ORKUSTOFNUN
NATIONAL ENERGY AUTHORITY

Explanatory Notes on the International Hydrogeological Map of Europe 1 : 1 500 000 Sheet B2 Island

Iceland:
Árni Hjartarsson
Faroe Islands:
Lars Jörgen Andersen
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OS79016/JKD03
Reykjavík, April 1979

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PART I

INTRODUCTION (Á. HJARTARSON, W. STRUCKMEIER)

During the preparation of the International Hydrogeological Map of Europe 1:1 500 000, it was decided to combine sheets A1, A2, B1 and B2 of the International Geological Map of Europe and the Mediterranean Region 1:1 500 000 into one sheet designated B2 Island. The topograhic base map has been corrected where necessary and many topographic names, especially those of hydrological importance, have been added.

The initial intention was to print Iceland on map C2 along with the Faroe Islands and part of Norway (Trondheim), as shown on the cover of the earlier explanatory notes, but in the summer of 1977, after the General Assembly of IAH in Birmingham, it was decided to establish an individual sheet, B2 Island, showing Iceland and the Faroe Islands. This decision was made in view of the geological, hydrological and geographical peculiarity of these countries. The present map, which was compiled in 1976-1979, was the first attempt at hydrogeological mapping of Iceland and the Faroes as a whole. Only two very limited areas in Iceland had been mapped before. Careful work was therefore needed in preparing the wide range of data and coordinating them with the standards given in the General Legend.

The hydrogeology of Iceland and the Faroe Islands is essentially one of a volcanic terrain, with recent volcanic activity and thermalism associated with heavy precipitation and run-off. In spite of the unusual hydrogeological conditions in the islands the General Legend proved to be very useful in representing the general hydrogeological features of these areas. The areal colours show the decreasing permeability of the bedrock from the leaky lavafields of the Holocene with their gushing springs of several m^3/s to the dense basaltic lava pile of the Icelandic Miocene and Pliocene and the Paleocene-Eocene of the Faroes where the groundwater resources are substantially reduced or even disappear.

Two lithological screens have been used to indicate the geological age of the volcanic rocks, i.e. Tertiary and Quaternary bedrock.

It should be noted that in Iceland the first signs of widespread glaciation are over three million years old. Therefore the Tertiary/ Quaternary boundary has been chosen at the Gauss/Gilberg magnetic reversal, 3.35 m years ago.

Magnetic reversals being of great importance in all stratigraphical exploration in Iceland, special symbols have been introduced for the most important ones. Areas in which acidic and intermediate volcanic rocks predominate are shown by the corresponding screens, although basic rocks are also present. These areas represent the old, now inactive silicic centres (central volcanoes), which have been eroded to varying degrees. The fine dotted limit between the screens must be considered as somewhat arbitrary, since there is a gradual transition from basic to intermediate and acid rock types.

Among the geological signs the special symbols for late Quaternary silicic centres should be mentioned. In these areas the acid differentiates of rocks testify to sub-recent or recent volcanic activity. Some of these central volcanoes have formed calderas.

Several new symbols have been introduced in the sheet legend in order to meet the special demands of hydrological cartography in Iceland. Some of them concern topographical features, such as braided streams. Other show very typical thermalism, features such as areas of great geothermism or meltwater reservoirs underneath glaciers. Sudden release of such meltwater as well as of ice-dammed lakes cause the terrible "jökulhlaups" (glacier bursts). Areas which are endangered by these phenomena are indicated on the map by blue and orange flashes.

Certain symbols of the General Legend (1974) have been used on the map in a slightly modified sense. These concern the classification of mineral-thermal and thermomineral springs. Pipelines for drinking water and for geothermal heating and warm water for domestic supply are shown with the same sign.

As a consequence of the abundance of springs with high discharge, only those springs and groups of springs yielding more than 1 m^3/s, have been represented on the map. Some of them are coastal springs which are submerged at high tide.

The mapping work of Iceland was begun in the summer of 1976 when Mr. Guttormur Sigbjarnarson, head of the department of Economic Geology, National Energy Authority, established contact with prof. Karrenberg and the Committee for the International Hydrogeological Map og Europe.

The scientific leadership and preparation of the sheet was in the hand of Árni Hjartarson, who from the beginning of the compilation work kept close contact with the scientific editors of the mapping project. This contact and many discussions have led to a representation which is in full accordance with the "General Legend for the International Hydrogeological Map of Europe 1:1 500 000" proposed by H. Karrenberg, O. Deutloff and C.V. Stempel (1974).

Heartfelt thanks are due to the experts of Orkustofnun, Department of Economic Geology, Freyr Þórarinsson, Freysteinn Sigurðsson, Sigurður G. Tómasson, Snorri P. Snorrason, Þóroddur F. Þóroddsson and Þórólfur Hafstað for their scientific advice and encouragement and many fruitful discussions; and to Sigurjón Rist for his valuable advice on the surface hydrology.

The mapping of the Faroe Islands was carried out in 1979 by Lars Jörgen Andersen, Johannes Rasmussen and Niels Kelstrup. The scientific redaction was presented by H. Karrenberg and W. Struckmeier. The editorship is the work of W. Struckmeier in collaboration with A. Voges (B.G.R. Hannover).

PART II ICELAND (ÅRNI HJARTARSON)

1 HISTORICAL PREFACE

Icelanders were showing an interest in hydrology as early as the 13th century. In the Prologue to the Snorra Edda we read that the ancient vikings were struck by the multifarious nature of the earth:

"They observed that in many respect the earth, birds and beasts have the same nature and yet exhibit different behaviour, and they wondered what it signified. For instance one could dig down into the earth on a high mountain peak no deeper than one would in a low-lying valley and yet strike water; in the same way in both birds and beasts, the blood lies near the surface of the skin of the head as of the foot".

"They knew that the earth was inconceivably ancient as years go and by nature, powerful; it gave birth to all things and owned all that died, and for that reason they gave it a name and reckoned their descent from it". (Snorri Sturluson).

The ancient Icelandic notions of the origin and nature of geothermal heat and water are related to the theories of the old Greek philosophers concerning the reasons for vulcanism. It was thought that burning sulphur and winds in caves and fissures deep in the ground caused the heating of rocks and waters as well as volcanism and geothermal activity. (Oddur Einarsson).

It is no wonder that these ideas appealed to the Icelanders, who had hissing fumaroles before their eyes and the smell of burning sulphur in their noses every day.

In the famous travelogue of Eggert and Bjarni Written in 1750-1760 the first classification of Icelandic drinking waters can be seen. There the water is grouped into six classes:

a. Glacier water. The water of the glacier rivers. It was only drunk in emergencies because of its mud; it is harmless, however.

b. Bog water (mirewater). The majority of well water in the country was of this type.

c. Rock water. This is the water of rivers and brooks that do not emerge from the glaciers. It was used as much for drinking as bog water.

d. Springwater. It was considered healthier than the abovementioned waters and more desirable, but was not as abundant.

e. Cool-warm water. It was believed to be especially healthy and refreshing. It does not freeze in winter and seems colder than other waters in the summers. In hardest frosts it seems warm.

f. Thermal water. Used in some places as drinking water. Sickness or discomfort following the consumption of thermal water is not recorded.

The soda springs , comprising the seventh class, were classified not as drinking water, but rather as a medicine.

This 200 year-old classification still serves as the basis for the present grouping of Icelandic waters. It has stood the test of time better than contemporary erroneous theories as to the origin of thermal water.

The first drilling of wells in Iceland took place in 1755 when Eggert and Bjarni drilled a borehole at the thermal springs in Reykjavík and later in Krísuvík. They found that the heat did not rise constantly accounting to depth. The hottest layers seemed to them to lie at a shallow depth, with colder layers below.

Working from these observations, they published the theory that geothermal heat originated in chemical reactions at a shallow depth, thus causing volcanism and thermal water (Eggert Ólafsson, Ferðabók)

Their mistake was a result of their being able to drill only shallow holes in the loose surface layers; the temperature in these layers was caused by hotwater flow in permeable layers from the thermal springs, rather than the general geothermal gradient.

In the last decades of the 18th century Sveinn Pálsson (1762-1840) studied glaciers, glacier-rivers and glacier-bursts. His dissertation on these explorations, Jöklaritiđ, written in 1795, would have become an undisputed classic of glaciology, comparable to the writings of de Saussures; but it was not published until 1945. It describes the movements of glacier transgressions and regressions and discusses the origin and nature of glacier-rivers and glacier-bursts with deep insight.

In the 19th century it became the general opinion that cold groundwater originated as precipitation and was a part of the hydrolic cycle; but thermal water was still thought of as originating in the depths.

Trausti Einarsson's essay, Über das Wesen heissen Quellen Islands (1942), was a very important contribution to geohydrology. Here it is stated for the first time that thermal water is mainly of meteorological origin, having penetrated to the depths and received its heat from the general geothermal gradient.

In 1945 Guđmundur Kjartansson published his classification of rivers as glacier rivers, direct run-off rivers, and springfed rivers.

This classification has proved both natural and useful; it is, however, a local Icelandic classification and is hardly practical in other countries.

These, then, are the salient points in the development of Icelandic hydrological sciences. During recent years great strides have been made and the international hydrogeological mapping of Europe plays an important role in this development.

2 GEOGRAPHY

Iceland is situated in the North Atlantic Ocean just south of the arctic Circle. A mountainous island, "child of ice and fire", it is characterized by a continuous struggle between the building forces of volcanism and the erosional activity of wind, water and ice. Although two-thirds of its 103 000 km^2 surface area is over 200 m in height, its highest points, the peaks of Vatnajökull, are only about 2000 m high. The most extensive lowlands are in the south, the goodlands of Suðurlandsundirlendi and the great wastelands of Skaftafellssýsla. Iceland is a barren country, the vegetated areas covering only about 24.000 km^2.

In the warmest period of the Holocene, 3000-4000 years ago, over 75% of the country was vegetative and about half of it covered by wood. Now only 25% of the country is vegetative and 1% covered by wood. Because of cooling climate 2500 years ago the woods began to decline and sudden vegetative changes accurred after the settlement around 900 AD (Th. Einarsson 1968) following the destruction of the forests in most districts during the first centuries after the settlement, as a result of the encroachment of man and his animals and steady climatic deterioration. The woods changed into grasslands with accompanying changes in groundwater conditions and run-off characteristics. These changes led to heavy soil erosion that stripped off extensive areas of the island, leaving sand deserts and barren lava-fields. In the last decades an all-out crusade against this erosion has been launched in the form of treeplanting and grass sowing. Now the turning point has been reached, and soil erosion is on the retreat.

Iceland is sparsely inhabited with a population of about 225 000, and a mean density of 2.2 inhabitants/km^2. The population is very unevenly distributed, 55% living in the south west corner, the so called Reykjavík conurbation (Stór-Reykjavíkursvæði), which includes the towns of Reykjavík, Kópavogur, Hafnarfjörður, Garðabær and Mosfellssveit. Outside this area the population is more evenly distributed along the coast and in valleys all around the island, apart from the uninhabited north western corner. The Central Highlands are and have always been uninhabited.

Fishery and fishing industry form the mainstay of Icelandic economics, accounting for 85% of the national exports.

Food production such as fishing industry demands more quantity of potable water than most other industries. The demands for good groundwater are therefore high. A fishing village with 1000 inhabitants usually needs 15-20 l/s of potable water, and about 10 l/s of industrial water.

Farming consists almost entirely of animal husbandry (sheep, cattle, poultry and pigs) and the product satisfies the domestic needs. Agriculture is on the other hand on a small scale. All cereals are imported. Irrigation has never played an important role in Iceland. However a few small irrigation systems were built in the first decades of this century. The largest and only one worth mentioning is Flóaáveitan (The irrigation system of Flói). It was built in 1921-1928 and has a total canal-length of 130 km.

Irrigation did not prove viable in Iceland so most of the irrigation systems, including the Flóaáveitan, have been abandoned.

Because of high precipitation and absence of woods, bogs and mires are extensive. Drainage of land has therefore been of great importance in farming. Accompanying it groundwater conditions have changed together with vegetation and other ecological components. In recent years protection of bogs and mires and their ecological chains has been an important issue of the Association for Nature Conservation.

Industries have been growing in recent decades. Practically all materials such as timber and metals must be imported. The only industrial minerals exploited in Iceland are diatomite and shellsand.

Iceland is on the other hand rich in power. The power resources are of two main types, hydropower used for generating electricity and geothermal power mostly used for house heating (see chapter 8).

3 WEATHER AND CLIMATE

3.1 General

Iceland is often said to be at the margin of the habitable world. If it were a little farther north it would be surrounded by polar ice during the greater part of the year and polar ice is the great enemy of a fishing nation. For Iceland the Gulf Stream is a vital artery. It keeps the sea clear of ice and warms up the winter climate. The Gulf stream comes from the south and flows north along the Norwegian coast. Part of it splits at the Faroes, and streams east of Iceland into the Polar Sea. A branch diverges from the main stem and flows along Iceland's south coast clockwise around the island. This is the Irminger Current.

