2010).

In the highly permeable Late Quaternary and Holocene formations, there are also open fissures and pervious formations more or less parallel to the volcanic zone through which the water can flow. Therefore, the permeability is even higher in the recent formations, as well as the anisotropy. Consequently, the groundwater component of the rivers is large as is the number of springs, some of which have very high discharge, entering the rivers.

When older Tertiary and Early Quaternary formations have been buried under newer formations, the strata have altered due to heat and pressure. Amygdales and zeolites are formed within cavities and the permeability has decreased. Nevertheless, in some regions such as in Northwestern Iceland the permeability of the Tertiary rocks can still be remarkably high. In the older formations that are semi- to impermeable; the surface runoff is high, and springs are rare (Sigurðsson & Einarsson, 1988). Table 2 introduces an estimation of the permeability of the Icelandic bedrock.

Table 2. Permeability of Icelandic bedrock (Sigurðsson & Sigbjarnarson, 1984).

Lithological type/ rock formation	**Estimated permeability (hydraulic conductivity)**
Postglacial basaltic lava	10^{-3}–10^{-0} m/s
Interglacial basalts, fresh pillow-lavas	10^{-4}–10^{-1} m/s
Subglacial eruptives (hyaloclastites), Plio-Pleistocene rocks Fresh Tertiary basalts	10^{-6}–10^{-2} m/s
Altered Tertiary basalts, altered pyroclastites	10^{-7}–10^{-3} m/s

The large difference in groundwater component of rivers due to differences in permeability of the rocks can be illustrated by comparing rivers from the respective river basins of Langjökull and Hofsjökull. The two glaciers are of approximately the same size (1000 km^2), and the groundwater basins of both glaciers are also more or less of the same size (3000–3500 km^2). The mean discharge from both basins in the largest rivers is 300–350 m^3/s. However, there is a large difference in the groundwater component of the rivers. The groundwater component in the rivers from the basin of Hofsjökull is 50 m^3/s, while the groundwater component in the rivers from Langjökull is 200–250 m^3/s. This is a groundwater component of around 15% and 70% respectively of the total runoff of individual glaciers (Sigurðsson, 1990). This can be explained by the underlying permeability and tectonics at the foundations of the glaciers.

3 The background of HydroOffice 2010

In this chapter characteristics of a hydrograph will be introduced. Subsequently, the genetic algorithm implemented in HydroOffice uses will be explained. Finally, the application of the genetic algorithm in HydroOffice to specific test sites will be described.

3.1 Hydrograph

A hydrograph is a plot of the variation of discharge with respect to time (fig. 6.). In the explanation below the individual segments of the hydrograph are explained as a hydrograph through a rainfall event.

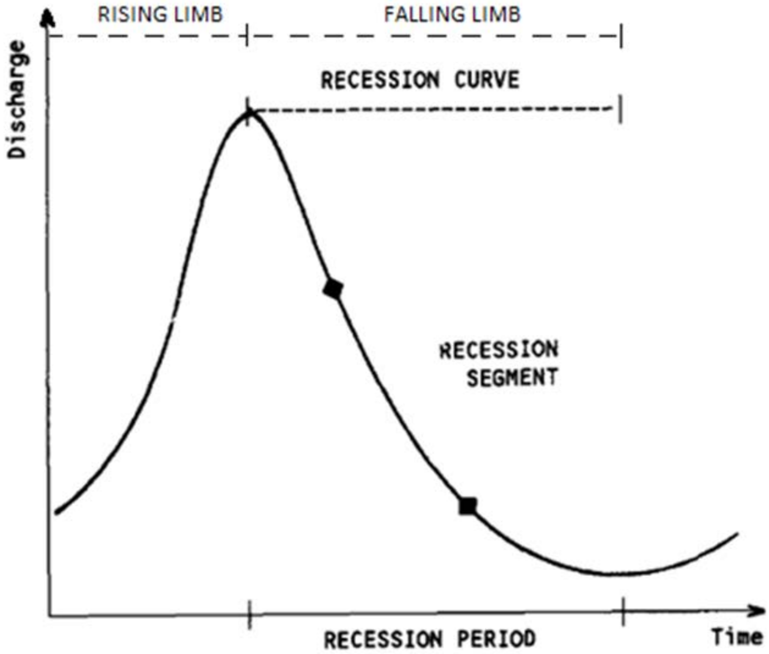

Figure 6. A hydrograph (Toebes & Strang, 1964, edited by I.W. Lugten, 2013).

The rising limb of the hydrograph represents the increased discharge after the start of a rainfall event. The falling limb of the hydrograph is the recession curve, which illustrates the period after the peak of the flood when discharge decreases again (Toebes & Strang, 1964). Usually, the gradient of the recession curve is lower than the gradient of the rising limb, as surface runoff is faster than groundwater depletion, leading to a rapid rise of discharge just after a precipitation event. One way of characterizing the hydrology of watersheds is to separate the surface runoff from the groundwater flow in the hydrograph. This separation is not an exact science as surface runoff and groundwater flow are in many cases interrelated and superimposed. For instance, a specific water package can move both through the groundwater and the surface water before it arrives at the outlet of the watershed. By identifying the recession part of a hydrograph the groundwater component of the upstream watershed can be estimated. Nevertheless, this remains a very rough estimate as the infiltration rate of specific water packages can vary due to the heterogeneity of soil types in natural watersheds. Hence, the exact determination of the groundwater component is difficult to assess and the separation of the hydrograph allows only a rough estimation.

There are various empirical and graphical methods for the separation of the surface runoff and the base flow component of the hydrograph. Some of the graphical methods are shown in figure 7

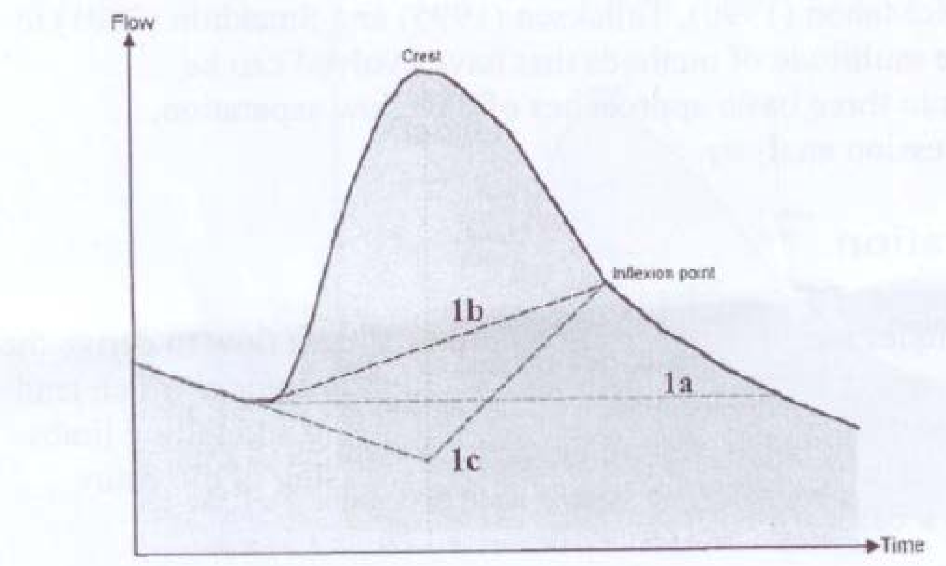

Figure 8.2: Graphical baseflow separation techniques including
(**1a**) constant discharge method
(**1b**) constant slope method and
(**1c**) concave method (Linsley *et al.* 1958)

Figure 7. Graphical baseflow separation (Brodie et al., 2007).

The recession curve contains information on the storage properties and the aquifer characteristics. This information is helpful for water resource planning and water management as it can forecast the water supply for human consumption, irrigation, hydroelectric power plants and wastewater dilution. Thus, it is useful to analyze the recession curves. There are many different methods to analyze recession curves of a catchment area, but all exhibit problems in defining the characteristics of the area. One main reason for this is the heterogeneity of recession segments of the same catchment. Every recession segment represents a different stage in the outflow process. Furthermore, there are seasonal variances, such as snow cover within the catchment, melting rates of snow and ice and vegetation cover, which influence the recession rate (Gregor & Malik, 2012b).

The National Environmental Research Council (NERC) of the United Kingdom developed another base flow separation method which is commonly used is the low flow estimation method (Gustard et al., 1992). The NERC-method determines the base flow by considering a 5-days-period (figure 8) rather than just looking at the flood peak illustrated in figure 7. For this purpose the hydrograph is divided into non-overlapping blocks of five days and the minima for each of these blocks is identified (Q_n).Then the blocks with minima are compared and the base flow line constructed applying method described by Gustard et al., 1992 and an updated version of it (Piggot et al. 2005).

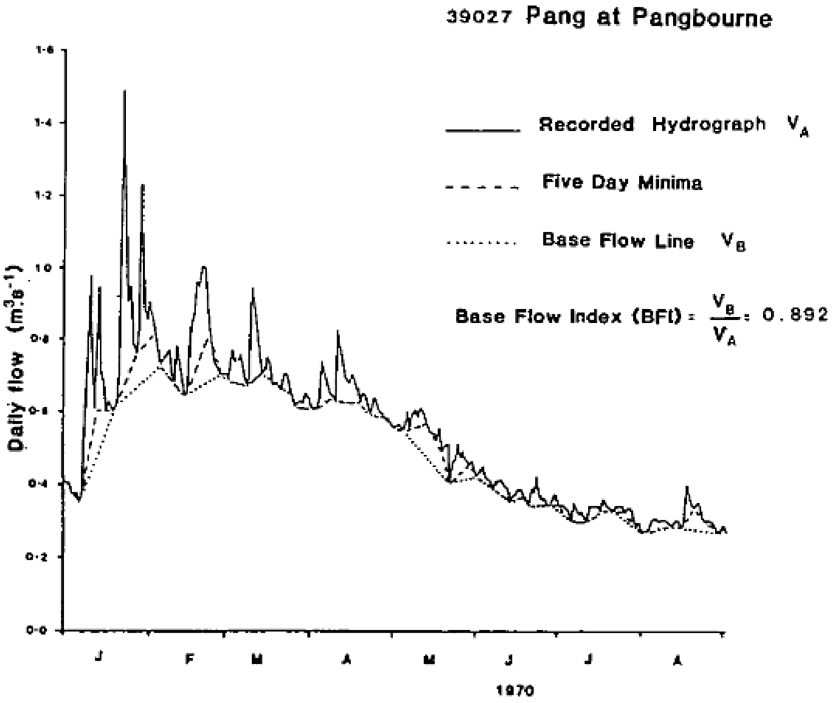

Figure 8. Derivation of the base flow (Gustard et al., 1992).

Although the individual recession curves can be analyzed, the problem is that they describe the process only partially as the hydrological processes in a watershed evolve throughout the seasons, e.g. between summer and winter seasons. Furthermore, the precipitation also varies throughout the year. Thus it is better to compose a master recession curve, which covers all possible solutions. One method of composing the master recession curve is the *matching strip method (MSM)*. In this method, the recession curves are plotted on a semi-logarithmic plot, in order to visualize low discharge rates better. By comparing several recession curves an overlapping sequence can be identified in the semi-logarithmic plot. By averaging the overlapping sequence the master recession curve for a watershed can be generated. This method is very time consuming and subjective. However, automated tools for the creation of the master recession curve have been developed. For example in Matlab by Lamb and Bevev (1997); this tool makes use of a prototype curve. Gregor and Malik developed also a macro in MS Excel, which can analyze complex types of recession curves. However, it needs a sufficient number of recession curves to generate significant results. Because all these methods have their restrictions, Gregor and Malik (2012b) have developed a new method wherein they tried to eliminate the limiting aspects of the former methods.

The recession curve contains static properties which remain the same over time, and dynamic properties that vary over time. The static properties are: geometry, catchment slope and aquifer hydraulic properties. And the dynamic properties are: the degree of structure repletion by water, the rate of water infiltration, rainfall/evaporation and its variation in time and space, and possible anthropogenic influences. These dynamic properties form the greatest obstacle for the creation of master recession curves (Gregor & Malik, 2012b).

3.2 Genetic algorithms

Genetic algorithms are based on Darwin's evolution theory on natural selection and genetic principles. Genetic algorithms are also used for other practices as network optimization and encryption. For a generalization of the master recession curve it is important to take care of the high variability in recession segments. The new method of Gregor and Malik (2012b) uses genetic algorithms to optimize the generation of the master recession curve. Genetic algorithms are widely used in the field of hydrogeology in order to optimize water resources abstraction (Čistý & Bajtek, 2009), and calibrate contamination transport models (Bayer & Finkel, 2004). For the construction of the master recession curves the genetic algorithm was implemented in the freeware executable program HydroOffice (2010) as described by Gregor & Malik (2012a). The next section outlines how the program works.

The genetic algorithm starts with an initial ensemble of random solutions. The solutions consist of data arrays. The solutions are being evaluated and subsequently ranked according to their rating value. Solutions with a high value have a higher probability to be withheld in the next ensemble. Several pairs of solutions are randomly chosen from the ensemble. A random procedure selects solutions favoring those with a higher rating, increasing their chance to be picked. The best rated solutions are used for the next generation. Each pair of the solutions that is selected merge into a new solution, which has the properties of both solutions from the previous generation (Gregor & Malik 2012a).

3.3 Using the genetic algorithms for the creation of the master recession curve

In a first step the data arrays of the recession curves from the hydrograph are selected. These arrays include short and long recessions that cover the whole process of the recession. An example of selected recession curves is illustrated in figure 9. Subsequently, these recession curves are being cut into segments of a chosen period of days (figure 10). The segments are numbered and being put into a table (figure 11). The table consists of 2 columns; the first column contains an integer which defines the segment, and the second column contains the shift on the timeline of the segment. The higher the integer in the first column, the higher the discharge values of the recession segment (Gregor & Malik, 2012b).