Along the east coast of Greenland flows the icy East-Greenland Current joining the West-Greenland Current south of Cape Farewell to form the Labrador Current. A small branch from the East-Greenland Current turns to the south-east north of Iceland and flows north of the country towards the Faroes. This is the East-Iceland Current, which in bad years often forces the polar ice to the coast of Iceland, filling each fjord and bay on the north and east coast. During the 18th and 19th centuries there were some very bad polar ice periods with accompanying severity and famine.

The climate of Iceland is oceanic near the shore, especially in the south and west, but the character is more continental in the central highlands. Although Iceland touches the polar regions, the average January temperatures along the coast resemble those of New York. The annual temperature range is narrow, with cool summers and rather mild winters. Precipitation is high and a considerable part of it falls as snow. According to the climatic classification of W. Köppen (1846-1940) Iceland is on the boundary between two climatic regions. In the South and West and inland in the North and East, the mean temperature of the warmest month of the year is above 10°C and mean temperature of the coldest above -3°C. At the northernmost points of the mainland, and in the central highlands the mean temperature does not reach 10°C during the warmest month, which means that the climate is arctic. Snow begins to gather in September and usually reaches its peak in March and April. Exceptions from this are common due to short periods of thaw during the winter. Such periods of thaw while ground is frozen cause small floods in spring-fed rivers, which otherwise have a relatively stable flow. Spring thaw usually starts in April and reaches its climax in May and the beginning of June, when maximum peak in the flow of direct run-off rivers occurs. Glacial rivers are at their maximum during the annual peak of glacial melting in July and August (S.Rist 1956).

3.2 Temperature

The annual mean temperature is about 5°C in the South of Iceland and about 3°C in the North. The coldest month is usually January, with July the hottest. Yearly temperature amplitude averages out at 12°C. Days of frost (that is when temperature falls below zero) are usually around 100 in the South and 150 in the North. Temperature below zero is rare during the period June 1. - Sept. 15. The ground is usually impermeable due to frost during the period Nov. - April (Fig. 10) (M.Á. Einarsson 1976).

This regularity in the average temperature does not, however, tally with the highly unstable weather conditions, especially in winter. A characteristic of Icelandic weather is rapid atmospheric circulation and high changeability due to the semipermanent low pressure erea off Labrador. Thus low pressure conditions prevail as warm oceanic air from the south encounters tongues of cold polar air. Changes of wind and temperature are quite frequent. During the winter this results in a wide fluctuation in temperature and frequent changes between freezing and thawing conditions.

3.3 Precipitation

Iceland lies in the route of maritime depressions, saturated with moisture, coming in from the south. The most common wind direction is south-easterly and southerly, these also being the directions of most precipitation. In the southeast and the Eastfjords there is high precipitation, nearly everywhere above 1400 mm/year on the low-land, and with two distinct areas of observed maximum precipitation. One is south of the glacier Vatnajökull and the other south of the glacier Mýrdalsjökull with annual measured precipitation 2000-3000 mm/year. The actual maximum areas of precipitation are on the glaciers themselves. On the southern part of the glacier Vatnajökull and on the glacier Mýrdalsjökull, the annual precipitation is estimated above 4000 mm/year. In the South West Lowlands up to Vestfirðir in the North the precipitation is 1000-1600 mm/year at most stations. In the North and North East the precipitation is much lower than in the South. In this part of the country the highlands drain much of the precipitation from the southern winds. Here northerly winds account for most of the precipitation, but because of the lower temperature of the air their humidity is much lower. In the lowlands the precipitation is therefore only 400-600 mm/year in most places. The highland north of Vatnajökull is the driest part of the country with precipitation below 400 mm/year. This is the effect of the glacier which causes a precipitation-shadow (Fig. 11). Usually the precipitation is highest in October and lowest in May.

In South Iceland one can expect 200 days of precipitation annually, compared to 140 in the north (M.Á. Einarsson 1976).

The proportion of precipitation falling as snow varies considerably over the island. From November to April snow often covers the whole country. On the south coast snow seldom lies for long periods because of frequent thaws.

In winter when the ground is frozen and most precipitation falls as snow, very little water is added to the groundwater storage.

Rain and melting snow during winter thaws runs off on the surface for the most part. In spring most of the melt water runs off on the surface too.

In the highly permeable areas of the volcanic zones however, some water always drains to the groundwater storage.

3.4 Evapotranspiration

Evapotranspiration in Iceland is highest in June and lowest in January. In summer it reaches somewhere around 100 mm/month and in wintertime it is around zero, especially inland.

Annual evapotranspiration is mostly in the range of 360-540 mm/year. The maximum area is north of Vatnajökull where the climate is dry and radiation high. The minimum area is in the western part of the

Central highlands. The greater part of Iceland has a positive annual water balance, the most favourable water balance obtains in southeast Iceland where the precipitation is highest (M.Á. Einarsson 1969, 1972).

3.5 Runoff

Average runoff per km^2 in Iceland is among the highest in Europe, because of high precipitation and low evapotranspiration. The highest average runoff per km^2 is on the southern flanks of the glaciers Vatnajökull and Mýrdalsjökull (about 140 l/km^2 s) but it is much lower in the north (about 25-30 l/km^2 l). Mean average runoff for the whole country is about 55 l/km^2 s.

The climatic characteristics are unfavourable for vegetation. Forests are rare and close to their northern limits. The island lies just south 10°C July isotherm, which represents fairly well the northern extent of forests. The vegetation is subartic with extensive grassland, which serves as pasture for sheep.

4 GEOLOGY

4.1 Geological formation

Iceland is a young volcanic island. Its bedrock is made up predominantly of effusive igneous rocks. The volcanics are mostly composed of basic rocks, basaltic lavas or palagonite.

Acid and intermediate rocks are of much more limited occurrence. Sedimentary strata between the lava layers are generally very thin. Intrusions are numerous and most often in the form of dykes. Their hydrological importance is unquestionable.

Iceland is on the Mid-Atlantic Ridge and is thought to lie on the boundary of the N-American and the European plates. Active volcanic zones run across the country. According to the theory of plate tectonics the island is drifting out from the volcanic zones in both directions. The continuous volcanism immediately fills up the gap between the plates (Morgan 1968, Pichon 1968). The age of the bedrock roughly reflects the drift. The rocks are youngest in the active volcanic zones but get older as the distance from the zones increases, the oldest rocks being found in the East and the West fjords. The majority of the flood basalts in the Icelandic lava pile originated in crater rows, cinder cones or in shield volcanos.

Silicic centres (central volcanoes) produce nearly all the acid and intermediate rocks in Iceland. These volcanoes are characterised by great but concentrated volcanic activity and lavas of developed magma and vary considerably in size. The smallest of them consist only of a few andesite or rhyolite lavas while the largest are vast volcanic cones which stand high above their surroundings, made of thick strata of rhyolite, andesite, ignimbrite, tephra and large quantities of basaltic rocks.

The best chronology for Icelandic geology is obtained by use of the geomagnetic reversal time scale. Iron minerals in the lavas faithfully preserve the orientation of the magnetic polarity which was dominant at the time of their eruption.

Magnetic reversals therefore play a big role in all geologic exploration in Iceland. On the hydrogeological map the two most important reversals are indicated, the Brunhes-Matuyama reversal, 0.7 m.y. old, and the Gauss-Gilbert reversal, 3.35 m.y. old.

In Iceland it has proved to be convenient to divide the geological history into four epochs: Tertiary, Eo-Pleistocene, Neo-Pleistocene and Holocene (Fig. 1)*. The strata piles of these epochs have strong characteristics of their own. Over 90% of the Tertiary pile consists of lavas, predominantly basaltic. Between them there are thin interbeds, usually thinner than 1 m. The regularity of the layering is disturbed in some places by central volcanoes buried in the strata. They are chacterized by irregular layering, local tectonics, dyke swarms and various petrology. The rocks are often hydrothermally altered and highly zeolitisized.

The Pleistocene pile is characterized by the cold climate of the ice age, glacial erosion and subglacial volcanism. It is quite different from the Tertiary one. Under the ice age the erosion changed its character and the volcanism too. Eruptions under water or ice sheet do not form ordinary lavas. An eruption at a great depth and under pressure forms pillow lava, while eruption at shallow depth mostly produces tephra which consolidates later into palagonite (G. Kjartansson 1943). The Icelandic palagonite mountains therefore often have a core of pillow lava. About half of the Quaternary volcanics are in the form of palagonite and related rocks. This heterogeneity results in highly variable permeability from place to place. Old palagonite is thought to be one of the most impermeable rocks found in Iceland whereas pillow lava is considered among the most porous.

The small scale of the hydrogeological map makes it impossible to separate the palagonite from the lavas of the Quaternary pile. It is customary in Icelandic geology to place the Tertiary-Quaternary boundaries at about 3 m.y. years ago. The oldest signs of extensive glaciation

* New proposals of this nomenclature are in progress aiming for more coordination with international time tables. Instead of the names Neo- and Eo-Pleistocene the names Pleistocene (0,01 - 0,7 m.y.) and Plio-Pleistocene for the prolonged icelandic lower Pleistocene (0,7 - 3,1 m.y.) will probably be used. (K.Sæmundsson pers. inform.)

in Iceland are of that age. Since then some 20-30 glaciations seem to have periodically overridden the country.

More periods of glaciation, or interstadials, are observable in Iceland than in any other country in the world. There are two main reasons for this. The first is volcanism. In each warm period, lavas have been formed covering extensive areas. Under them, moraines and palagonite from the latest glaciation are protected from erosion by the glaciers of the next glaciation period. In this way the moraines and palagonite indicate glaciations and the lavas warm ice-free periods. The second reason is the northerly position of Iceland and its mountainous landscape. Fluctuations in weather conditions are immediately followed by recessions and transgressions of the glaciers.

The main differences between the Eo- and Neo-Pleistocene formation are that the Eo-Pleistocene pile is deeply eroded and secondary mineralisation is well on its way. The Neo-Pleistocene formation is moderately eroded and the secondary mineralisation is of low degree.

The silicic centres of this last epoch often stand out in the landscape as high, graceful stratovolcanoes. Calderas often form in these mountains, vast fissure swarms cross them and high temperature areas are common.

The Holocene formations include all the unconsolidated surface layers of Iceland and the recent lavas. They will be described later.

4.2 The permeability of the bedrock

The permeability of Icelandic geological formations seems to decrease with increasing age. This is the general rule for effusive, intrusive and sedimentary rocks. There are 3 main reasons for this: Secondary mineralisation and alteration, compression, and intrusion of dykes. Under Icelandic conditions these phenomena increase with age. Secondary mineralisation makes the rocks densier by filling up and narrowing the pores and gaps.

The Tertiary strata pile had, since it was formed, been overflowed and buried by younger lavas and other beds. Under the great pressure of the overlying strata compression takes place and makes the layers very impervious. The layers which were originally the most permeable, such as scoria and loose sediments, now show the highest compression.

When these layers were buried in the pile, they were simultaneously intruded by dykes and intrusions. These intrusives often form dense walls and thresholds which act as barriers on the groundwater flow. The oldest bedrock of Iceland has become so dense that it is almost impermeable. It is to be found in the lowest part of the Austfirðir pile at the east coast.

Hydrothermal alteration and zeolitisation occur because the rocks are buried under younger lavas and sediments and are subjects to great heat and pressure. As a general rule it can be stated that the older Icelandic rocks are, the more zeolitisized they are. However there are some exceptions. Old rocks in the mountaintops of Vestfirðir seem never to have been under any considerable pressure; at all events they look rather fresh and are without secondary minerals. Their permeability is therefore rather high. Rocks of the same age in Austfirðir are on the other hand highly zeolitisized and dense. The number of dykes in Austfirðir, in the east is higher than in the west, adding to the difference between these regions. This difference is reflected in the behaviour of the groundwater flow. In Vestfirðir, springlines are formed at the top of the zeolite zone and rivers are more perennial than in the east, where most rivers are more or less intermittent in their uppermost reaches. In the West, thermal springs are common. The groundwater seems to penetrate easily into the depths. In the East thermal springs are rare. The deep layers seem practically impermeable. There are doubtless many reasons for these differences but it is considered that the different states of erosion in these regions are the main reason. The main direction of precipitation in Iceland during recent millennia has been from the southeast. Therefore the glaciers of the ice age have always been thickest and most enduring in the East and Southeast and eroded these regions accordingly. This statement is born out by the present erosion due to the glacier Vatnajökull. The northwest peninsula has on the other hand been in the shadow of precipitation from these glaciers and has been moderately eroded.

Hydrological influences of Tertiary central volcanoes are not known at present, but there are reasons to believe that they are even denser than their surrounding bedrock. They are the most zeolitisized parts of the bedrock, thermal metamorphism and high temperature hydrothermal alteration being common, the number of dykes and faults high and intrusions not uncommon.

The younger central volcanoes have quite a different character from the older ones. Most often they stand above the environment and form heights in the groundwatertable. The role of intrusions and dykes is not known, but great active fissure swarms that often cross these mountains probably increase the permeability. The great fissure swarms of Iceland always seem to be in close connection with the central volcanoes or high temperature areas. They exert a strong influence on the groundwater flow. Many of the largest Icelandic springs and spring areas seem to be in connection with swarms such as Vellankatla at Þingvellir, Gvendarbrunnar and Elliðavatnslindir near Reykjavík, Hafragilslindir and Blikalónslindir in Melrakkaslétta.

The lavafields in Iceland are valuable freshwater aquifers. The lavas are highly permable, 10^{-3} m/s in their dense level and 10^{-1} m/s in the scoria at their upper and lower levels. Almost all precipitation that falls on the lava fields and does not evaporate, penetrates into them and runs off as groundwater.

Icelandic lava fields are in some ways similar to the karst regions in Europe. Vast amount of water can be discharged in limited areas. The volume of the flow often reaches tens of m^3/s in a spring area. The springs in Vaðalda discharge 20 m^3/s and the spring area of Mývatn 25-30 m^3/s. In the same way rivers can suddenly disappear into the lavas.
In other respects, however, the situation in the lavas is quite different from that in the karst. The water does not stream along in tunnels or

veins but flows through the porous scoria layers underneath the lava or in fissure swarms from one crack to another. The water gets a good filtering on its way in the lavas and the lavaspring most often discharge an exellent drinking water.

4.3 Unconsolidated rocks

Loose sediments in Iceland are in most places very thin. Sediments thicker than 50 m are rare. This is due to the fact that the glaciers of the iceage covered just about the whole island and swept all sediments into the sea. The outer part of the Icelandic shelf is made up of these sediments; here they are several hundred meters thick (L. Kristjánsson 1976).

On the hydrogeological map the loose sediments of Iceland are divided into four classes according to their origin and into two groups, according to permeability. Highly permeable layers are: fine fluviatiles and coarse fluviatiles. Semipermeable layers are: moraines and valley fillings. Moraines are only shown on the map where they have considerable thickness and extent. The permeability of a moraine can be very different from one place to another. It depends mainly on the clay and silt fraction. Where there is much silt and clay the moraines are dense and impermable, whereas the less silt it contains the more permeable is the moraine.

In most of the bigger valleys of the country, valley fillings have been formed in finiglacial and Holocene times. They are composed of rather heterogeneous sediments: layers of moraines, marine sediments, fluviatiles, glacifluvial sediments and soil with various thicknesses. The permeability is therefore variable, but as a whole it is rather low. Fluviatile and glacifluvial deposits are most extensive on the south coast. The majority of these deposits comes from the glacier rivers but a good deal is volcanic ash, especially in Mýrdalssandur and Skeiðarársandur. The tephra here comes from two of the most active volcanoes in Iceland, Katla and Grímsvötn. Both these volcanoes are covered by glaciers. Subglacial eruptions always produce a lot of tephra. Besides the eruptions vast glacier bursts (jökulhlaups) overflow great areas on their way to the sea and carry millions of tons of sediment down to the adjacent lowlands (H. Tómasson 1974).

5 SURFACE HYDROLOGY

5.1 Rivers

Icelandic rivers display strong individual characteristics according to their origin. Rivers flowing side by side are often of different character. One may have occasional tremendous floods while the other will not change its flow throughout the year regardless of the weather. One river may always be crystal clear, while its neighbour has a permanent dark brown or greyish colour. One river flows quietly even under thick winter ice, while the neighbouring streams remain ice-free all winter. Iceland has been called the child of ice and fire; it has been moulded by continuous interaction between these two elements and their opposite characters are reflected in the various features of the rivers. The common and general hydrological phenomena of Iceland cannot be explained nor understood without digging deep into the laws of glaciers and the nature of volcanism.

Icelandic rivers have been divided into three well characterised groups between which various intermediate stages exist. The groups are: Direct run-off rivers (dragár), spring-fed rivers (lindár) and glacier rivers (jökulár) (G. Kjartansson 1945), see fig. 2.

Direct run-off rivers are to be found where the bedrock is dense, that is in the Tertiary areas in West, North and East Iceland. These rivers usually have no distinct origin but are made up of contributions from a number of small brooks and intermittent creeks. Their flow is very much dependent on the weather, they increase when it is raining and then decrease and may dry up in dry seasons. In the same manner the water temperature responds quickly to variations in the air temperature. The water is warm in the summer but cold in winter. Ice forms quickly in these rivers when the air temperature falls below 0°C. During periods of frost the direct run-off rivers are small and can easily disappear. As thaw sets in, the rivers swell rapidly and tumultuously burst open the icecover that has formed over the winter. Ice dams are often formed under such a condition and the river overflows its banks. In flood these rivers carry great volumes of mud, but when they are not flooding they are crystal clear.

A good example of a direct run-off river is Grímsá in East Iceland. Its average run-off is 30.7 m^3/s. Maximum undisturbed flow is 312 m^3/s but it has reached 800 m^3/s in a flood crest caused by an icedam burst. In special weather conditions (frost and snowstorm) it has been known to dry up completely (S. Rist 1956).

The spring-fed rivers are in most respects entirely different from the direct run-off rivers. They are mainly found in areas of permeable Quaternary bedrock and recent lavas. Spring-fed rivers have distinct origins, often gushing springs, in which case the flow reaches its full capacity not far form the headsprings. The flow is very even all year round, and so is the temperature. The temperature of most of the springs is between 3-5°C depending on the rock temperature of the drainage area. They never freeze near the headsprings even in the hardest frost. Floods are rare and occur only in thaw perods in winter or early spring, when the ground is flozen and the water cannot penetrate into it. An example of a springfed river is Ytri-Rangá in South Iceland. Its average run-off is 38.5 m^3/s with very small variations (S. Rist 1956).

Glacier rivers originate in the glaciers and are fed by their meltwater. Their flow fluctuates considerably and is in close connection with the air temperature, precipitation being of much less importance. The flow increases in early summer and reaches its height in July and August.

Winter descends on the glaciers in September and there is a sudden decrease in the meltwater flow. Glacial rivers are very small all through the winter. A violent torrent gushing from an ice tunnel at the edge of the glacier on a hot summer day may dwindle to an insignificant brook or even disappear completely in late winter.

In the same way as the flow follows the annual temperature cycle, it takes daily fluctuations along with the temperature. The temperature of the water is close to 0°C at the glacier edge throughout the year (S. Rist 1956).

The main characteristic of glacial rivers is their brown or greyish colour caused by mud originating in the glacier bed. Vast amounts of gravel and sand are carried from the glacier bed and these form great sands as soon as the river reaches a level area and the current velocity declines. There it forms a braided stream with countless branches, constantly changing their courses as a result of their load and fluctuating flow.

The course fluctuation of glacier streams can be characterized under two headings, internal and external. The internal and most obvious ones concern changes of the flow and location of the river branches. They can take daily fluctuations and are usually irregular.

External changes occur when the whole river, with its triangular branch system, changes its location. These changes are slow but often regular and can take tens of years or even centuries (S. Þórarinsson 1974), see fig. 3.

The main cause of fluctuations is the deposit of glaciofluvial sediments in the river bed.

The main groups and characteristics of Icelandic rivers have now been dealt with. Broadly speaking, they display typical characteristics near to their origins, whereas further downstream their character tends to become less distinct as a result of intermixture with other streams (S. Rist 1956).

TABLE 1

The greatest rivers in Iceland

Name	Type*	Catchment area, km^2	Length	Mean ann. run-off m^3/s	Glacier in the catchment area km^2
1 Jökulsá á Fjöllum	J+L+D	7750	206	230	1500
2 Þjórsá	D+J+L+S	7530	230	405	1200
3 Hvítá-Ölfusá	L+J+S+D	6100	185	415	690
4 Skjálfandafljót	D+L+J+S	3860	178	95	140
5 Héraðsvötn	D+J	3650	130	120	225
6 Hvítá in Borgarfj.	D+L+J+S	3550	117	195	365
7 Jökulsá á Brú	J+D	3700	150	220	860
8 Lagarfljót	D+S+J	2900	140	150	190
9 Blanda	D+J	2370	120	60	200
10 Laxá í S.Þingeyjars.	L+S	2150	93	50	0

* The letters show the type of the river. Most rivers are a mixture of two or more types.

J = Glacier river (jökulá)

D = Direct run-off river (dragá)

L = Spring-fed river (lindá)

S = A lake influences the river (S. Rist 1965).

5.2 Glacier bursts

One phenomenon of the glacial streams which has made them most famous abroad are the so-called glacier bursts (jökulhlaups), the violent outbursts of water at the margin of the glaciers. They orginate mainly from two causes:

Firstly, glacier-dammed lakes. A glacier moving down a main valley passes the mouth of a tributary valley and prevents drainage from it, thus damming up a lake. Eventually if the dammed water attains a depth equal to 9/10 of the thickness of the glacier, it breaks its way through under the glacier, forming a glacier-burst. Such glacier-dammed lakes often outburst periodically. On a geological time-scale these lakes are short living phenomena. The fluctuating glaciers make them very unstable.

Secondly, subglacial geothermal and/or volcanic activity. In geothermal areas covered by glaciers the ice melts and water accumulates in melt-water chambers. Periodically a glacier burst escapes from these chambers. Volcanic eruptions sometimes cause or are accompanied by such bursts.

The flow of a glacier burst may be from a few cubic meters per second up to tens of thousands of cubic meters per second. The most violent glacier bursts in Iceland are accompanied by eruptions in Katla or Grímsvötn. The maximum flow in glacier bursts in Katla has been estimated at 100.000-200.000 m^3/s, which is the same order of magnitude as the largest rivers of the world. The total quantity of water discharged in these bursts may be several km^3. Glacier bursts do not last for a long time, usually only one or two weeks with a very sharp maximum peak. They may occur any time of the year (see figs. 4 and 5).

5.3 Lakes

In Iceland there are many lakes but only few are of a large size. Their basins have various origins. In the Quaternary areas the basins have often been formed by volcanic and/or tectonic activity. Volcanics such as lavas and palagonite formations dam up valleys. Mývatn and Langisjór are examples of such lakes. Explosive eruptions sometimes form deep circular craters

(Maar) that fill up with water. There are several small lakes of this type such as Ljótipollur and Grænavatn. After great eruptions, central volcanoes may collapse into a caldera in which a lake forms. This happend in 1875 after a violent outburst of Askja when Iceland's deepest lake, Öskjuvatn, with a depth of 220 m, was formed. Grabens are fairly common in Iceland. The most famous of them is the Þingvellir area. The largest lake of the country, Þingvallavatn, is partially due to this graben. Glacier-formed lake basins are also to be found in the Quaternary area. In the Tertiary areas, lake basins eroded by glaciers are the most prominent. Lagarfljót (Lögurinn) is an excellent example of such a lake. Landslides have in a few places dammed up heads of valley thus forming small lakes. Icedammed lakes have already been mentioned. Finally, lagoon lakes are frequently found, parted from the sea by narrow gravel banks. These lakes are differentiated from ocean lagoons only by the fact that their water is fresh or only very slightly saline. Examples are Hóp and Höfðavatn.

Kettle holes left by the melting of masse of stagnant ice after burial or partial burial by glacifluvial drift form a common type of pond all over the country. Alluvial fans, levees and other river deposits often dam up small lakes. Altogether there are 27 lakes of 5 km^2 or more and a good 80 in excess of 1 km^2 (S. Rist 1956).

5.4 Glaciers

Iceland derives its name from the glaciers that cover the highest mountains of the country. The glaciers of Iceland are the largest ones in Europe. They cover 11-12 km^2 of the country. The biggest one is Vatnajökull 8400 km^2, then comes Langjökull with nearly 1000 km^2 and Hofsjökull, just over 900 km^2. Mýrdalsjökull is 700 km^2. The Thickness of Vatnajökull is in most places 600-800 m, but can reach 1000 m. Its volume was estimated 3520 km^3 in 1955, but since then it has diminished considerably. The total volume of glacier ice in Iceland is 4000-4500 km^3. The glaciers reached their maximum extent around 1890, but have been recessing continuously since then. The line of demarcation between ablation and accumulation zones in glaciers is known as the equilibrium line. Above it the glacier has a net gain of mass over the year, below it there is a net of loss. The height of the equilibrium line depends on temperature and precipitation. On the southern slopes of Vatnajökull it is 1000-1100 masl. but 1300-1400 masl. on northern slopes. The equilibrium line is lowest in north-west Iceland at 700-800 masl. in the glacier of Drangajökull. Glaciers act as vast reservoirs of water, sometimes swallowing a considerable fraction of the precipitation and keeping it for decades, to return it later when the climate changes. The total shrinkage of Vatnajökull in the interval 1894-1968 has been estimated around 310 km^3 of ice and the shrinkage of Langjökull for same interval is thought to be 31 km^3 (G. Sigbjarnarson 1967, 1970). This has had a considerable influence on the run-off of glacier rivers and in fact some of the spring-fed rivers too. In cold periods such as in the decades leading up to 1890 all glaciers were retreating and the average run-off in rivers fed from glaciers was relatively low. During warm periods such as the years 1890-1965 all glaciers were recessing and the average run-off of these rivers was high.