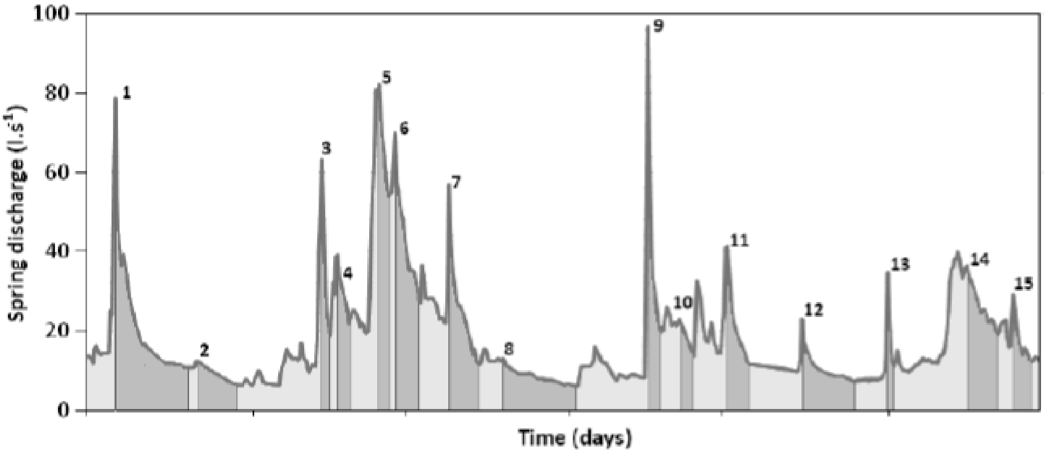

Figure 9. Selection of discharge recessional successions and its sections from discharge time series (Gregor & Malik, 2012b).

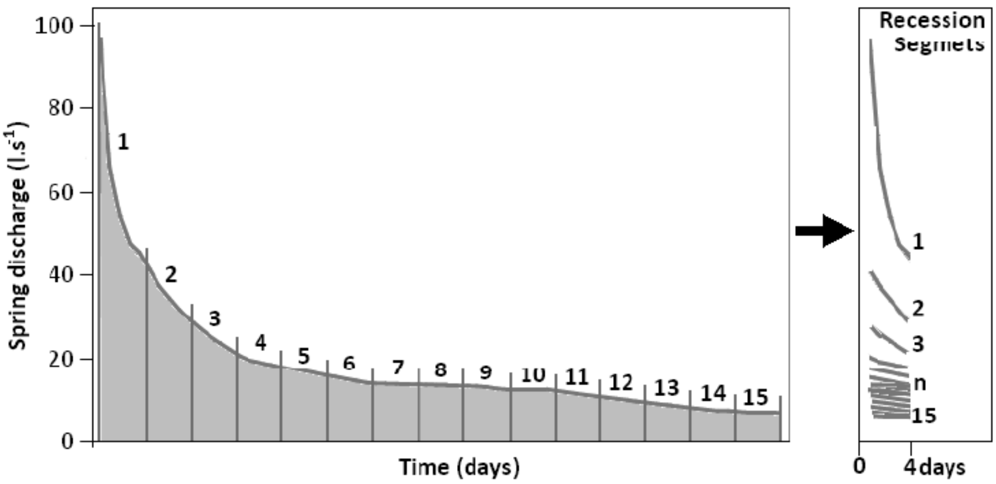

Figure 10. Division of a selected recession into N-day segments (Gregor & Malik, 2012b).

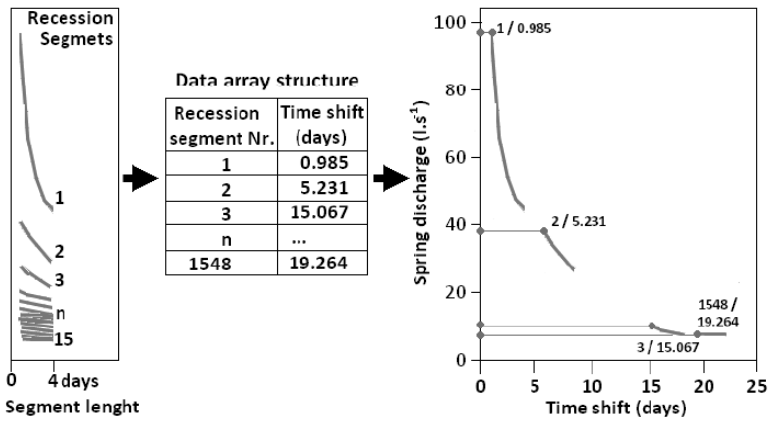

Figure 11. Definition of data structure for each individual solution in the ensemble of solutions (Gregor & Malik, 2012b).

Creation of the first generation of solutions

The first time-shift in the second column of the table is a random shift on the timeline which is done by the program. This is how the first generation of solutions is created. This first shift on the timeline is influenced by the program as in that segments with lower discharge values have a larger range of possible time shift values. Thus this first generation of ensembles has the shape of a recession curve (figure 11).

Creation of the second and next generation of solutions

After the first generation has been created, the program will assess each solution by checking its dispersion area (fig. 12). The smaller the dispersion area, the better the solution. For the next generation this assessment of the solutions is being used. The program picks pairs of solutions that will be used for the next generation. Not all solutions will be used and for this purpose the “roulette selection mechanism” is applied. As stated above, better solutions with lower dispersion areas have a higher chance of being picked for the next generation.

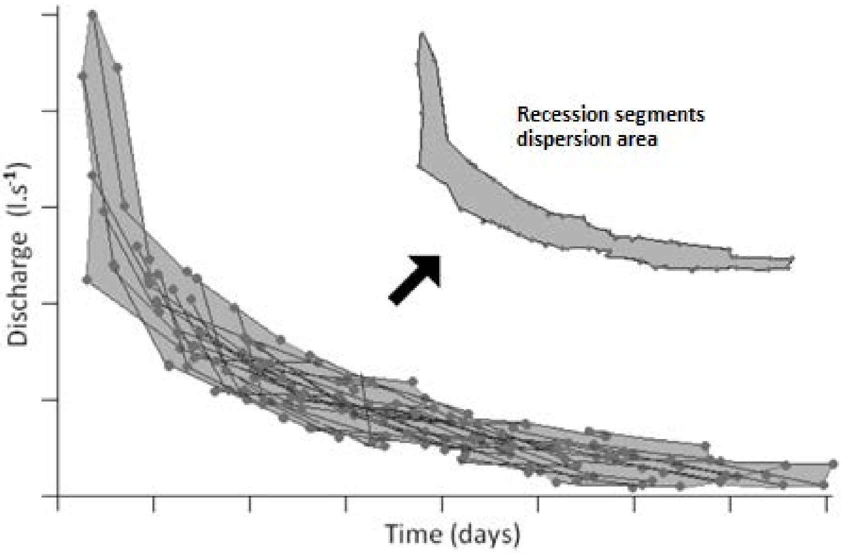

Figure 12. Definition of segments’ dispersion area (Gregor & Malik, 2012b).

From each pairs that was picked, one solution will be made by the crossing process. Gregor and Malik suggest using ‘crossing by averaging’, which means that the time-shifts of each segment are averaged (figure 13).

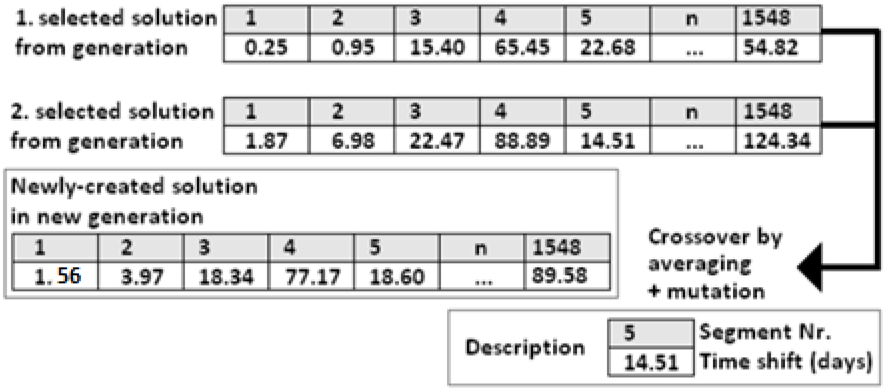

Figure 13. 'Crossing by averaging', used for creating of new solutions (Gregor & Malik, 201b2; edited by I.W.Lugten, 2013).

After averaging the time-shifts of the two segments, the newly created segment is shifted in time in order to avoid the regeneration of the exact same solutions within one generation. For this purpose the segment is either shifted forward or backward in time from the new segment, this depends on the position of the first point of the segment. If this point lies within in the lower half of the dispersion area, the temporal shift is added, and if this point lies in the upper part of the dispersion area, the temporal shift is subtracted (figure 14).

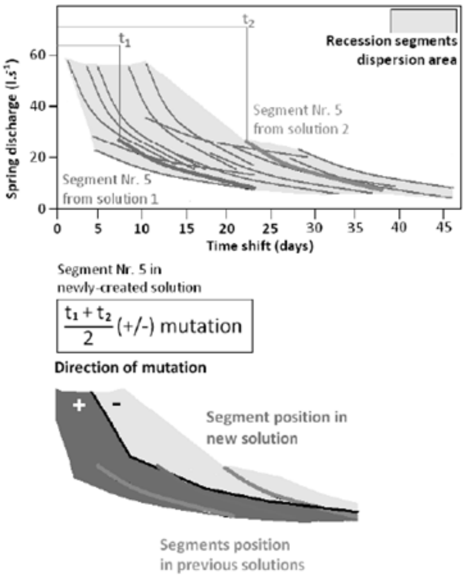

Figure 14. Description of the temporal shift process application on creation of new solutions (Gregor & Malik, 2012b).

The range wherein the value of the temporal shift is being chosen for each generation decreases as the process evolves. If this range would not decrease, it would not be possible to develop a master recession curve as the dispersion area would stay too large. The creation of new generations continues until the number of generations converges to a predefined value.

The recession curve

The falling limb of the recession curve can be described with mathematical formulas. Two well know formulas are from Boussinesq (1904) and Maillet (1905). With these equations the flow at a specific time (Q_t) and the flow at the start of the recession Q_o can be calculated. The Boussinesq equation is of hyperbolic form:

$$Q_t = \frac{Q_0}{[1+\alpha(t-t_0)]^2} \quad \text{(Equation 1)}$$

Wherein:

t = time since the start of the recession for which the flow rate is calculated,
t_0 = time at the beginning of the recession.

The Maillet is an exponential equation that is more commonly used;

$$Q_t = Q_0 * e^{-\alpha(t-t_0)} \quad \text{(Equation 2)}$$

Wherein;

α = a dimensionless parameter representing coefficient of discharge, which depends on the aquifer transmissivity and specific yield.

When the Maillet equation is plotted on a semi log scale, a straight line appears with the coefficient of discharge α being the slope. So the master recession curve is plotted on a semi-logarithmic scale, where discharge (Q) is plotted on the logarithmic y-axis, and time (t) on the natural scale x-axis. When plotted in this way, the recession curve can, at least in theory, be separated into three linear components; namely, surface, unsaturated and saturated flow. These three components correspond to the different flow paths in the catchment that are therefore characterized by specific outflow rates (Kresic & Stevanovich, 2009) (fig. 15). The slope of the curves is decreasing, which reflects the temporal change of the outflow rate. As illustrated in figure 15 the surface runoff reaches the outflow first (V1), subsequently the unsaturated flow (V2) reaches the outflow and finally the saturated flow (V3) with the lowest outflow rate arrives at the outflow.

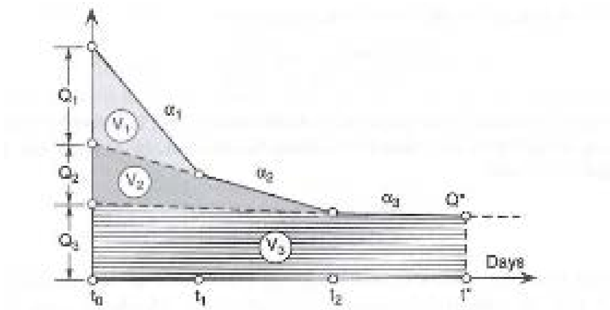

Figure 15. Schematic presentation of the recession with micro regimes of discharge, and the corresponding volumes of discharged water (Kresic & Stevanovich, 2009).

The recession curve can also be modeled as three superimposed linear curves. Then the outflow from the aquifer is assumed to be linear and the linear curves are the linear reservoirs that each have recession constant C_i :

$$Q_t = \sum_{i=1}^{n} Q_{0i} \; e^{-t/C_i} \quad \text{(Equation 3)}$$

Wherein;

C_i = $1/\alpha_i$. (Tallaksen, 1995)

The base flow in the master recession curve can be described as a straight line. The empirical coefficient α can be calculated using the following formula:

$$\alpha = \frac{\log\left(\frac{Q_1}{Q_2}\right)}{t_2 - t_1} \qquad \text{(Equation 4)}$$

α contains information about the above mentioned static properties, i.e. geometry, catchment slope and aquifer hydraulic properties. Rorabough (1964) concluded that

$$\alpha = \frac{T\pi^2}{4SL^2} \qquad \text{(Equation 5)}$$

Where;

T = transmissivity (m^2/s),

S = storage coefficient (-),

L = average distance to the groundwater divide.

It should be kept in mind that regions with a complex geology, as for example karstic regions, their recession curves could show shapes that are different from the ones described above. Accordingly, the theory on recession curves described above is only valid for basins with a simple geology and ideally very homogeneous soil characteristics (Gregor & Malik, 2012b).