TABLE 2

The largest lakes of Iceland

		Height above sea level m	Area km^2	Depth m max	Depth m mean	Volume GL
1	Þingvallavatn	101	83.7	114	34.1	2855
2	Þórisvatn	571*	70.0*	109*	41.4*	2900*
3	Lagarfljót	20	53.0	112	50.7	2688
4	Mývatn	278	36.5	4.5	2.5	90
5	Hvítárvatn	421	29.6	84	27.6	817
6	Hóp	1	29.0	8.5	5.5	163
7	Langisjór	663	25.7	73.5	18.5	476
8	Skorradalsvatn	57	14.7	48	22.5	333
9	Apavatn	59	14.0			
10	Svínavatn	123	11.8	39	12.5	147
11	Öskjuvatn	1050	10.7	217	115	1231
12	Höfðavatn	1	10.1	6.4	3.9	39

* This was before Þórisvatn was made into a reservoir. Now its size is variable (S. Rist 1975).

6 HYDROGEOLOGY

6.1 Cold groundwater

Due to heavy precipitation and little evapotranspiration the average surface run-off in Iceland is the highest in Europe at 55 l km^2/s. (S. Rist 1956). Where the bedrock or the surface layers are permeable a high fraction of the precipitation drains into the ground. This water often appears again in springs or springhorizons in lower areas or as coastal springs at the shore. As run-off map (fig. 12) shows, virtually no surface run-off is to be found on a 1330 km^2 area on the Reykjanes peninsula and on 370 km^2 area on Melrakkaslétta. All the precipitation falling on these areas drains towards the sea underground and discharges in coastal springs.

In the permeable areas of Iceland, springs are very common. Only a few the largest ones can be shown on a small scale map. On the International Hydrological Map of Europe, only springs and springgroups discharging more than 1 m^3/s are indicated outside the smaller supplied springs. About 80 such springs are shown. Nearly all these gigantic springs are inside the volcanic zones and always connected to lava fields and/or fissure swarms.

Very little is known about groundwater divides in Iceland and they are nowhere shown on the map. In the volcanic zone they are in some places thought to differ from the surface water divides. In the older parts of the country, the Tertiary regions, they are likely to be in close connection to the topography.

In most cases the groundwater flow in the uppermost groundwater layers is thought to be parallel to the dip of the groundwater table. Anisotropy might occur under those special circumstances where a fissure swarm cuts the rocks oblique to the dip of the groundwater table.

In deeper aquifers the groundwater flow is characterized by high anisotropy between horizontal and vertical permeability. In a lava pile the permeability is much higher parallel to the layering than perpendicular to it.

TABLE 3

Aquifers in Iceland

1. Aquifers in unconsolidated rocks.
   a. Gravelly and sandy fluviatile and fluvioglacial deposits.
   b. Rock slides and screes.
   c. Eskers and terraces.

2. Aquifers in recent lavas.

3. Aquifers in permeable bedrock.
   a. Interglacial lavas and fresh Tertiary lavas.
   b. Pillow lavas and pillow breccia.
   c. Active fissure swarms.

In addition to third class there are thermal water aquifers at greater depths. They will be discussed later.

Aquifers of class 1 are best represented in Tertiary regions, while in the Quaternary regions class 2 aquifers tend to occur in the volcanic zones and class 3 aquifers outside the volcanic zones.

Icelandic coldwater aquifers can be divided into three classes as shown in table 3.

6.2 Thermal waters

Iceland is characterized by a very high geothermal gradient, ranging from about 40°C/km in the oldest Tertiary rocks to about 160 °C/km in the Eo-Pleistocene rocks adjacent to the volcanic zones; while a still higher gradient can be found inside the high temperature areas. Assuming thermal conductivity to be the most effective form of heat transport, the thermal gradient should continue to increase towards the volcanic zone axis, but due to water circulation in the Quaternary strata which becomes increasingly permeable towards the zone, a trend reverse to that of the regional gradient is found (G. Pálmason 1973).

In view of this high geothermal gradient it is not surprising that wide-spread hydrothermal activity exists in Iceland (fig. 2).

Thermal waters of Iceland are divided into two groups: high thermal waters and low thermal waters. This division fits well into the general classification of thermal and thermomineral water. In general the terms mineral spring and thermomineral spring are restricted to springs that contain more than 1000 ppm of total dissolved solids.

All Icelandic high temperature water can be defined as thermomineral water. Nearly all cold water and low temperature water contains less than 1000 ppm dissolved solids and is not defined as mineral water. Exeptions are the soda springs and salt water intrusions (see table 6).

The nature of the thermal water aquifers of Iceland is still somewhat of a mystery. However it is obvious that dykes, faults and fissures play an important role, since most warm springs and thermal areas are connected to these features. They most likely act as drainage systems in extensive stratiform aquifers of semi-permeable layers, rather than as real aquifers themselves. Thermal water is of less viscosity than cold water and is able to flow through rocks of much lower intrinsic permeability. Thermal water aquifers can therefore be expected in rocks where no cold water aquifers exist.

Thermal water flow seems to exist at great depths under most parts of the country. Generally speaking it streams outwards from Mid-Iceland independent of small scale topography (Bragi Árnason 1976). Here and there the water rises to the surface because of faults and dykes, causing low temperature springs. In high temperature areas the water seems to undergo further heating, probably from relatively shallow recent intrusions. More than 250 low temperature areas exists in Iceland. They vary considerably in size, from one single thermal spring up to tens of them. The run-off form these areas also varies from almost nothing up to 250 l/s.

Deildartunguhver, the world's largest thermal spring, discharges 180 l/s of boiling water.

The total natural discharge has been estimated at approximately 1500 l/s of 75°C thermal water. The temperature of the water at depth is always less than 150°C and all the water is in a liquid state. In the springs themselves the temperature is seldom over 100°C. Dissolved elements are most often between 200 and 400 ppm (Table 6).

Unlike the high temperature areas, the low temperature areas are not connected to the volcanic zones. They are spread all over the country, although rare in east and southeast Iceland.

The thermal water of the low temperature areas is discharged in hot springs, boiling ponds and sometimes geysers.

Geysers appear in both high and low temperature areas. The archetype of them all, Geysir in Haukadalur, is now inactive, but the neigbouring geysers Strokkur, Smiður and Óþerrishola erupt periodically. Geysers are also to be found in a few other places in Iceland.

Geysers are rather shortlived, variable phenomena. Earthquakes affect them considerably, sometimes stimulating active geysers or even forming new ones, as well as destroying others.

Geysers are extremely rare. Outside Iceland they are best known in Yellowstone, USA, New-Zealand and Kamchatka.

The 15-20 **high** temperature areas of Iceland (the number depends on definition) are all inside the volcanic zones and are usually connected to central volcanoes. Their water temperature is very high, 150-300°C at shallow depth. The amount of dissolved solids ranges between 1.000-40.000 ppm. In some places a high fraction of the thermal water is in the form of steam. The most common form of springs are fumaroles (steam vents) and solfataras (mud springs).

TABLE 4

The high temperature areas of Iceland

Name	Height	Area	Notes
Reykjanes	20-40 masl	3 km^2	Thermal brines, fumaroles, geysers.
Svartsengi	40-60	2 "	Thermal brine, heating service.
Krísuvík-Trölladyngja	135-350 "	25 "	Thermal brine, fumaroles solfataras, old sulphur mine.
Brennisteinsfjöll	500 "	< 1 "	Old sulphur mine.
Hengill	50-500 "	75 "	Fumaroles solfataras, soda springs.
Geysir	100-150 "		Geysers.
Kerlingarfjöll	880-1020"	13 "	
Hveravellir	600-640 "	1 "	Geysers.
Torfajökull	600-1050"	120 "	Fumaroles.
Vonarskarð	1000-1100"	11 "	Solfataras.
Grímsvötn	1300-1719"	≃55 "	Covered by glacier.
Sólheimajökull	1000-1200		Covered by glacier.
Kverkfjöll	1500-1920"	30 "	Fumaroles, solfataras.
Askja	1050-1200"	25 "	Solfataras.
Hrúthálsar	1000 "	3 "	
Fremri Námar	820-930 "	3 "	Old Sulphur mine.
Námafjall	340-450 "	11 "	Solfataras, fumaroles.
Krafla	500-680 "	25 "	Solfataras, fumaroles, geothermal power plant.
Þeistareykir	280-320 "	20 "	Fumaroles, old sulphur mine.

6.3 Soda springs

Soda springs are characterized by high CO_2 content. They are abundant in Snæfellsnes peninsula and at the margin of many high temperature areas. In other places they are rare. Icelandic soda springs can be divided into three groups according to their geological site.

1 Soda springs independent of recent volcanic activity.

2 Soda springs connected to high temperature areas.

3 Short-lived soda springs (and mofettes) accompanying volcanic eruptions.

The soda springs of Snæfellsnes belong to the first group. Outside Snæfellsnes few others are known. Soda springs connected to high temperature areas are abundant in the Torfajökull area, in Kerlingafjöll, in Hengill and elsewhere. An example of the third group is the CO_2 rich water that appeared in springs near Hekla accompanying the eruption of 1947-1948 (G. Kjartansson 1957). During the famous 1973 eruption of Heimaey Vestmannaeyjar, great difficulties were caused by the presence of CO_2 gas.

The gas and the water of the soda springs are of different origin and follow different tracks underground. The direction of the groundwater flow is controlled by the groundwater head and is generally from the highlands towards sea. The flow of the gas is controlled by the CO_2 pressure. The gas originates in the degassing of cooling magma in the crust. It rises towards the earth's surface and has to flow through the groundwater belt, where it at least partly dissolves in water. The gas seems to follow rather narrow tracks through the groundwater belt, perhaps along faults and dykes. On reaching the surface it most often appears in springs. These springs are of all kinds: thermal springs, cold permanent springs and even small temporary springs.

Here we have an indication of the independent movement of the gas; it appears in springs which occur incidentally in places where it reaches the surface.

6.4 Saline groundwater

Both warm and cold saline groundwater occurs in Iceland. The salt content can have one of two sources, the more common being seawater which mixes directly with groundwater in some places. This type of water includes all the cold saline groundwater as well as the greater part of the thermal saline water. It is indicated by a $mgCl^+/mgCl^-$ ratio of approximately 0.6.

In addition to this, water at high temperatures can easily wash out Na^+ and Cl^- from the bedrock. The high temperature areas in most places discharge water rich in these elements. Its $mgNa^+/mgCl^-$ ratio ranges between 9.3 and 1.9 depending on the temperature and rock type (B. Árnason 1976). High temperature water should however not be classified as saline water unless it is more or less mixed with seawater. In some places seawater is to be found in silty marine layers of late glacial times.

The biggest seawater intrusion in Iceland occurs in the Reykjanes peninsula. The peninsula is mostly made up of young lavas and palagonite formations. The regional permeability is so high that in spite of considerable precipitation, no surface runoff exists. Seawater is to be found in all the western part of the peninsula underneath a lens of fresh groundwater. On the border between the fresh and saline water there is a thin mixing zone. Evidence points to deep partially confined thermal water flow westwards the Reykjanes peninsula. This water becomes more and more mixed with saline water the farther it flows west, as shown by rising salinity in the high temperature areas on the peninsula. (F. Þórarinsson et. al. 1976, J. Elíasson et. al. 1977).

Saline thermal water is common in boreholes in the lowlands of south Iceland. The extent and origin of this water is unknown at present.

Seawater intrusions are to be found in some other places but they have not been studied sufficiently to be mapped.

6.5 Chemical classification of the groundwater

The groundwater can be divided into groups according to its chemistry. The elements in solution are of three main sources.

1 Primary elements. These elements are already dissolved in the water when it percolates into the ground. Precipitation contains traces of dissolved solids and water can dissolve elements from the earth's surface before it drains down to the groundwater. Subterranean sea is also an example of groundwater containing primary elements.

2 Secondary elements. These elements are dissolved by the groundwater from the host-rock. Their concentration is controlled by temperature and rocktype. The majority of dissolved solids in the groundwater usually originates in this way.

3 Additional elements. These are the juvenile elements (gasses and liquids) originating in the earth's interior. They are thought to be most abundant in geologically active areas, such as volcanic- and orogenic terranes. Water from the soda springs is a good example of this group.

The temperature of the groundwater exerts exact control over the concentration of the dissolved solids. In Iceland the concentration of many elements in the water of warm springs and wells is used as an indicator of the original temperature of the geothermal groundwater systems at depth.

On the basis of temperature it is possible to subdivide all the above mentioned classes to obtain a scheme of the main groundwater types of Iceland.

TABLE 5

The groundwater classes

Temp.	Primary elements	Secondary elements	Additional elements
Cold	Cold subterra-nian sea	Cold freshwater	Soda springs
Warm	Warm subterra-nian sea	Low temperature water	Warm soda springs
Hot	Hot brine	High temperature water	

Groundwater in most or all cases is a mixture of two or more of these groups. However it is usually possible to decide the dominant chemical character and thus classify the water.

Table 6 gives the chemical composition of samples of water from 6 of the above mentioned groups.

TABLE 6

Chemical composition of typical samples from the main groups of Icelandic groundwater. Concentrations in ppm.

	1	2	3	4	5	6
Temp. C°	270	84	98	57	2	3.8
pH/C°	6.27/270	8.7/84	8.8/98	6.72/19	6.21/22	7.22/20
SiO_2	592	509	127	219	77	12.8
Na^+	9854	209.0	78.8	451.2	660.0	7.1
K^+	1391	22.4	2.1	34.2	26.8	0.4
Ca^{++}	1531	0.8	4.1	86.8	256.1	4.7
Mg^{++}	1.15	0.03	0.01	20.7	60.5	1.4
Co_2 tot*	1437	136.6	13.5	1500	4100	12.7
SO_4	28.7	114.5	62.1	41.2	125.4	3.1
H_2S tot**	31.5	0.7	0.7	0.1	0.1	0.0
Cl	18827	122.0	56.3	80.0	239.0	12.2
F^-	0.1	11.5	2.1	5.0	0.61	0.1
Total	33653	1133	372	1649	2584	54.5

*$H_2CO_3 + HCO_3^- + CO_3^{--}$ **$H_2S + HS^- + S^{--}$

1. Reykjanes thermal brine.
2. Geysir high temperature area.
3. Reykjavík (Laugarás) low temperature area.
4. Lýsuhóll thermal soda spring. (Well no. 6).
5. Ölkelda in Snæfellsnes: Soda spring.
6. Lækjarbotnar in Mosfellshreppur: fresh water springs.

References: 1,2,3 S. Arnórsson 1974
4 and 5 J. Benjamínsson pers. inf.
6 Þ. Þóroddsson pers. inf.

7 TUNDRA

No real tundras occur in Iceland since the highlands of the country are mainly bare lava fields, sand-gravel-deserts and ground-moraine. The soil of vegetative areas is very thin. Considerable areas covered by vegetation occur here and there especially north of the great glaciers. In these vegetative highland areas palsa and cryokarst forms occur in almost every large moor and swamp region. They are most common at heights of 450-700 m above sea level. The upper limit of palsa areas coincides with the limit of close vegetation. The lower limit is controlled by climatic conditions. Palsa and cryokarst are due to long time clima-changes. In the warm years of 1930-1960 they declined considerably but since 1965 they have been on the increase.

Palsa and cryokarst are the Icelandic forms of tundra.

8 WATER RESOURCES MANAGEMENT

8.1. Power resources.

The power sources of Iceland are to be found in water. Rivers and streams produce nearly all the island's electrical power. Geothermal water heats the majority of the houses.

Total generation of electricity in 1978 was 2674 GWh, made up as follows:

hydropower	97.4%
geothermal power	0.7%
oilpower	1.9%

In 1978 there were 15 hydroelectric plants in the country designed to produce an average yearly total of 3320 GWh. Fourteen of these plants had reservoirs with a total capacity of 1480 Gl; of these, 1000 Gl were accounted for by the reservoir in Lake Þórisvatn which feeds the great hydroelectric stations at Búrfell and Sigalda. Although still far from being fully exploited, Icelandic hydropower and other domestic power resources are scheduled to supercede the use of oil for generating electricity in the not too distant future.

Geothermal water is of great economical importance for Iceland, over 60% of the inhabitants living in houses heated geothermically. The biggest geothermal power station in Iceland is the Reykjavík Municipal Heating Service. It is 450 MW, larger than any hydropower plant in the country. The numerous swimming pools all over the country nearly all use geothermal water. The hothouse industry, which is of considerable importance, is entirely based on geothermal heat; geothermal hydropower plants are in construction and fish-cultivation in heated ponds is a growing industry.

In most cases it is possible to use geothermal water directly in the heating service system, but in some places the water is so corrosive that heat transfer is necessary. Geothermal water is used as drinking water in many places. In Reykjavík for instance a part of the drinking water is of geothermal origin.

8.2 Water works.

Drinking water management does not pose very great problems in Iceland. In most places enough groundwater is available, although surface water is however still used. As a rule it is easiest to harness groundwater inside the volcanic zones, where all the precipitation percolates into the ground and the groundwater flow is quantitative.

The first waterworks in Iceland were built in Ísafjörður in the year 1902 and in Hafnarfjörður in 1904.

Up to 1902 the drinking water of Reykjavík was taken from small wells here and there in the city and carried in pails to the houses. The first pipelines were laid in 1902. This was a primitive system where the water was pumped by handpumps from the wells to the houses. The Reykjavík Waterworks were built in 1908-1909. They originally took water from the river Elliðaár but in 1910 the Gvendarbrunnar wells were harnessed. They have met the demands of the town for the most part up to the present.

The water supply area of Reykjavík, Gvendarbrunnar,is just out of town on the borders of the Reykjanes volcanic zone, where great springs occur at the margin of a lava field and in connection with a fissure zone. The average freshwater utilization of the town is about 850 l/s. All this water is taken from a limited area at Gvendarbrunnar. Very productive aquifers are known south of Reykjavík, so in the near future freshwater should not pose any problems in the capital. The longest pipeline for water supply in Iceland is that of the Vestmannaeyjar. Laid in 1960, it is 32 km in length, of which 12 km are in the sea. The water supply is at one of the great springs of Eyjafjöll, emerging from pillow breccia at the base of the stratovolcano Eyjafjallajökull.

In the older parts of the country the bedrock is much denser than in the volcanic zones and the water supply therefore more problematical. Here the best aquifers are in the unconsolidated rocks, especially in river deposits and rockslides.

Annual water consumption from public water works and geothermal heating services in Iceland has been estimated at 95 million tons. 41 million tons or 43% is groundwater but about 6 million tons or 6% is surface water.

The geothermal water consumption is approximately 48 million tons or about 51% of the total consumtion. About 75% of the geothermal water is used for space heating but the rest is for public and industrial use (Þórólfur H. Hafstað, pers. inf.).

TABLE 7

Hydro Power Stations and Storage Reservoirs

Hydro Power stations	Mean generation capacity per hydrological year, GWh	Storage Reservoir 1966 Gl	1966 GWh	1977 Gl	1977 GWh
Þórisvatn				1000.0	450.0
Sigalda	800.0			150.0	67.0
Búrfell	1,640.0			0.3	0.8
Sogsstöðvar	500.0	166.1	28.1	166.2	28.1
Elliðaár	4.5	2.0	-	2.0	-
Andakíll	32.0	31.7	3.3	31.7	3.3
Rjúkandi	7.3	0.0	-	0.0	-
Mjólká	49.0	0.4	0.2	4.7	4.5
Reiðhjalli	2.8	0.0	-	0.0	-
Fossavatn and Nónhornsvatn	5.0	0.8	-	0.8	-
Sængurfoss	2.0			0.0	-
Blævadalsá	1.0			0.0	-
Mýraá	0.3			0.0	-
Þverá	4.2	9.8	0.9	9.8	0.9
Laxárvatn	3.7	21.2	0.7	21.2	0.7
Gönguskarðsá	8.9	0.0	-	0.0	-
Skeiðsfoss	20.0	28.5	2.5	28.5	4.5
Garðsá	1.1	0.0	-	0.0	-
Laxá	160.0	0.0	-	0.0	-
Lagarfoss	48.8			50.0	2.0
Fjarðará	1.2	2.0	-	2.0	-
Grímsá	18.0	5.0	0.4	5.0	0.4
Búðará	1.0	0.0	-	0.0	-
Smyrlabjargaá	10.0			5.5	1.1
Total	3,320.8	267.6	36.1	1,480 4	563.3

(Orkumál 1978)

PART III FAROE ISLANDS (L.J. Andersen, J. Rasmussen, N. Kelstrup)

1 INTRODUCTION

1.1 Location

The Faroe Islands are situated in the Atlantic Ocean between 64° 24′ to 61° 26′ N and 7° 41′ to 6° 15′ W.

The island-group consists of 18 inhabited islands with a total area of 1400 km^2. Mean height is 300 m, the highest point being 882 m above sea level.

The distance to the sea nowhere exceeds 5 km. The drainage density is high.

1.2 Climate

The Faroe Islands have an oceanic climate characterized by a small temperature difference, 7° C, between summer and winter. The mean temperatures in the period 1926 - 1950 for Tórshavn have been 4.1°C for February and 11.1°C for August. The mean annual precipitation shows large variation for different localities, for example Tórshavn 1422 mm, and Klaksvik 2711 mm during the period 1926 - 1950. The increase due to altitude amounts to about 5% per 100 m elevation. Precipitation occurs throughout the year with a maximum within the period October - January and a minimum in May. Winter precipitation often falls as snow, which normally melts within a few days. The actual evapotranspiration is about 470 mm per year.

1.3 Vegetation and land use

Natural vegetation consists of heather, grassy heaths and bogs. Only 6% of the area is under culture. The rest of the area is used for extensive sheepfarming.

The soil on the grassy heaths is developed as peat with a low infiltration capacity, thus overland flow occurs as a common phenomenon.

1.4 Water consumption

Almost all water consumption is taken from surface water. The public water supply to larger communities is based on water reservoirs.

Locally springs are utilised for the public water supply.

2 GEOLOGY

2.1 General description

The Faroe Islands are situated on the submarine ridge between Scotland and Iceland, the Wyville-Thompson ridge and the Iceland-Faroe ridge. Geologically the islands belong to the North-Atlantic basalt province.

The islands are build up of floodbasalt which is extruded subaerially in the earliest tertiary (paleocene-eocene). Layers of minor importance consists of coal, tuff-agglomerate and intrusives. The total thickness of the basalt and subordinate layers is about 3.000 m.

During the Quaternary the Faroe Islands were an independant glaciated area. Quaternary deposits are mainly tills with a thickness of less than 5 m. The glacial erosion led to creation of cirques, with the consequence that the islands are split up in to numerous minor catchment areas.

To postglacial times belong numerous peat deposits.

2.2 Hydrogeology

The basalts are build up of dense lavaflows with an thickness up to 20 m. Porosity is of secondary origin and is found in joints and faults.

Low storage capacity is found in these rocks, but high permeability is found in (faultzones) fissures.

The agglomerates and coals, occuring only on two islands, have the ability to conduct water, but are of only minor extent and thickness.

The tills are less than 5 m thick and do not cover coherent areas.
The peat deposits have high storage capacity and rather wide distribution, but however, low permeability.

In conclusion, no major aquifers are found on the Faroe Islands.

Most of the springs utilised for water supply to small communities emerge from the basalts.

So far 4 thermal springs (10-20°C) have been found on Streymoy and Eysturoy. The thermal springs are probably connected to restricted fissure systems which conveys the recharge water deeper into the basalt than normal for fissure systems on the islands. Total dissolved solids in the water from the thermal springs are below 100 ppm and deviate only slightly from other springs by containing $NaHCO_3$, and in a higher SiO_2-content.

No sign of recent volcanic activity has been recorded in the islands; thus most authorities exclude a volcanic origin of the springs.

3 CHARACTERISTICS OF THE GROUNDWATER SYSTEM

All information about ground water is obtained from springs since no water wells have been drilled on the islands. The flow directions of the ground water do not necessarily follow the flow direction on the surface water. This is the case at Klaksvik, where the topographic catchment of the spring is very small. The circumstances indicate that the ground water catchment is determined by an impermeable basalt layer crossing the surface water divide and dipping south east towards the springs.

Only a few analyses of groundwater are available. These indicate a $NaCl+CaHCO_3$ groundwater type with an amount of total dissolved solids less than 100 ppm.