4 Method

The runoff of 16 rivers on Iceland was analyzed with the software HydroOffice (2010). The period of the hydrographical data from the discharge of the rivers that was used varies from 6 to 70 years. It contains daily average measurements of the discharge at the station. The hydrographical data were analyzed by HydroOffice (2010) in two different ways:

- Different durations of the segments were used, namely; 3, 5, 7, 10 and 15 days,
- Two different number of generations were used, namely; 50 and 100.

The different durations of the time segments were tested to see whether including the short recession periods would make a difference on the shape of the recession curve. The different numbers of generations were tested to investigate whether using more generations would change the shape of the recession curve.

The analyzes to test the characteristics of the river catchments are;

- The creation of the MRC and fitting in a recession curve,
- The summer and winter data was analyzed separately; for the summer period is 1st of May until 31st of October and the winter period is 1st of November until 30th of April.
- The creation of the master recession curve and making a fit was created to see whether the static characteristics of the catchments would be reflected in the curves.

The runoff characteristics in Iceland during summer and winter period are different. During the winter period most of the highlands are covered by snow and the soil is usually frozen at the surface, preventing the precipitation and the melted water to percolate into the soil. In light of that the summer and winter periods were tested separately to see whether the changing conditions of the water and the soil, namely ice and frost, these seasons would result in a different hydrograph. Furthermore, the method was applied to 16 rivers in order to investigate how these differences are comparable for different rivers in various geological areas.

After the analysis of the hydrographical data of all the rivers, the fits with the master recession curves were analyzed to see if typical geological characteristics could be associated to specific rivers. For this purpose the rivers were divided into five groups that have approximately the same geological characteristics.

Finally, the advantages and disadvantages of the HydroOffice tool will be discussed and possible ways to use the outcomes for further analysis will be suggested.

5 Analysis of the software

In this chapter the use of different periods for the segments creating the MRC is analyzed first. Then the numbers of generations in the evolution of the MRC will be analyzed.

5.1 Analysis of the differences between the different time-steps

Appendix I shows the different MRCs for different time-steps of each river. In figures 16–18 the differences between the various periods of the MRCs of Dynjandi, Tungufljót and Fellsá are illustrated. The id no. (vhm xxx) is the unique number of the water level gauge.

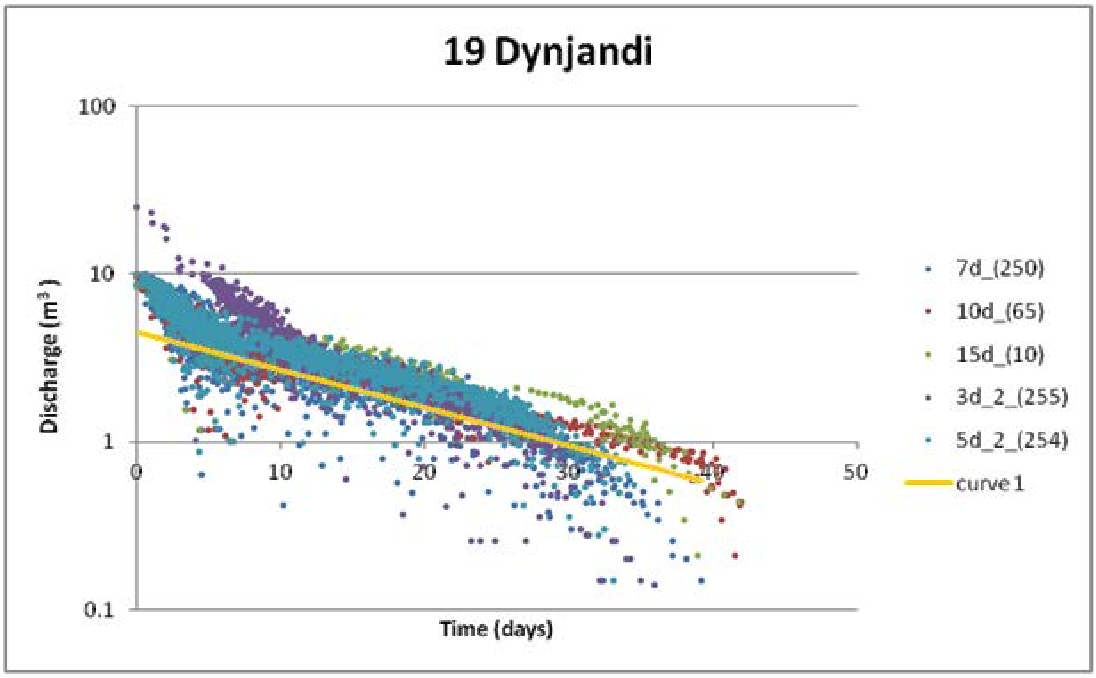

Figure 16. Dynjandisá, Dynjandi (vhm 19).

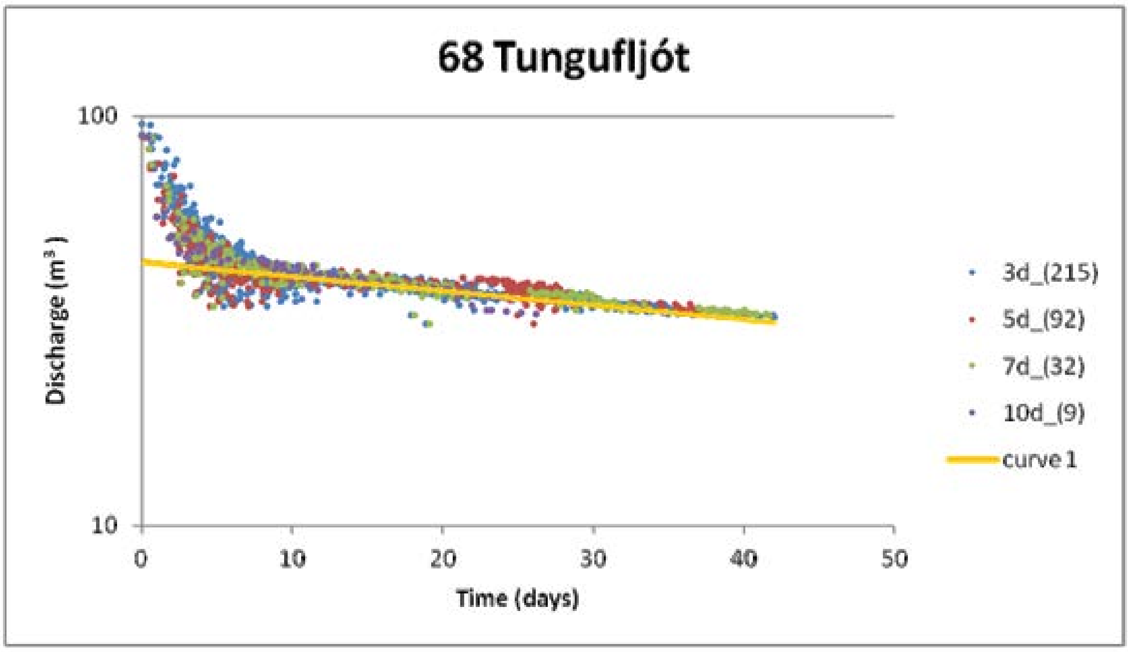

Figure 17. Tungufljót, Biskupstungum (vhm 68).

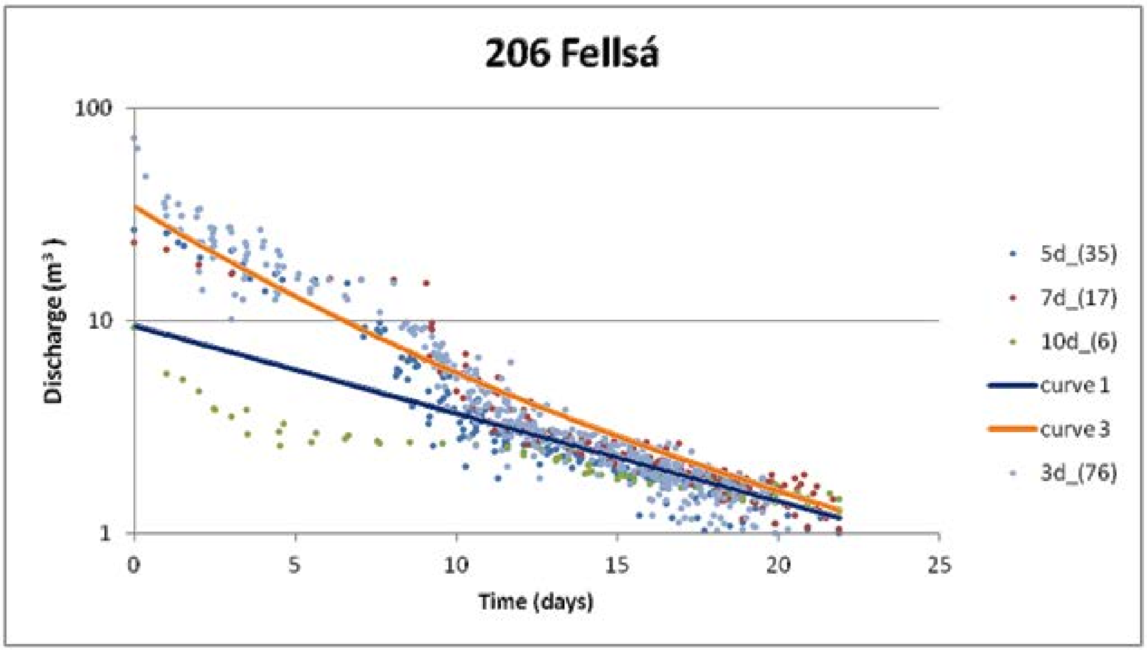

Figure 18. Fellsá, Sturluflöt (vhm 206).

The short segments show that the MRCs of the 3-day segments capture in most of the rivers the highest discharges. The graphs of Dynjandisá (figure 16), Tungufljót (figure 17) and Fellsá (figure 18) show these characteristics best of all the catchments analyzed in this research. In the graph of Tungufljót (figure 17) the MRC of 3-day segments have the highest discharge levels. The graphs of Dynjandisá (figure 16) and Fellsá (figure 18) illustrate very clear that at the start of the recessions the discharges are larger for the 3-day segments. This is caused by the fact that the extreme peaks are short ‘rainfall triggered floods’; especially in small catchments, and therefore these events are only captured in the short segments.

Dynjandi, Tungufljót and Fellsá belong to the smaller catchments that we analyzed, so this is probably the reason that these rivers reveal these phenomena best.

In all rivers, in particular the longer segments, low discharge rates are more frequent than high discharges (see Tungufljót and Fellsá). In Tungufljót there are a small number of discharge rates in the 10-day segments during the peak of the MRC. The low discharge events are related to the base flow and in some cases also to snowmelt. Accordingly they last longer than the rainfall triggered floods. So for longer periods, there are relatively more low discharge segments.

For short time segments there are on average more dots in the scatter plots. This is caused by the fact that for the short recessions more time periods can be selected. The total time is divided by a smaller number than the longer time segments. This can be seen in the graphs of Dynjandi, Tungufljót and Fellsá. The legend shows the number of segments between brackets; for Tungufljót this is the clearest. The number of 3-days segments is 215, while for 5-days it is 92, for 7-days it is 32 and for 10-days it is 9.

Preliminary Conclusion

The short segments cover most parts of the recessions and therefore they are better suited for our purpose. However, the longer segments have a better coverage of the tail of the master recession curve. Accordingly, it is also helpful to use the 5-day segments to cover the tail. This is especially the case for small catchments.

5.2 Analysis of different number of generations

Appendix II shows for six of the rivers the MRC’s created by 50 generations and the MRC’s created by 100 generations. Below in figs (19–21) only Hólmsá, Ormarsá and Fnjóská are shown.

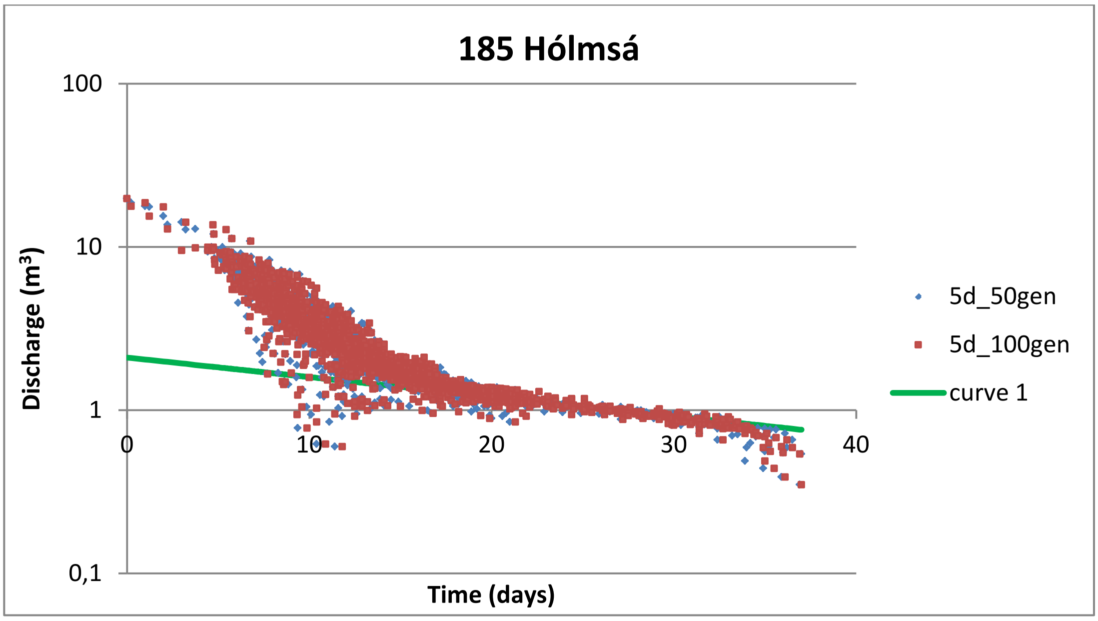

Figure 19. Hólmsá Gunnarshólmi (vhm 185).