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MYNDIR

ORKUSTOFNUN

The age divition of the Icelandic bedrock and its relation to neighbouring basaltic areas

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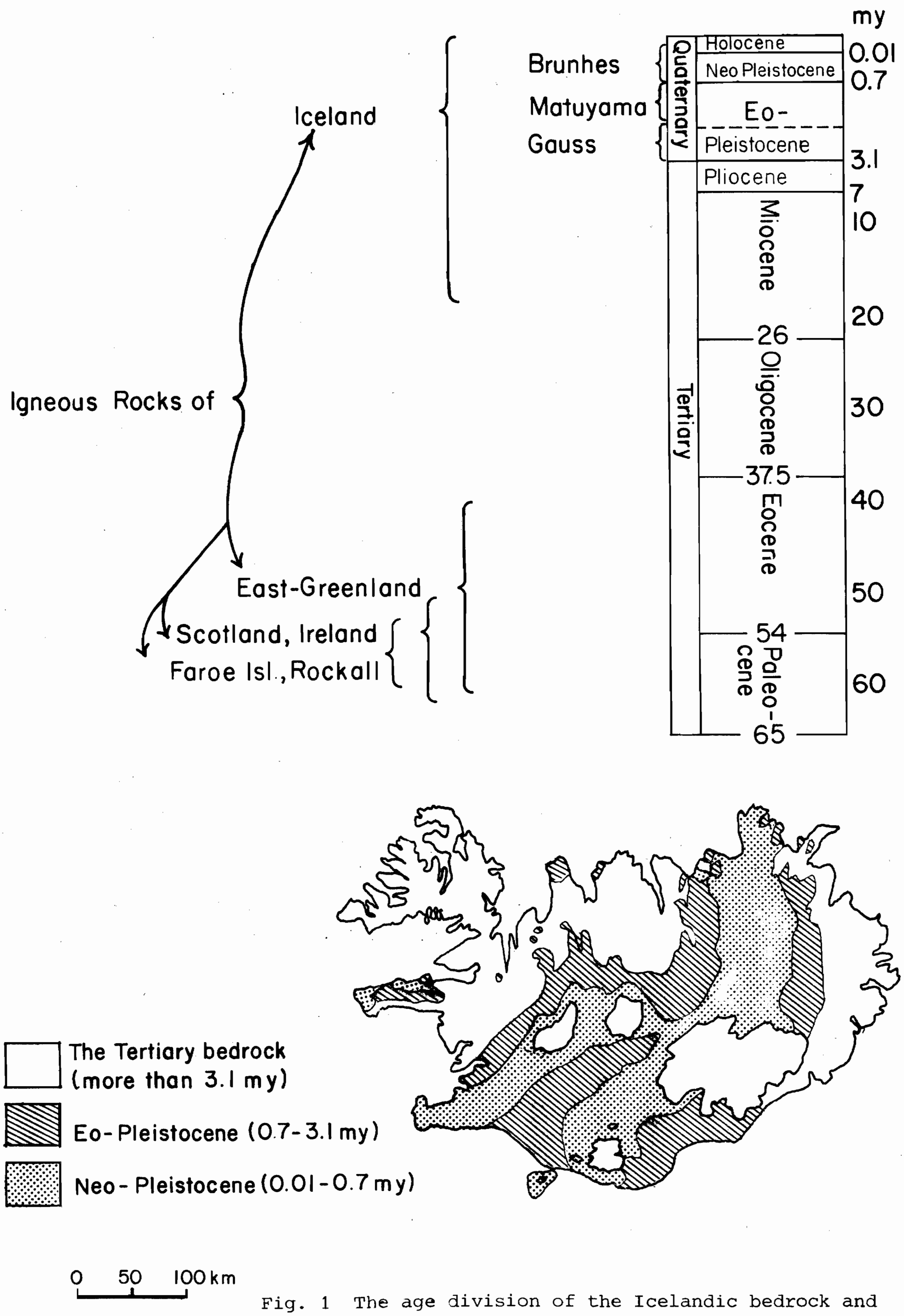


Fig. 1 The age division of the Icelandic bedrock and its relation to neighbouring basaltic areas.

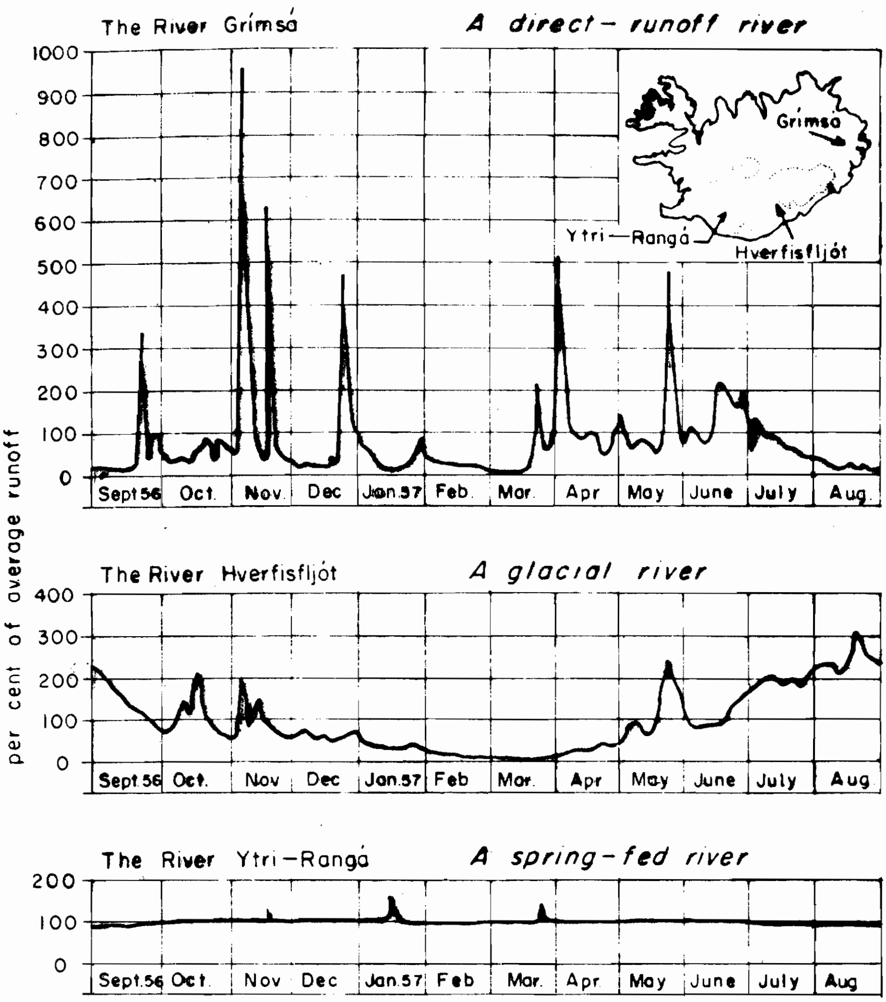


Fig. 2

Comparative flow graphs for the three types of rivers in Iceland, showing % of the average flow (G. Kjartansson 1943).

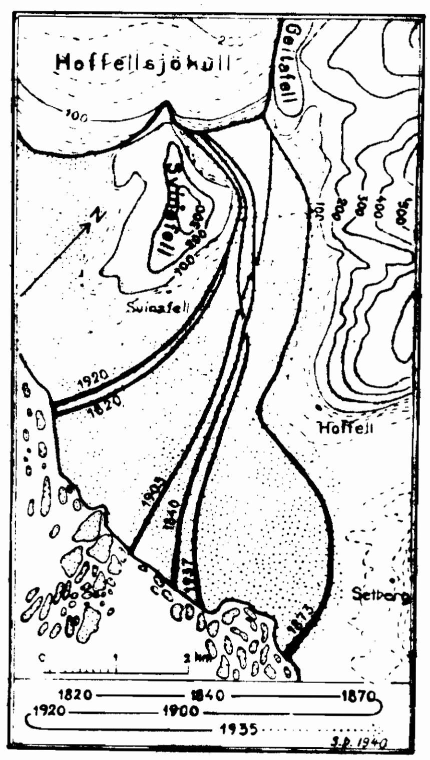


Fig. 3 The braided glacier stream Hoffellsá SE-Iceland. The figure shows the fluctuations of its main channel during the period 1820-1937 (S. Þórarinsson 1940).

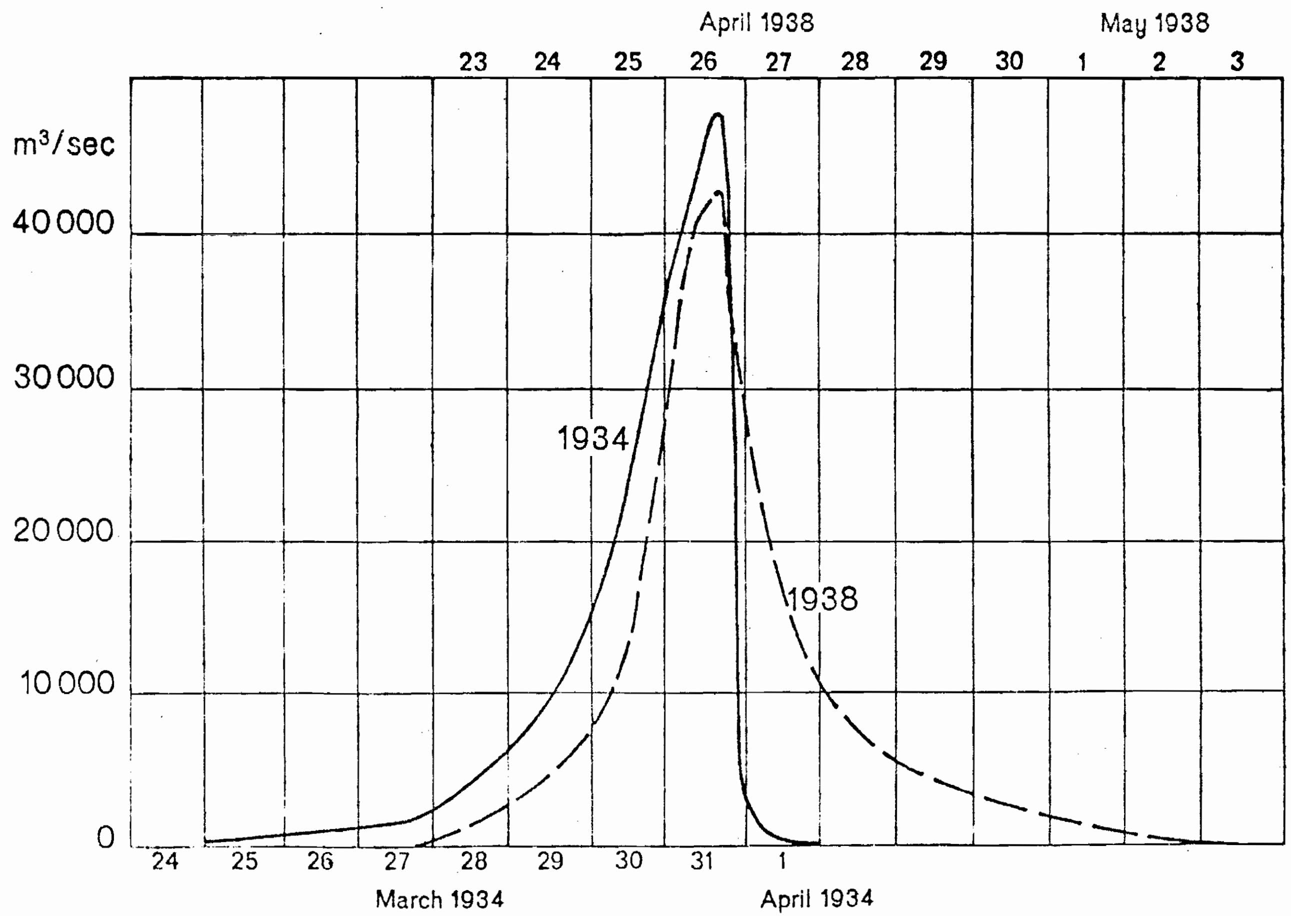


Fig. 4 Discharge graphs of the glacier bursts from the Grímsvötn central volcano in Vatnajökull in the years 1934 and 1938 (S. Þórarinsson'74).