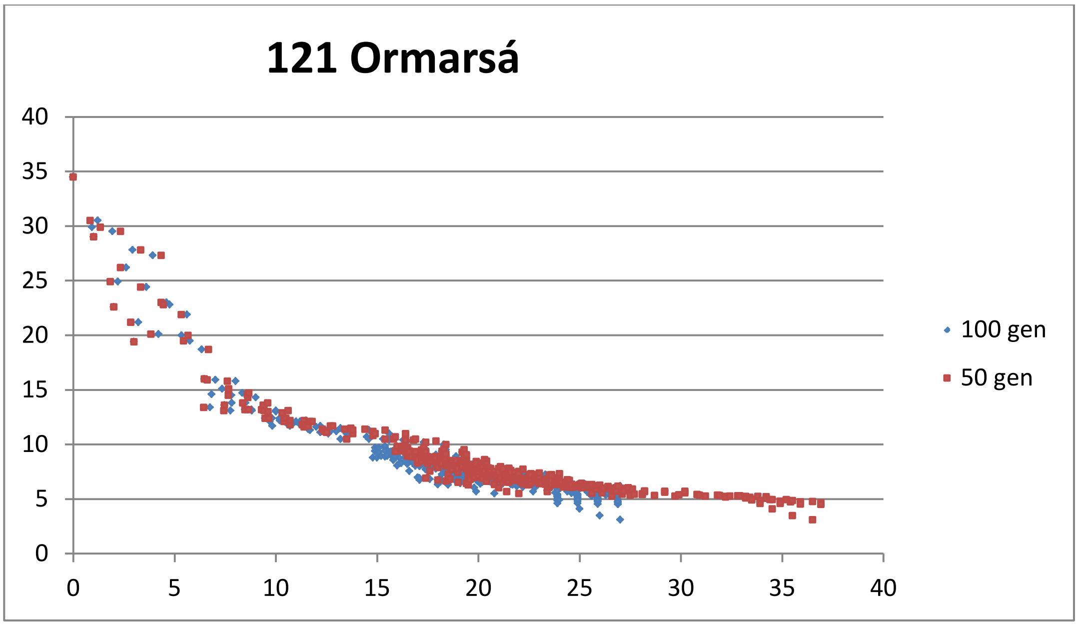

Figure 20. Ormarsá á Sléttu (vhm 121).

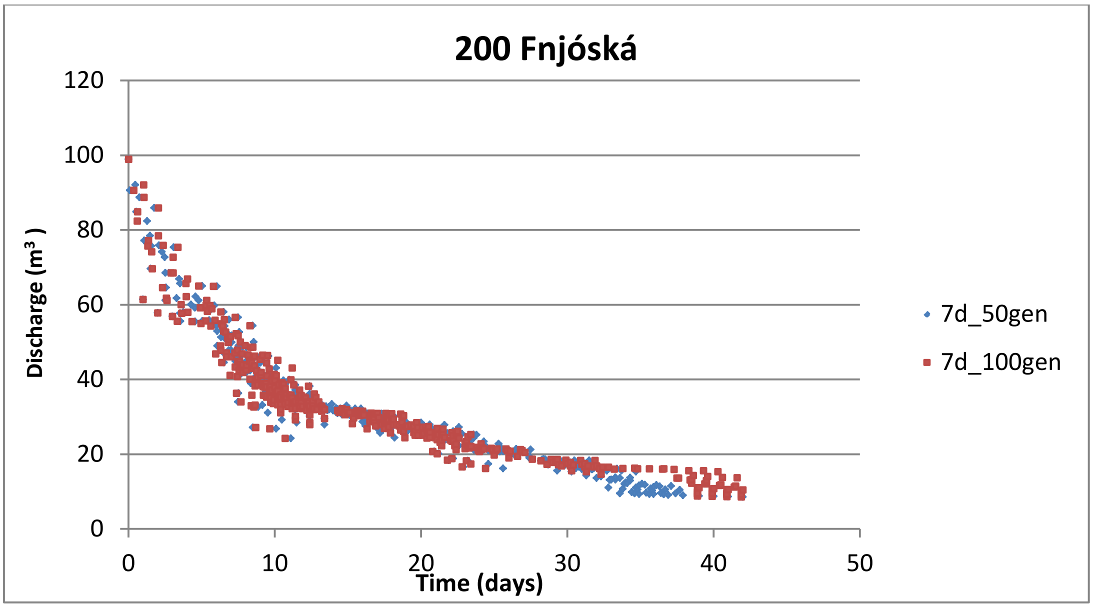

Figure 21. Fnjóská (vhm 200).

From these comparisons of the MRCs with different numbers of generations can be seen that there are no large differences between the outcomes of 50 and 100 generations. Approximately the same MRCs are created for 50 and 100 generations.

Conclusion

There is no need to extend the number of generations over 50.

6 Analysis of the created MRCs

In this chapter the MRCs that were created will first be analyzed, then the differences between summer and winter and finally the discharge of the rivers after 25 years will be discussed to see whether something can be concluded on the characteristics of the catchments.

6.1 Analysis of the created MRCs

The master recession curves that were created with the different segments lengths were used to draw an average recession by hand. All the recessions can be found in Appendix I. The recessions for Hólmsá, Kelduá and Ása Eldvatn, (Figs 22–24) are shown below. In each figure “curve 3” shows the fitted curve for the total recession, “curve 1” reflects to the base flow component of the recession. The slope of this linear component is α. This α contains information on the transmissivity, the storage coefficient and the distance to the groundwater divide (Rorabough, 1964), as explained in section 3.3.

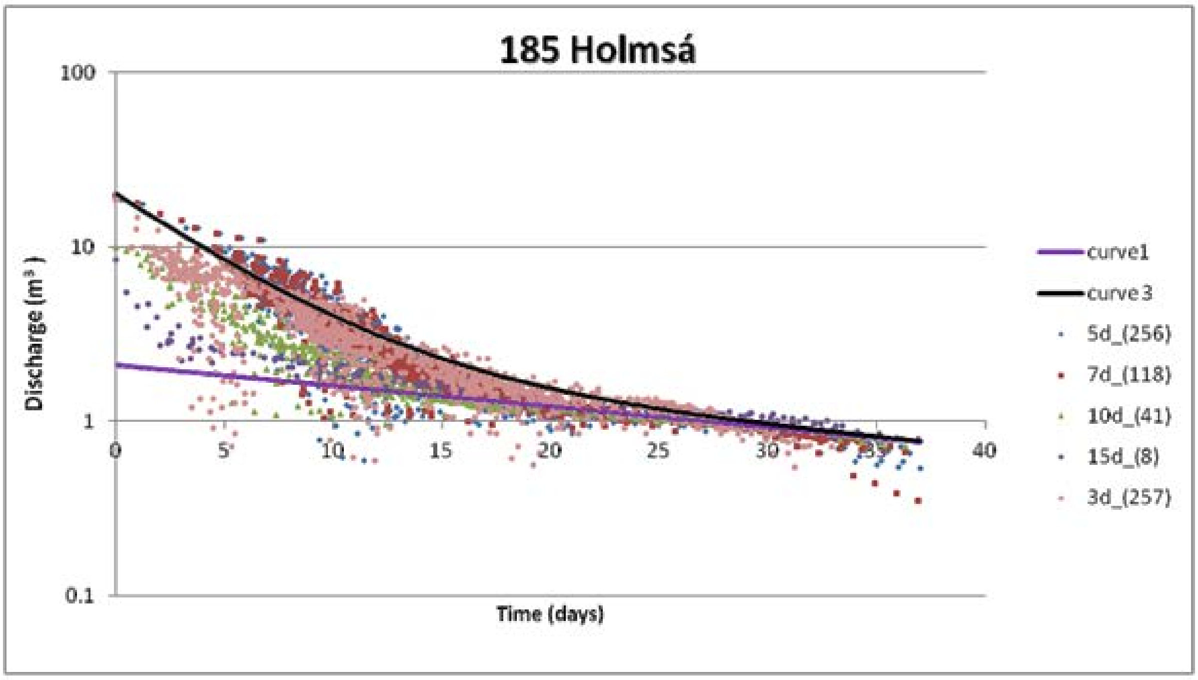

Figure 22. Hólmsá, Gunnarshólmi. (vhm 185)

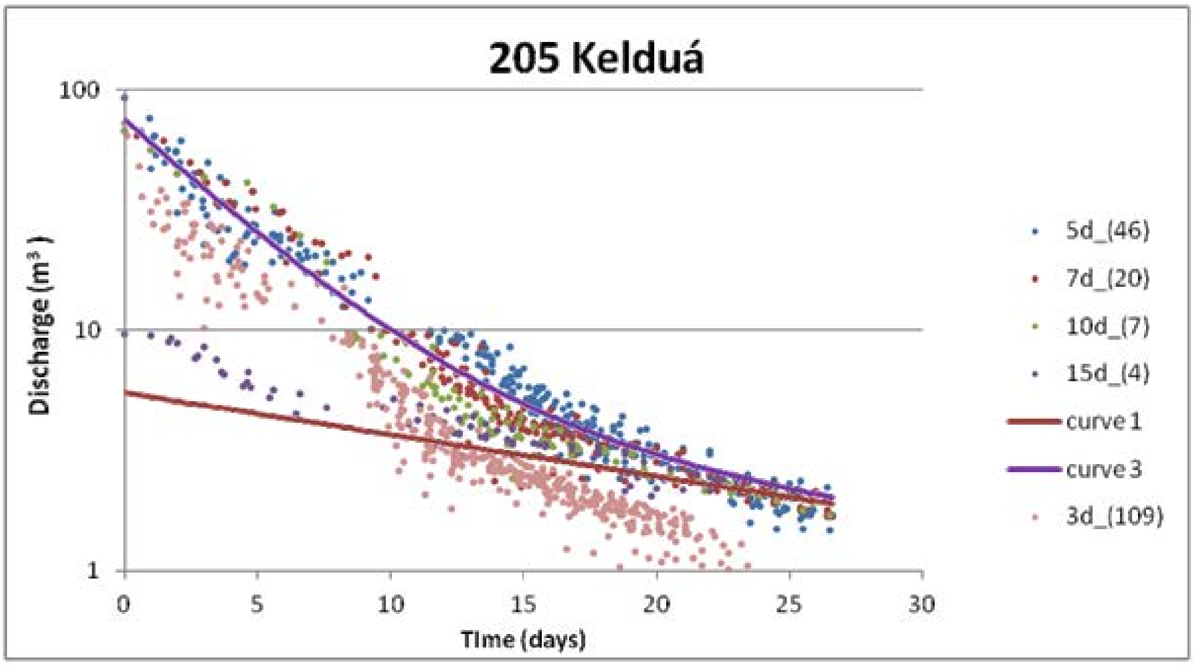

Figure 23. Kelduá, Kiðafellstunga (vhm 205).

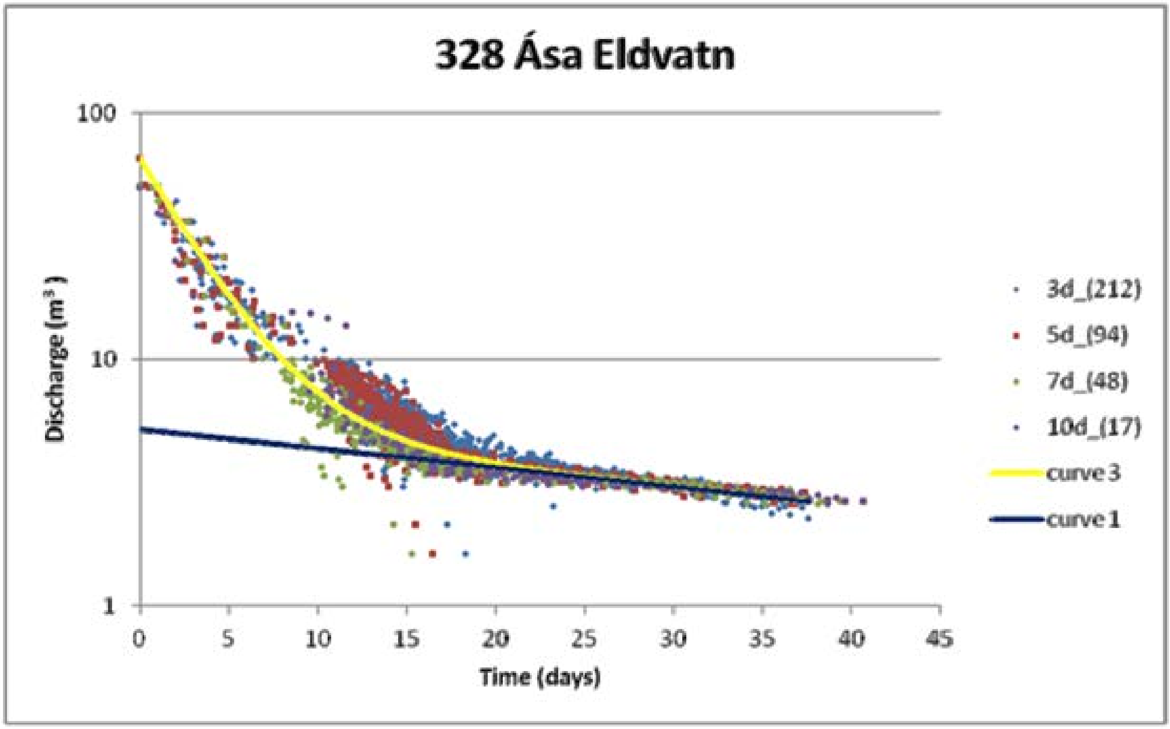

Figure 24. Ása Eldvatn, Eystri Ásar (vhm 328).

The generic equations for the base flow that were found for each catchment (curve 1) are presented in table 3 Furthermore, the discharge after 25 days (Q_{25}) and the initial volume (Q_0) is given. The discharge after 25 days (Q_{25}) was calculated by setting t=25 in the generic equation for the base flow.

The initial volume of the groundwater component was calculated using the equation of Moore (1992):

$$Q_0 / \lambda = V_o$$

Wherein;

Q_0 = This value is found by filling in 0 for 't' in the generic equation,

λ = This lamba is per second. It is calculated by converting the λ from the generic equation (per day) into lambda per second.

Table 3. Fitted curves, discharge after 25 days and the initial volume of the rivers.

River	**Fitted curve (t in days)** $Q_t = \alpha * e^{-\lambda*t}$	Q_{25} **(m^3/s)**	**Initial volume of the groundwater component (m^3) (V_0)**	λ **(day)**
Hvalá vhm 198	-	-	-	-
Dynjandisá vhm 19	$Q_t = 4,5 * e^{-0,052*t}$	1,23	7.476.923	0,052
Þverá vhm 38	$Q_t = 3 * e^{-0,065*t}$	0,59	3.987.692	0,065
Kelduá vhm 205	$Q_t = 5,5 * e^{-0,04 * t}$	2,02	11.880.000	0,04
Fellsá vhm 206	$Q_t = 9,5 * e^{-0,095*t}$	1,07	8.640.000	0,095
Vatnsdalsá vhm 45	$Q_t = 7 * e^{-0,044 * t}$	2,33	13.745.454	0,044
Fnjóská vhm 200	$Q_t = 54 * e^{-0,04 * t}$	19,1	116.640.000	0,04
Bægisá vhm 92	$Q_t = 1,25 * e^{-0,025*t}$	0,70	4.320.000	0,025
Brúará, Dynjandi vhm 43	$Q_t = 85 * e^{-0,015 * t}$	58,4	489.600.000	0,015
Skaftá vhm 70	$Q_t = 270 * e^{-0,045*t}$	87,7	518.400.000	0,045
Tungufljót vhm 68	$Q_t = 44 * e^{-0,008*t}$	36,0	475.200.000	0,008
Ytri Rangá vhm 59	$Q_t = 52 * e^{-0,0065 * t}$	44,2	691.200.000	0,0065
Jökulsá á Fjöllum vhm 102	$Q_t = 230 * e^{-0,025*t}$	123	794.880.000	0,025
Ormarsá vhm 121	$Qt = 10 * e^{-0,02*t}$	6,07	43.200.000	0,02
Ása Eldvatn vhm 328	$Q_t = 5,2 * e^{-0,018 * t}$	8,16	24.960.000	0,018
Hólmsá vhm 185	$Q_t = 2,1 * e^{-0,0275*t}$	1,06	6.597.818	0,0275

6.2 Analysis of the differences between the summer and winter period

The summer period is from the 1st of May until the 31st of October and the winter period is from the 1st of November until the 30th of April. The differences in graphs for the various rivers will now be discussed.

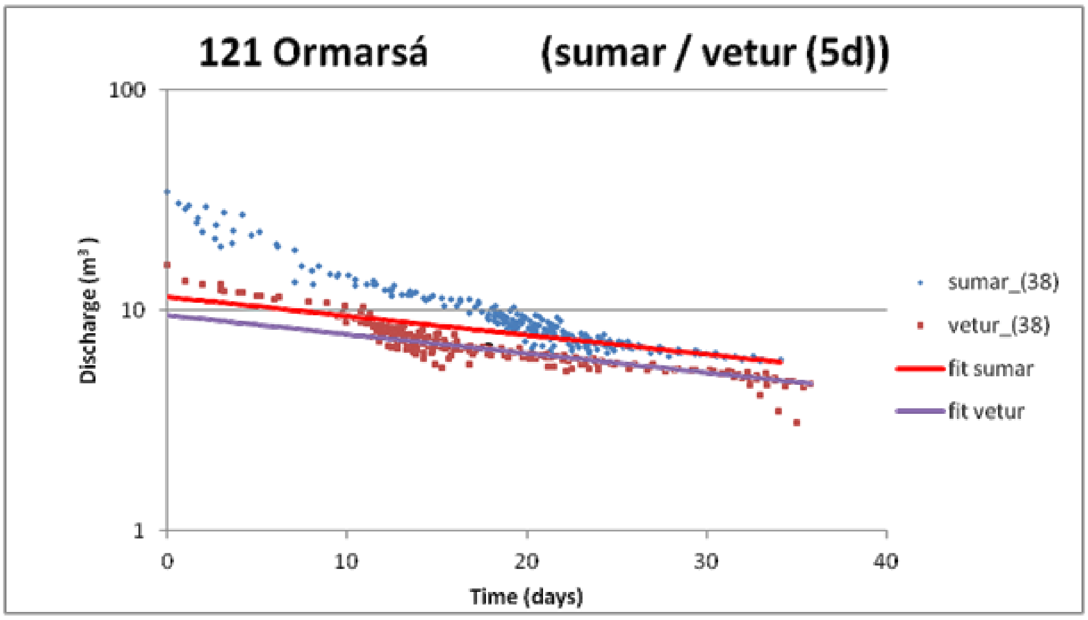

Figure 25. Ormarsá á Sléttu (vhm 121). Summer and winter discharge.

Due to snow and ice melt summer discharge is higher than winter discharge.

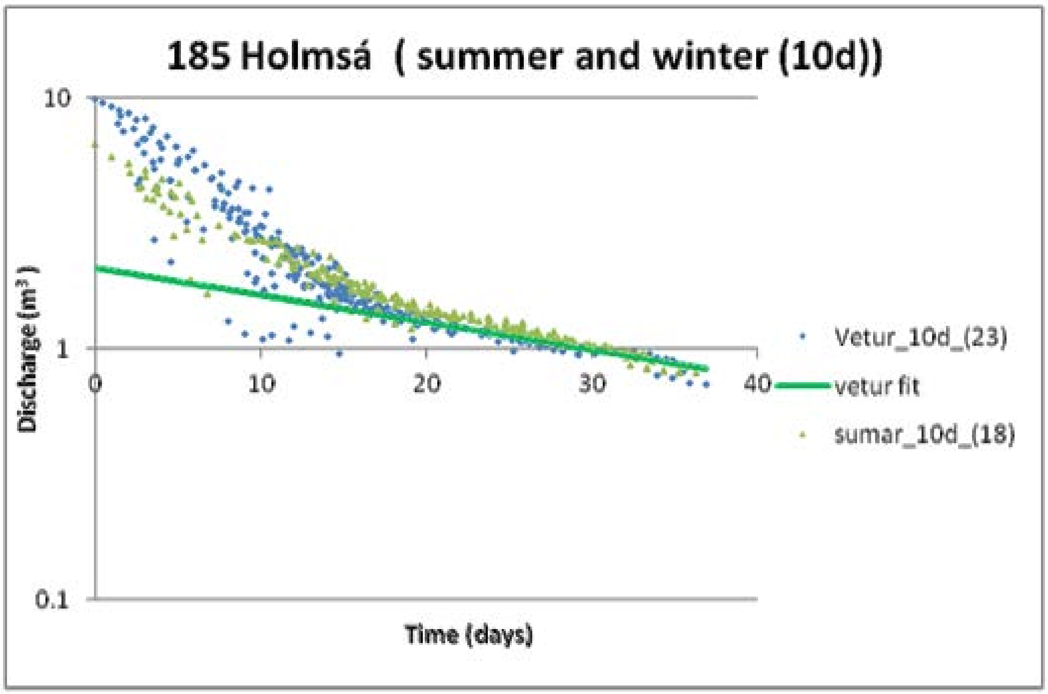

Figure 26. Hólmsá Gunnarshólmi (vhm 185). Summer and winter discharge.

Hólmsá shows more surface flow in winter. This could be due to the frozen ground, because then the water cannot infiltrate into the soil, as explained earlier in the report.

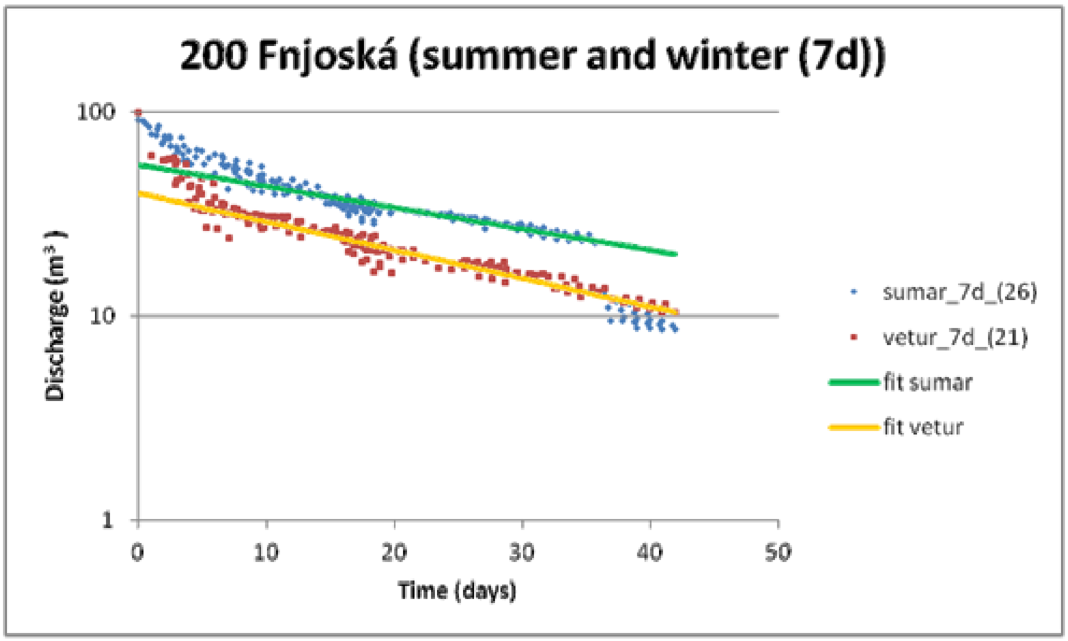

Figure 27. Fnjóská (vhm 200). Summer and winter discharge.

Fnjóská shows more discharge in summer, which is most likely due to more meltwater in this period.

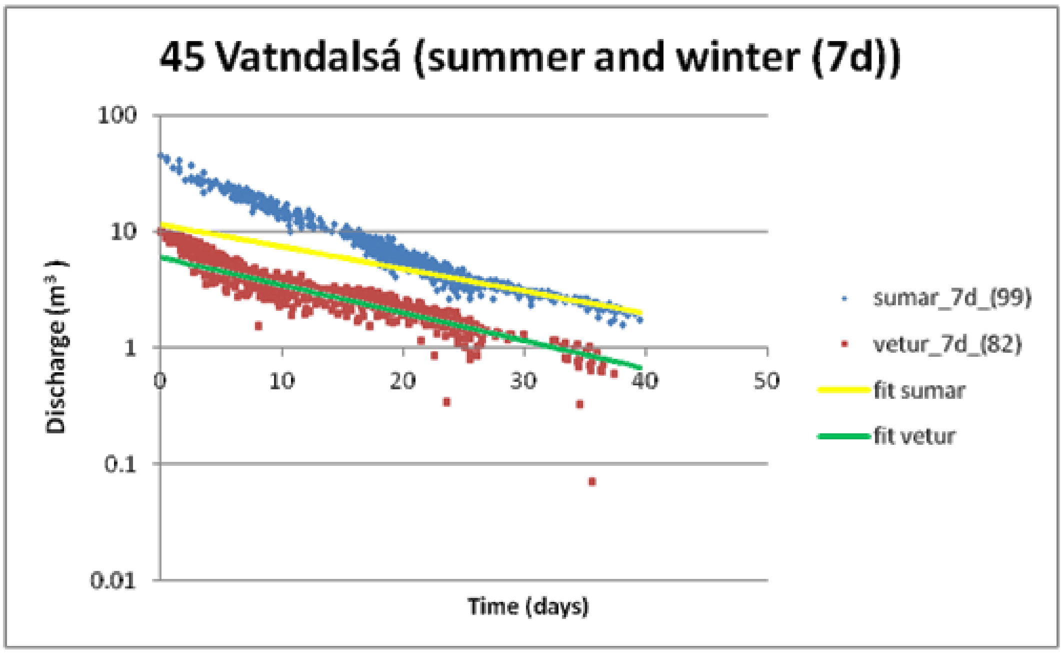

Figure 28. Vatnsdalsá (vhm 45). Summer and winter discharge.

In Vatnsdalsá the direct runoff is delayed because the water is first retained in several heath lakes. Rainfall runoff water flows from lake to lake and wetlands towards the river. If the surface soil is saturated water can also flow directly over the surface into the river. In the summer there is more water in the river due to more melt water from the snow and glaciers.