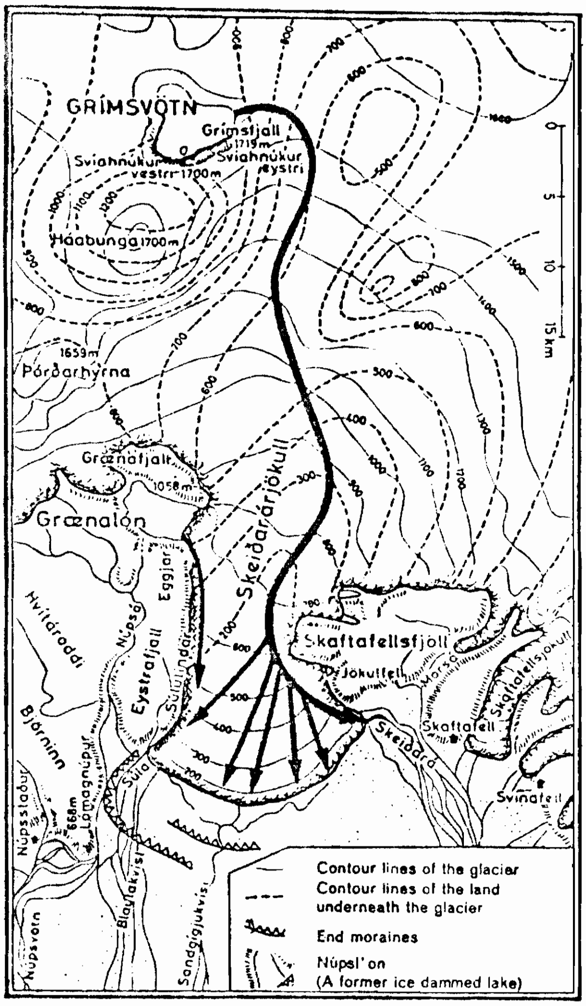


Fig. 5 Courses of the glacier burst from the meltwater chamber of Grímsvötn and the lateral lake of Grænalón. The end moraines of Skeiðarárjökull from the 18th and 19th centuries and the former lateral lake of Núpslón also shown.

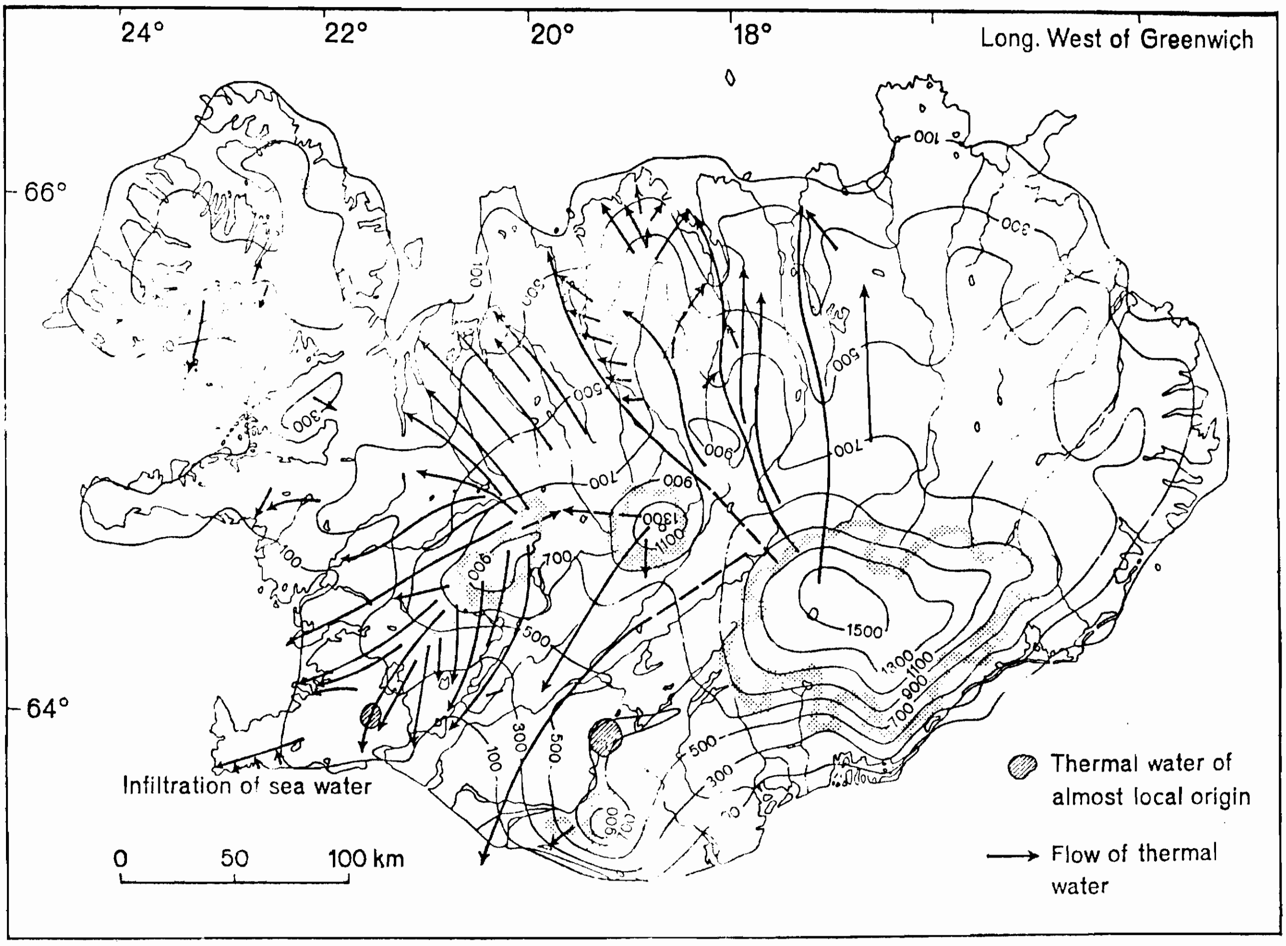


Fig. 6 The recharge areas and the general pattern of flow of thermal groundwater systems in Iceland as indicated by deutrium content. Isolines shown are average topographic heights in meters (Based on B. Árnason 1976).

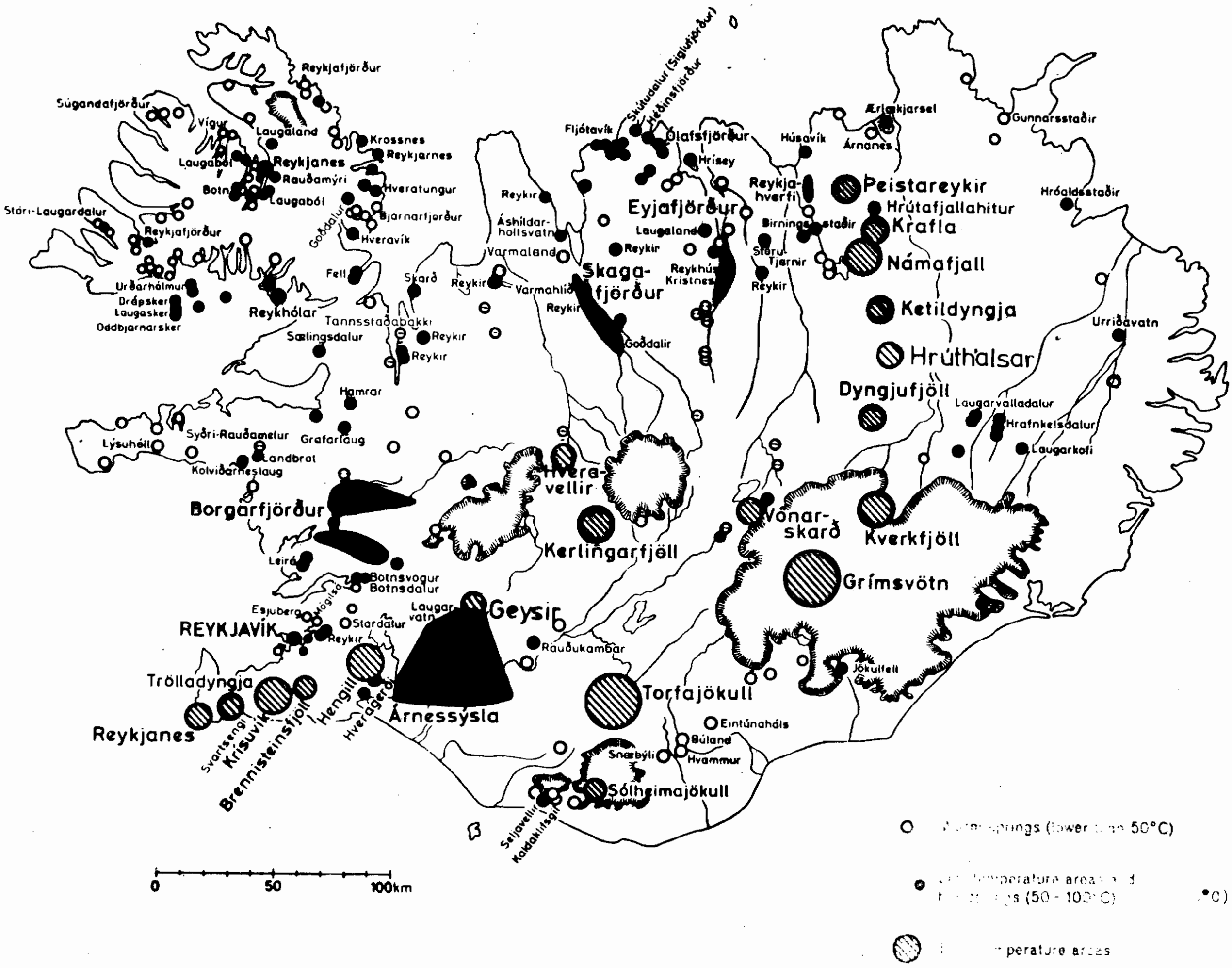


Fig. 7 Thermal springs and spring areas of Iceland. Figures 8 and 9 give a closer view of the thermal areas of Borgarfjörður and Árnessýsla (Based on W. Schutzbach 1976).

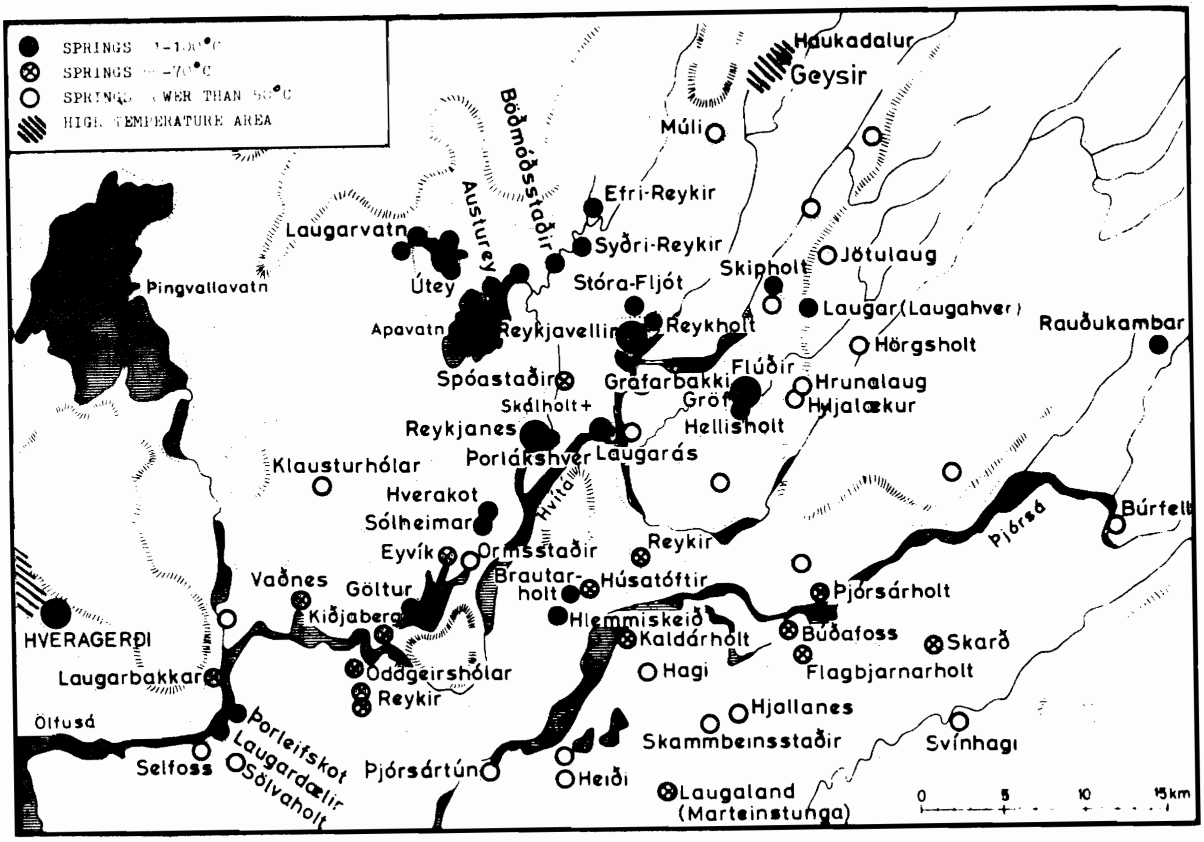


Fig. 8 Thermal springs of Árnessýsla (Based on W. Schutzbach 1976).