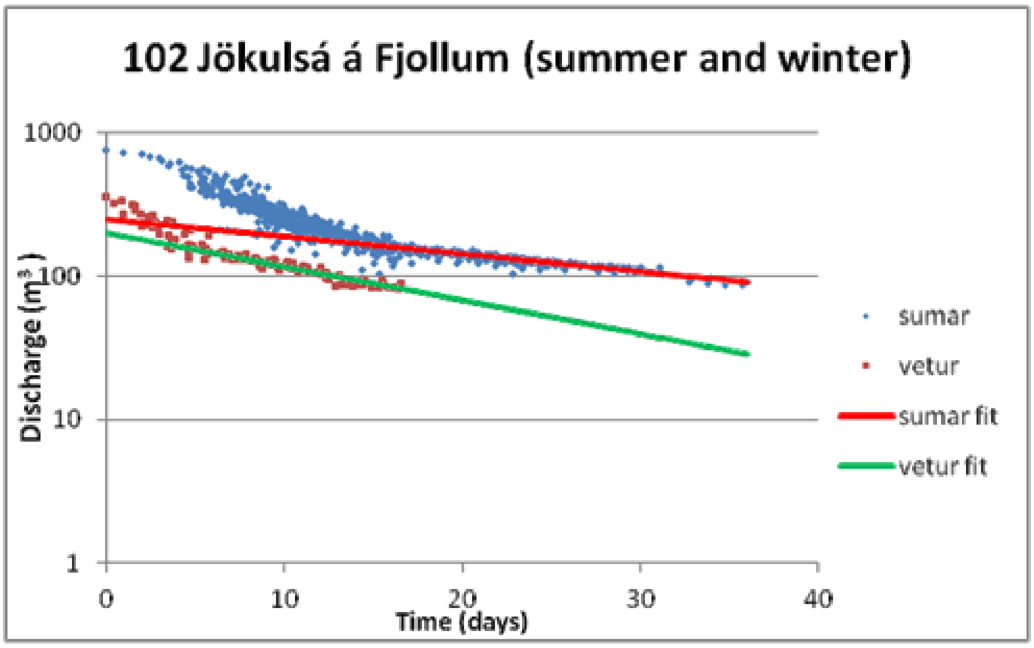

Figure 29. Jökulsá á Fjöllum at Grímsstaðir (vhm102). Summer and winter discharge.

In Jökulsá á Fjöllum at Grímsstaðir there is also the usual relation between summer and winter. In the summer there is more discharge in this river due to snow and ice melt.

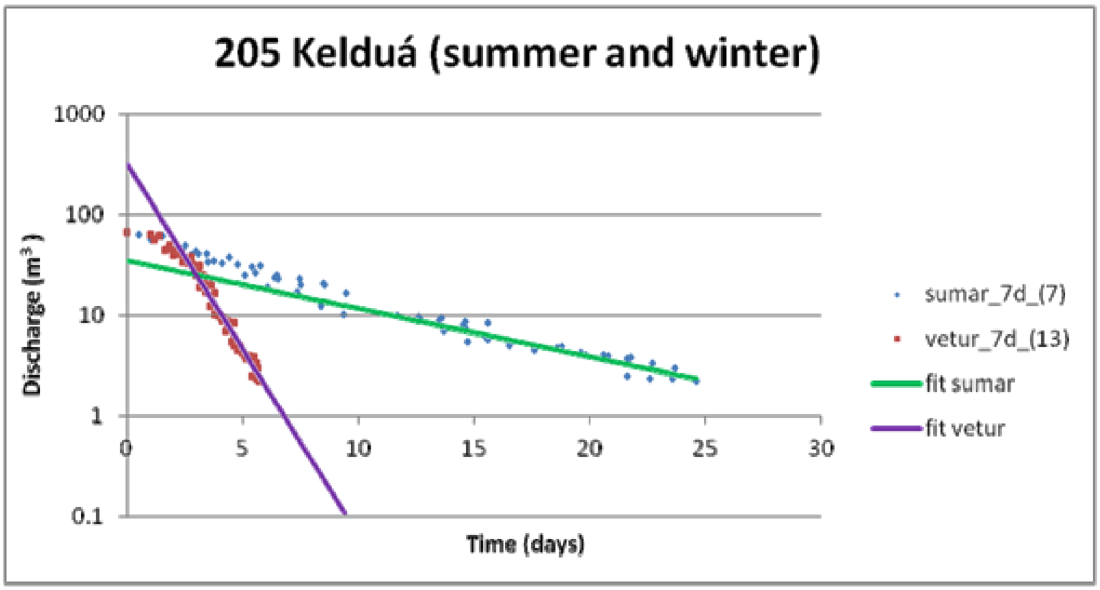

Figure 30. Kelduá, Kiðafellstunga (vhm 205). Summer and winter discharge.

Kelduá dries out in winter; there is only sometimes discharge from meltwater from sudden heat periods. In summer there is meltwater in this river. It is a typical direct surface runoff river.

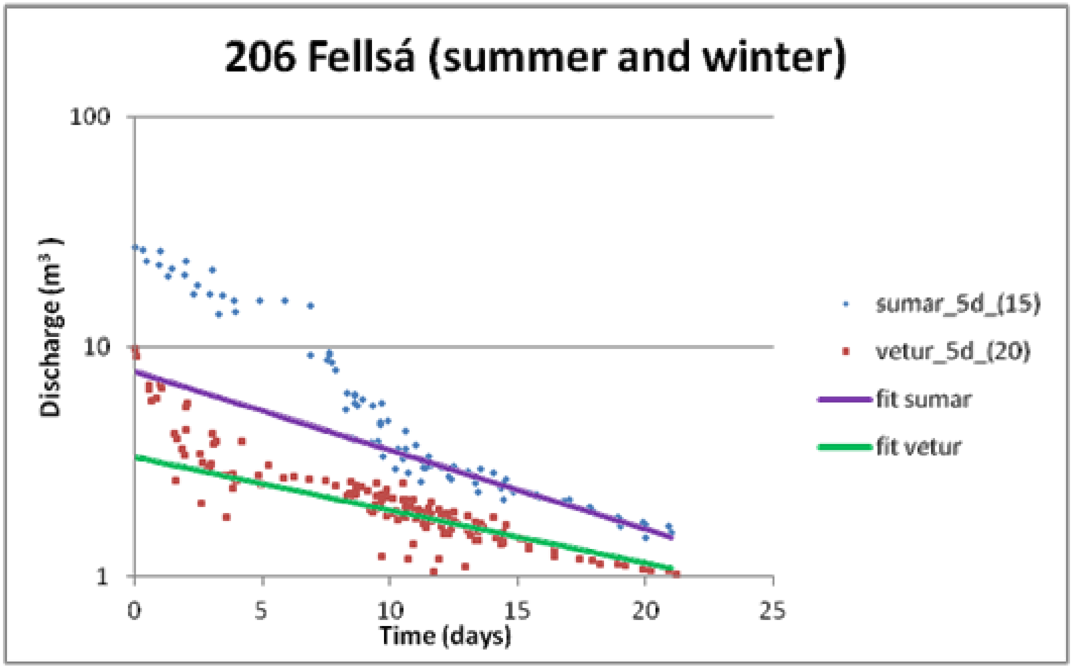

Figure 31. Fellsá, Sturluflöt (206). Summer and winter discharge.

Fellsá dries also out in winter, like Kelduá. There is only sometimes discharge from snow and ice melt during sudden heat periods. In summer there is mainly snow and ice melt in this river reflecting its direct runoff characteristics.

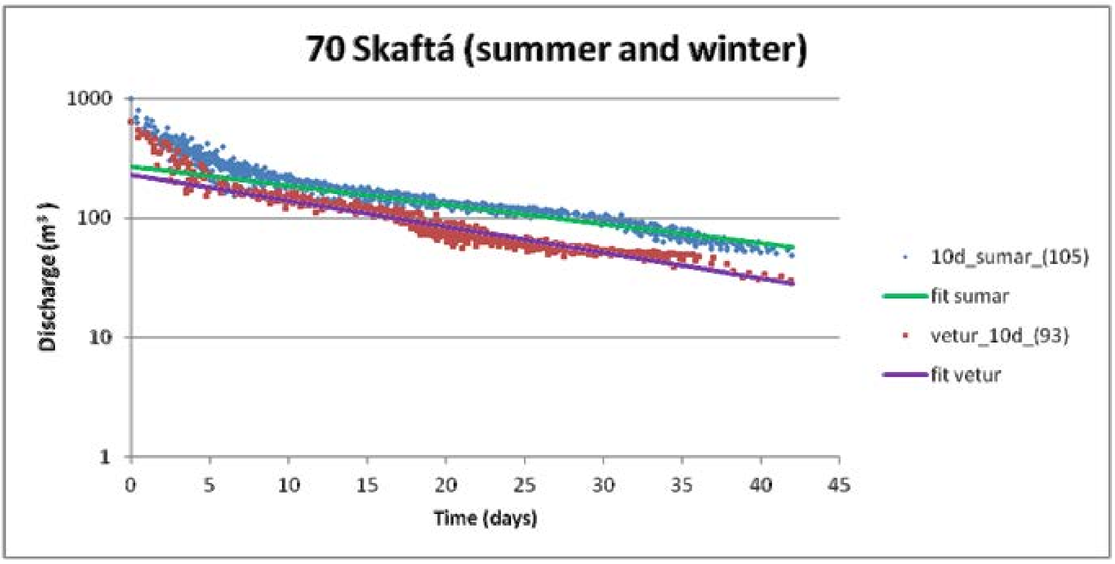

Figure 32. Skaftá, Skaftárdalur (vhm 70). Summer and winter discharge.

In Skaftá there is also the usual relation between summer and winter. In the summer there is more discharge in this river due to snow and ice melt.

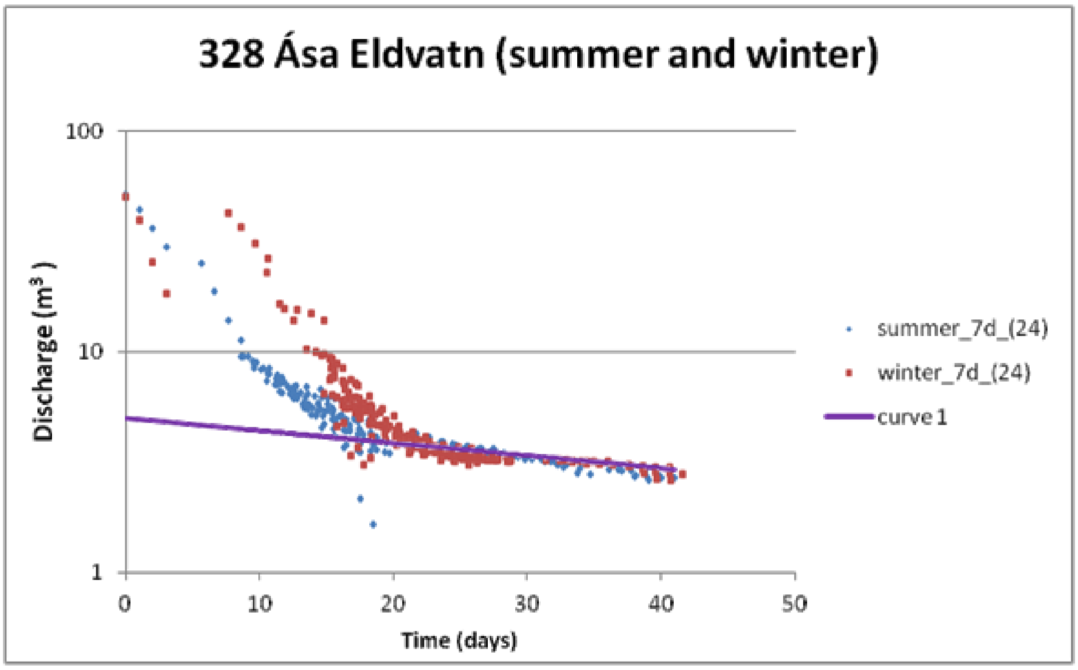

Figure 33. Ása Eldvatn at Eystri Ásar (vhm328). Summer and winter discharge.

The winter curve has a strange curve which might have to do with the fact that Ása Eldvatn is a tributary which is initially diverted from Skaftá. Ása Eldvatn also receives water from a separate catchment. This might be the reason that the discharge in winter shows peculiar characteristics.

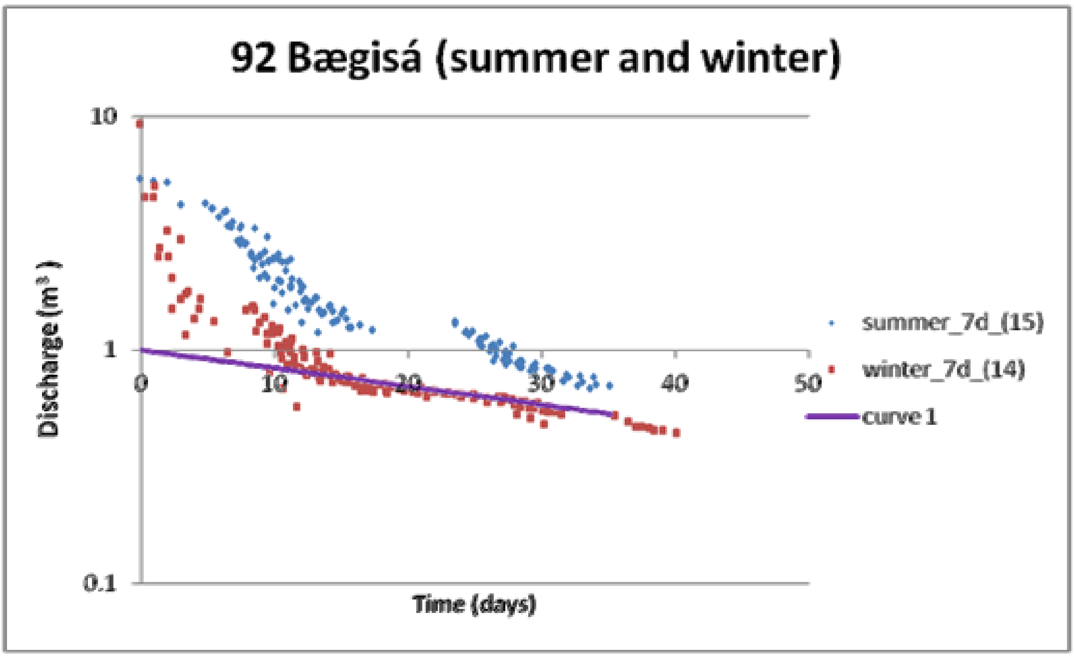

Figure 34. Bægisá (vhm 92). Summer and winter discharge.

The summer curve of Bægisá is also peculiar. This could be due to incorrect measurements. Therefore, no conclusions can be drawn on the difference between the summer curve and the winter curve for Bægisá.

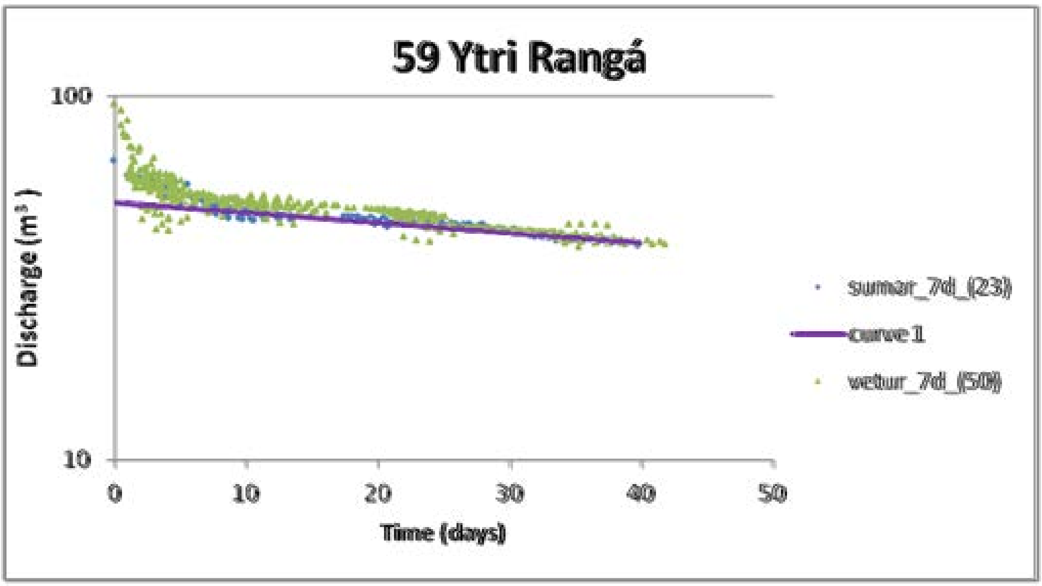

Figure 35. Ytri Rangá (vhm 59). Summer and winter discharge.

Ytri Rangá is a by and large a springfed river, the water flows through the highly-permeable and fractured volcanic formations into the river. There does not seem to be a large difference in this flow between the summer and winter periods.

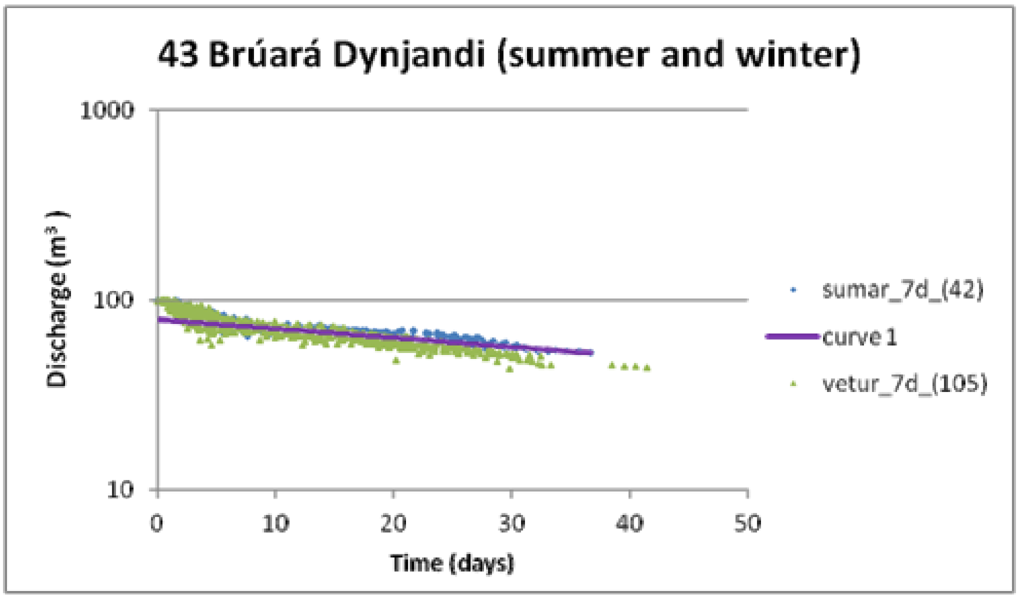

Figure 36. Brúará, Dynjandi (vhm 43). Summer and winter discharge.

Brúará at Dynjandi is also a springfed river like Ytri Rangá. The water flows through the highly-permeable basalt rock and the graph shows that this flow is approximately the same for the summer and the winter period.

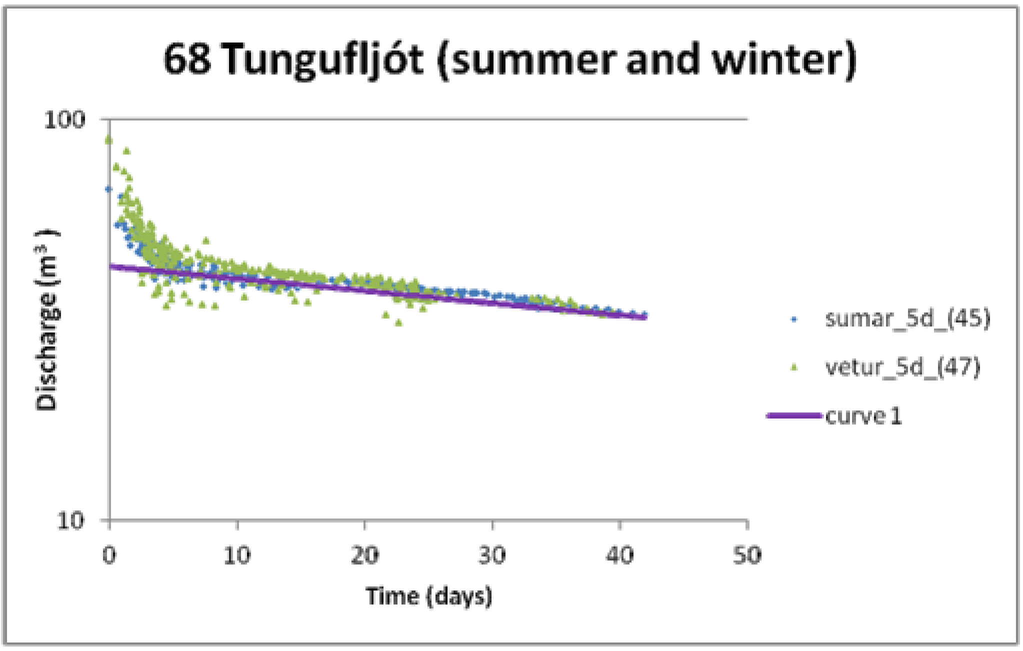

Figure 37. Tungufljót (vhm 68). Summer and winter discharge.

The catchment of Tungufljót has approximately the same characteristics as Ytri Rangá and Brúará Dynjandi. Therefore, there is also not much difference between the MRC of the winter period and the MRC of the summer period.

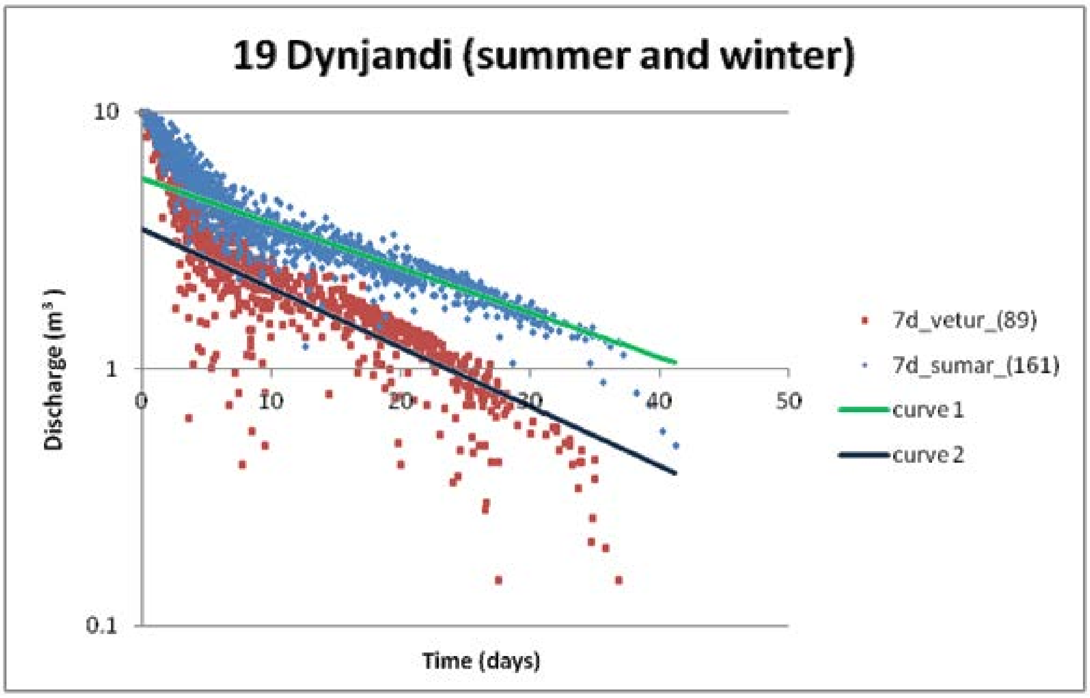

Figure 38 .Dynjandisá (vhm 19). Summer and winter discharge.

For Dynjandisá the graph shows that there is more direct runoff. This is caused by the low-permeability of the soil in this area. Therefore, the water does not percolate into the ground so there is relatively little baseflow.

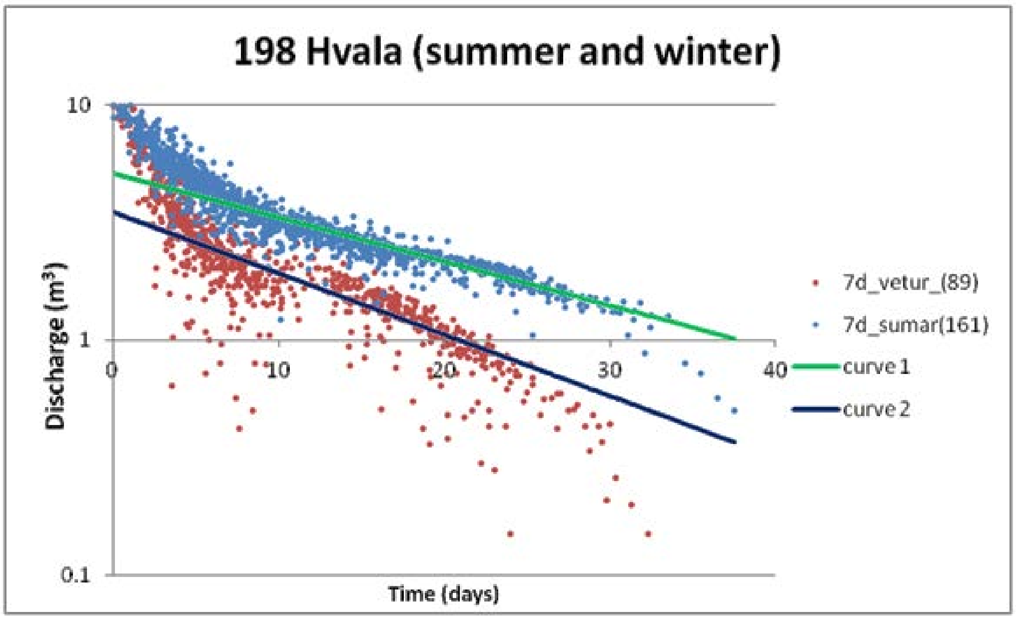

Figure 39. Hvalá, Ófeigsfjörður (vhm 198). Summer and winter discharge.

The curve for the winter is too dispersed and the other curves of Hvalá were also strange. Therefore, the data might be incorrect, which plausible as the measuring station of Hvalá is in a very inaccessible area.

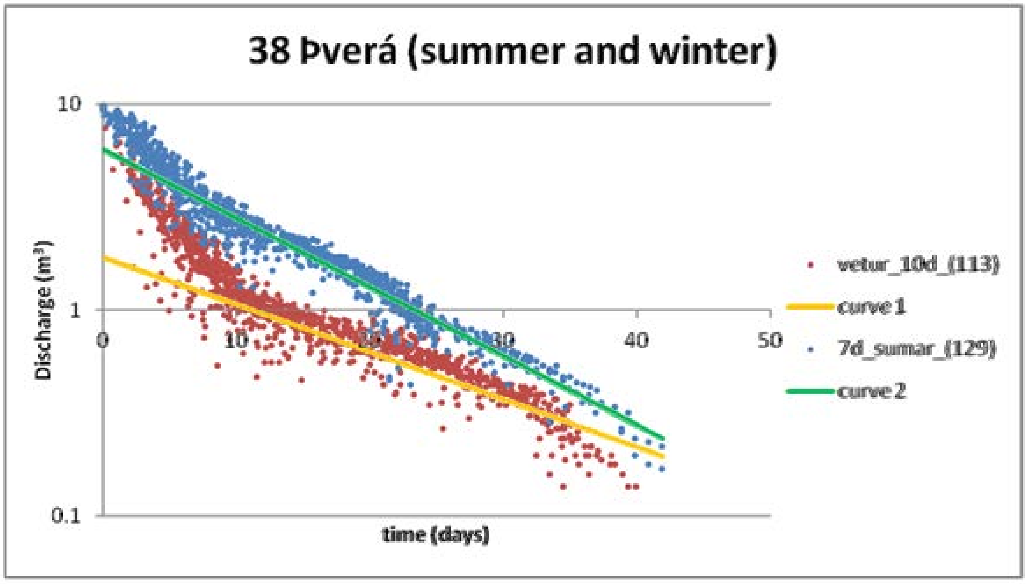

Figure 40. Þverá, Nauteyri (vhm 38). Summer and winter discharge.

The data for Þverá might be incorrect as the curve for winter is very dispersed. This measuring station is also in a very inaccessible area.

Dynjandi, Hvalá and Þverá show the same behavior in summer and winter.

6.3 Analysis of MRCs from with different catchment characteristics

In figure 41 the discharge after 25 days (Q_{25}) divided by the mean discharge caused by precipitation ($P_{discharge}$) is illustrated. This allows comparison of runoff characteristics in different catchments. The figure demonstrates that $Q_{25}/P_{discharge}$, is similar for catchments from the same region.

The values for the rivers in the south for example, are all except one above 1. The values for the rivers in the south-east are just below 1. The values for the rivers in the north are in between 0.1 and 0.4 and the values for the rivers in the west are between 0.2 and 0.3. The two eastern rivers both have a value in between 0.1 and 0.2.

High discharge after 25 days indicates that the baseflow component is high because it can be expected that all overland flow has passed after 25 days. The master recession curves in section 6.1 reflect this quite well; all MRCs show a linear component after 25 days, which means that the streamflow is dominated by baseflow. Furthermore, high base flow after 25 days indicates that the permeability of the surface soil is high, as a lot of water has apparently infiltrated.

The aquifers in the south and in the north-east of Iceland are highly permeable, as in these areas there are young rock formations due to the Mid-Atlantic ridge which is crossing Iceland from the south-east to the north-west. This geologic characteristic can explain the high quotient for $Q_{25}/P_{discharge}$ of catchments in the south and in the north-east. Accordingly, the baseflow in rivers located in these regions is relatively high in comparison to the baseflow in the other 3 regions. The result is in line with the information given in chapter 2, wherein it was explained that discharge in catchments with highly permeable rocks has a large groundwater flow component.

The three remaining regions reveal lower quotients for $Q_{25}/P_{discharge}$ (figure 41). The rocks in these regions are older (Tertiary Bedrock) so the permeability is lower; therefore, there is relatively low baseflow in comparison to catchments with younger rocks. The graph shows that the discharge after 25 days in the catchments in these three regions is more or less the same. The outcome corresponds quite well to the information in figure 42 that indicates that all the catchments in these three regions have a similar geology. The map in figure 42 shows one apparent discrepancy for rock-type of the south-western region, i.e. the catchment of Ytri Rangá. The source of the Ytri Rangá is indeed in the young geological formation although the gauging station is outside it. The method using the quotients $Q_{25}/P_{discharge}$ seems to give quite plausible results as the geological background supports the $Q_{25}/P_{discharge}$ -values found for the different regions. Accordingly, the method might be used to regionalize the permeability of rocks in the catchments. Furthermore, the $Q_{25}/P_{discharge}$ quotient may also provide an indication on subsurface overflow of groundwater from areas outside the topographic watershed.

A limiting factor if this method is the size and complexity of the watershed. The watersheds that were analyzed are relatively small and they have a quite homogeneous and distinct origin.

Another factor that possibly should be taken into account is elevation of the catchment. The conditions change with elevation, as with the presence of snow and ice.

Table 4. Rivers with discharge after 25 days (Q25), mean precipitation discharge (Pdischarge), Q25/Pdischarge, and catchment area (A).

River	**Q_{25} (m^3/s)**	**$P_{discharge}$ (m^3/s)**	**Q_{25} (m^3/s)/ $P_{discharge}$ (m^3/s)**	**A (km^2)**
Hvalá, Ófeigsfjörður (vhm 198)	-	11,1		178
Dynjandisá, Dynjandi (vhm 19)	1,23	4,09	0,30	43
Þverá, Nauteyri (vhm 38)	0,59	2,38	0,25	43
Kelduá, Kiðafellstunga (vhm 205)	2,02	15,9	0,13	262
Fellsá, Sturluflöt (vhm 206)	1,07	7,61	0,14	125
Vatnsdalsá, Forsæludal (vhm 45)	2,33	13,1	0,18	487
Fnjóská ofan Árbugsár (vhm 200)	19,1	47,1	0,41	1132
Bægisá, Öxnadal (vhm 92)	0,70	2,27	0,31	37
Brúará, Dynjandi (vhm 43)	58,4	45,8	1,28	596
Skaftá, Skaftárdalur (vhm 70)	87,7	109	0,80	1469
Tungufljót, Biskupstungum (vhm 68)	36,0	11,8	3,05	198
Ytri Rangá, Árbæjarfoss (vhm 59)	44,2	38,1	1,16	572
Jökulsá á Fjöllum (vhm 102)	123	168	0,73	5178
Ormarsá á Sléttu (vhm 121)	6,07	7,01	0,87	167
Ása Eldvatn, Eystri Ásar (vhm 328)	8,16	116	0,07	1516
Hólmsá, Gunnarshólmi (vhm 185)	1,06	16,8	0,06	221

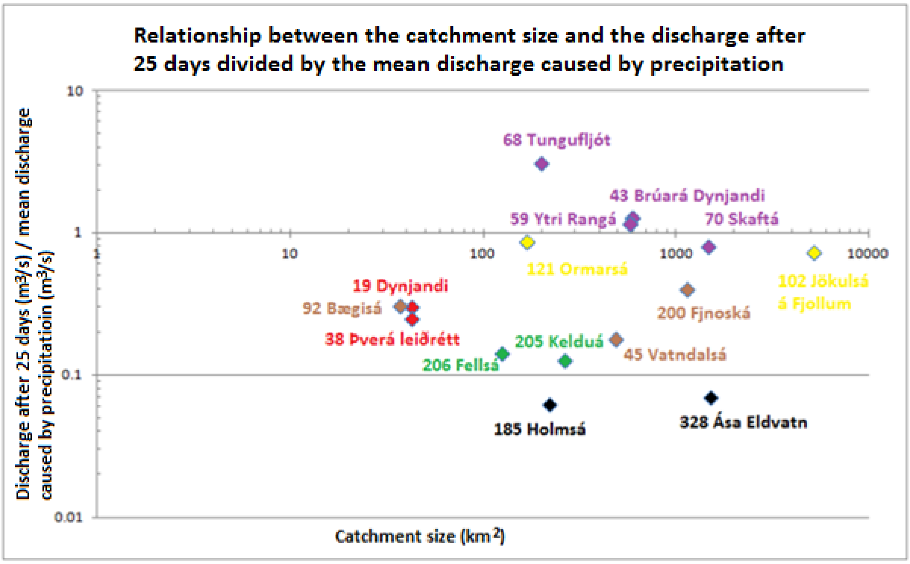

Figure 41. Relationship catchment and discharge after 25 days divided by precipitation in the catchment. Red = West, Green= East, Brown= North, Purple= South, Yellow = North East, Black=no category.

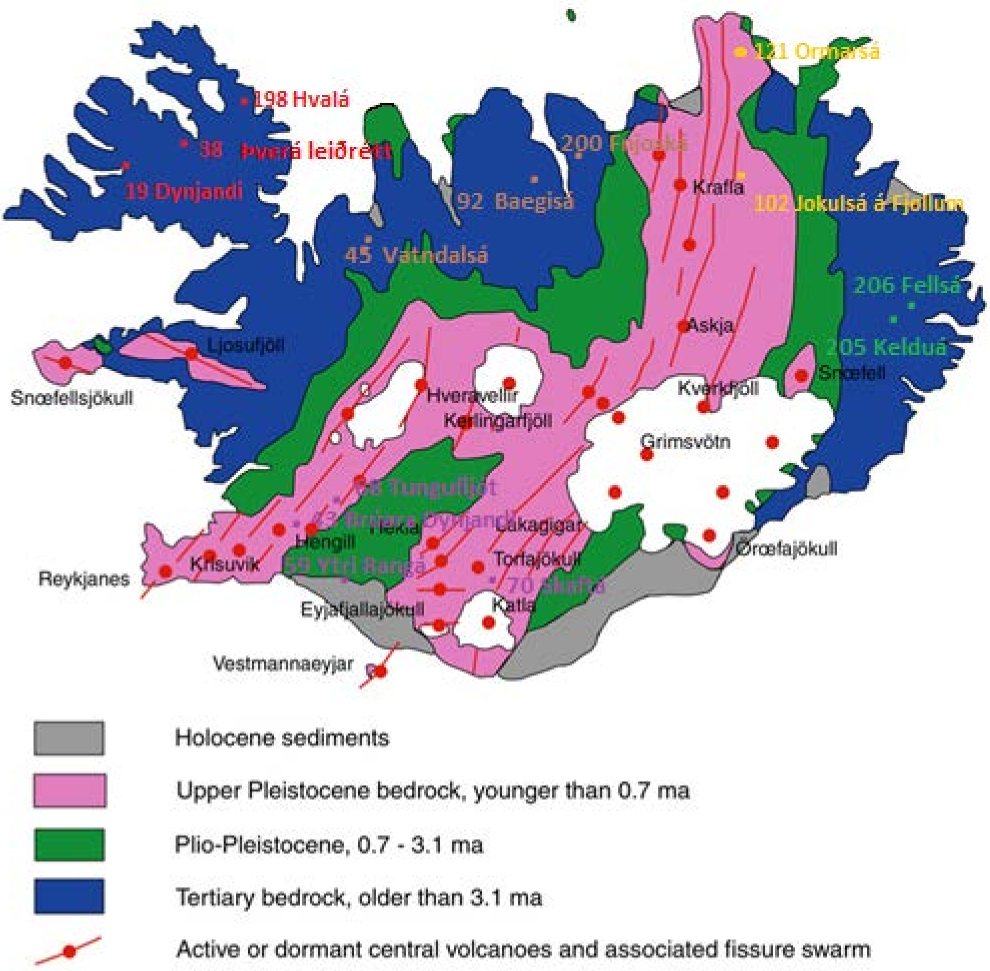

Figure 42.Geology of Iceland with the locations of the measuring stations (Weisenberger, 2010).

7 Pros and cons of the RC-tool in HydroOffice (2010)

The RC tool of HydroOffice (2010) is very useful for the creation of master recession curves. The software is very user-friendly and the procedure is relatively quick. It can be used for all kinds of discharges as spring yields and river discharge, but also for wells and boreholes (e.g. Gregor& Malik, 2012b).

A disadvantage of the software is that it is limited to a maximum of 255 segments to create MRCs. This is problematic for longer data sets where the maximum number of segments should be higher. In this study long data set had to be cut and different MRCs were created. This is an inconvenient limitation as it would be better to create a MRC for the whole period of the data set. The capacity of the software should be extended. With the current limitation to maximal 255 segments the best way to proceed is to select periods of data of the same length and create master recession curves with the data from these periods. This allows comparing the MRC of these periods and possible conclusions on the conditions in these periods can be drawn.

A weakness of the method used in this study is that the manual creation of the fit for the MRC is objective. Therefore, the fit should be atomized by a program that analyses the statistics of the MRC, e.g. R or Python. Automatic fitting would improve the method making it less subjective and thus the characteristics of the catchment area could be better described.

The length of the segments in the RC tool of HydroOffice (2010) should be three days. By using 3-day segments nothing will be left out and all parts of the recessions will be captured. A segment of two days would even be better, but this is not possible because of the algorithm behind the method (Gregor, 2012). So three days is the best and for small catchments the 5-days segments might also be helpful, as these cover more of the low discharge parts of the recession curve.

8 Conclusions & recommendations

Based on our investigations we conclude that the RC-tool of HydroOffice (2010) is a very user-friendly and practical software package to analyze hydrographs of flood events. The program is based on the theoretical background of creating master recession curves. While applying this program to discharge data from rivers in Iceland, we encountered some difficulties in finding an adequate fit for some recession curves. As fitting was performed manually the method is still very objective, and therefore our conclusions about the characteristics of the river catchments have to be considered with precaution. Nevertheless, based on our findings we have the following recommendations for using HydroOffice (2010) to analyze the characteristics of river catchments:

1. Only 3-day segments and possibly 5-day segments should be used, as these cover the recession curves in the best way.
2. 50 generations is sufficient to create a proper MRC. Using 50 and 100 generations gave almost the same MRCs.
3. A statistical method should be used to make a fit in the MRC which is created with HydroOffice (2010). This could be done with programs like R or Python.

When the discharge of the fitted recession curves is compared, they will have to be normalized by the mean discharge caused by precipitation ($P_{discharge}$). When corrected for the total volume of precipitation, it seems to be a good method to determine similar geological characteristics in between different catchments. However, point three of this conclusion should be carried out first. The results of the catchments in Iceland that were analyzed in this study show that the permeability of the aquifer influences the baseflow component of the flow. Therefore, this method could be used to classify the investigated catchments according their typical soil permeability.

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