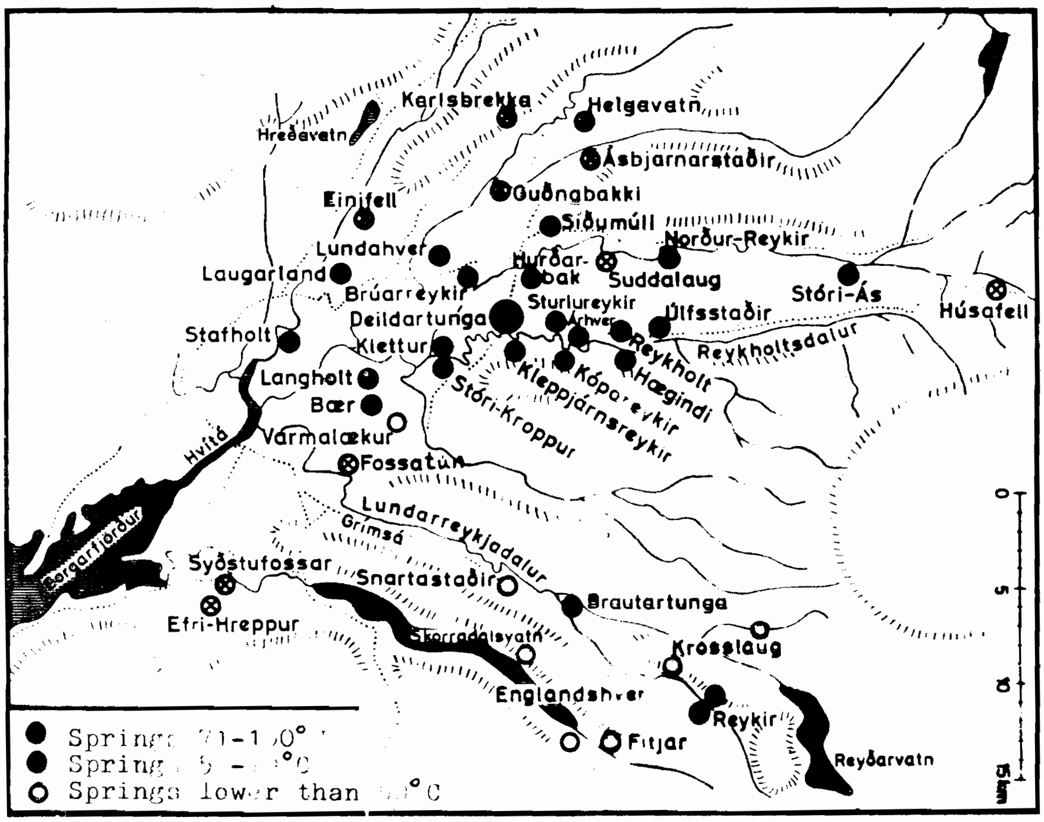
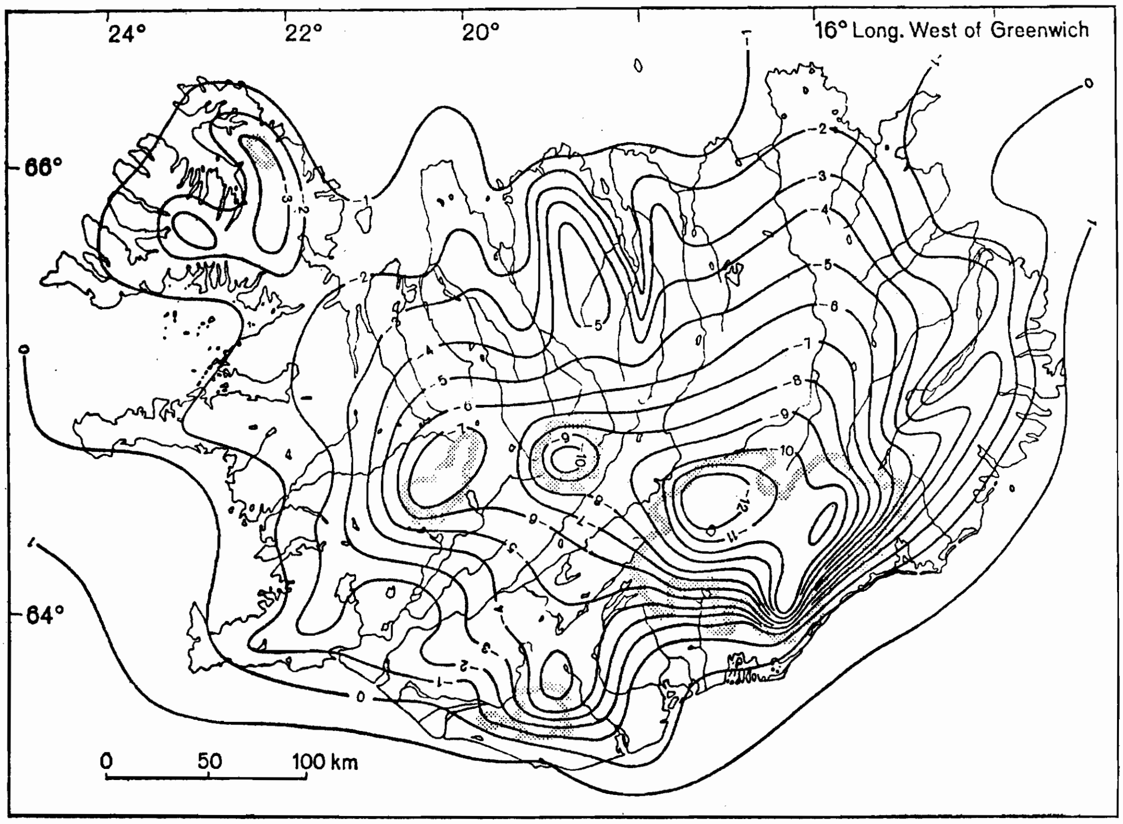


Fig. 9 Thermal springs of Borgarfjörður (Based on W. Schutzbach 1976).



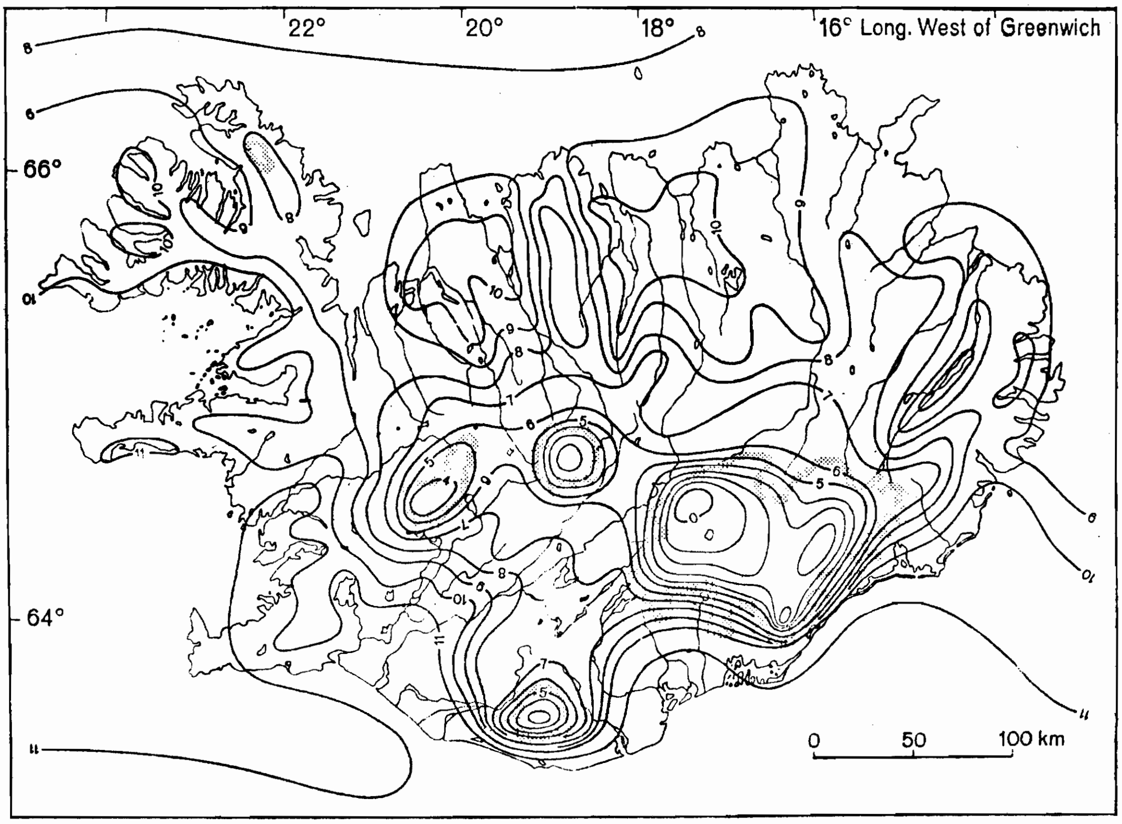


Fig. 10 The mean temperatures in January and July. Averages for 1931 -1960, isoterms in °C (Hlynur Sigtryggsson).

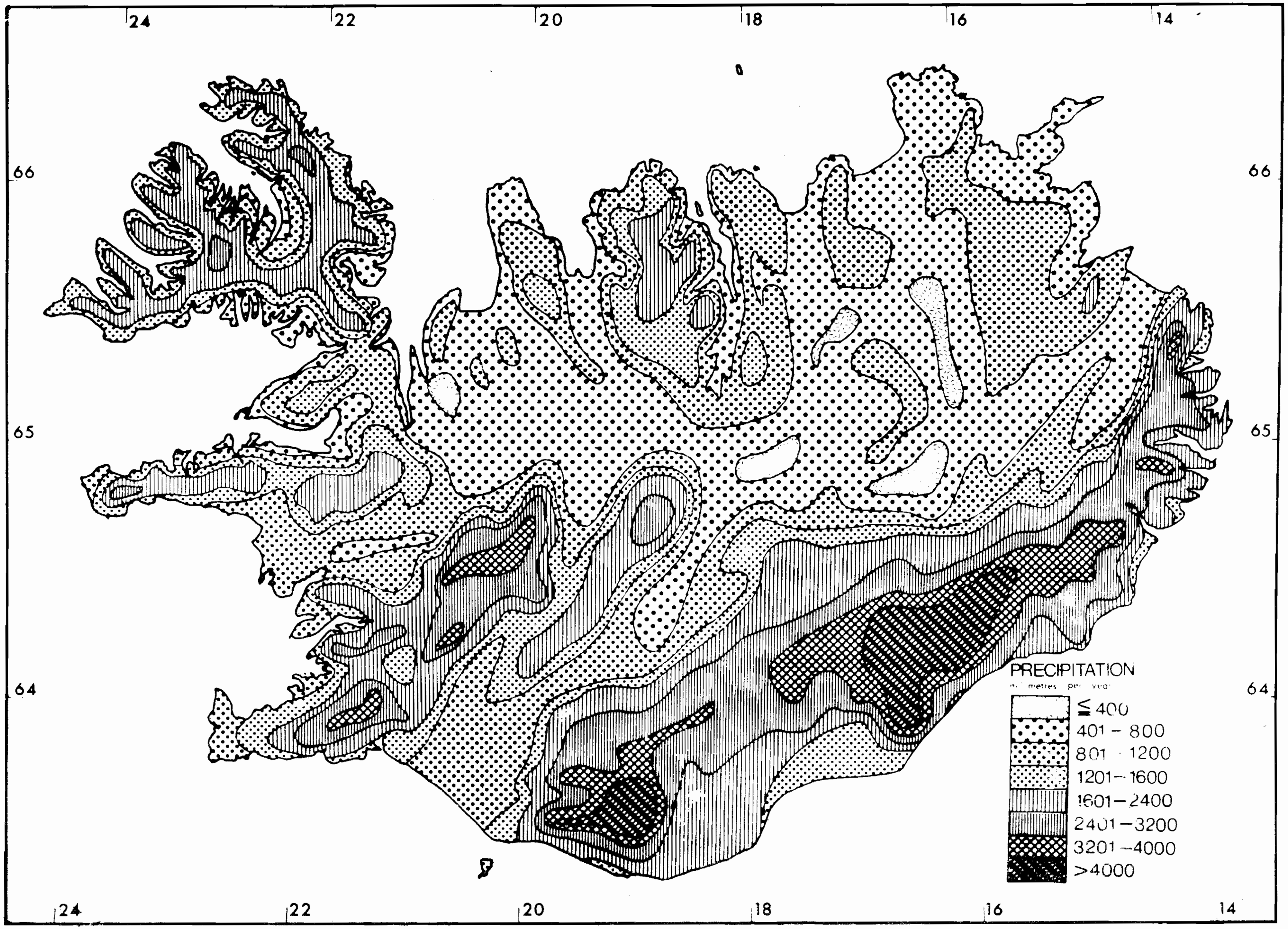


Fig. 11 Distribution of precipitation (A.B. Sigfúsdóttir 1965).

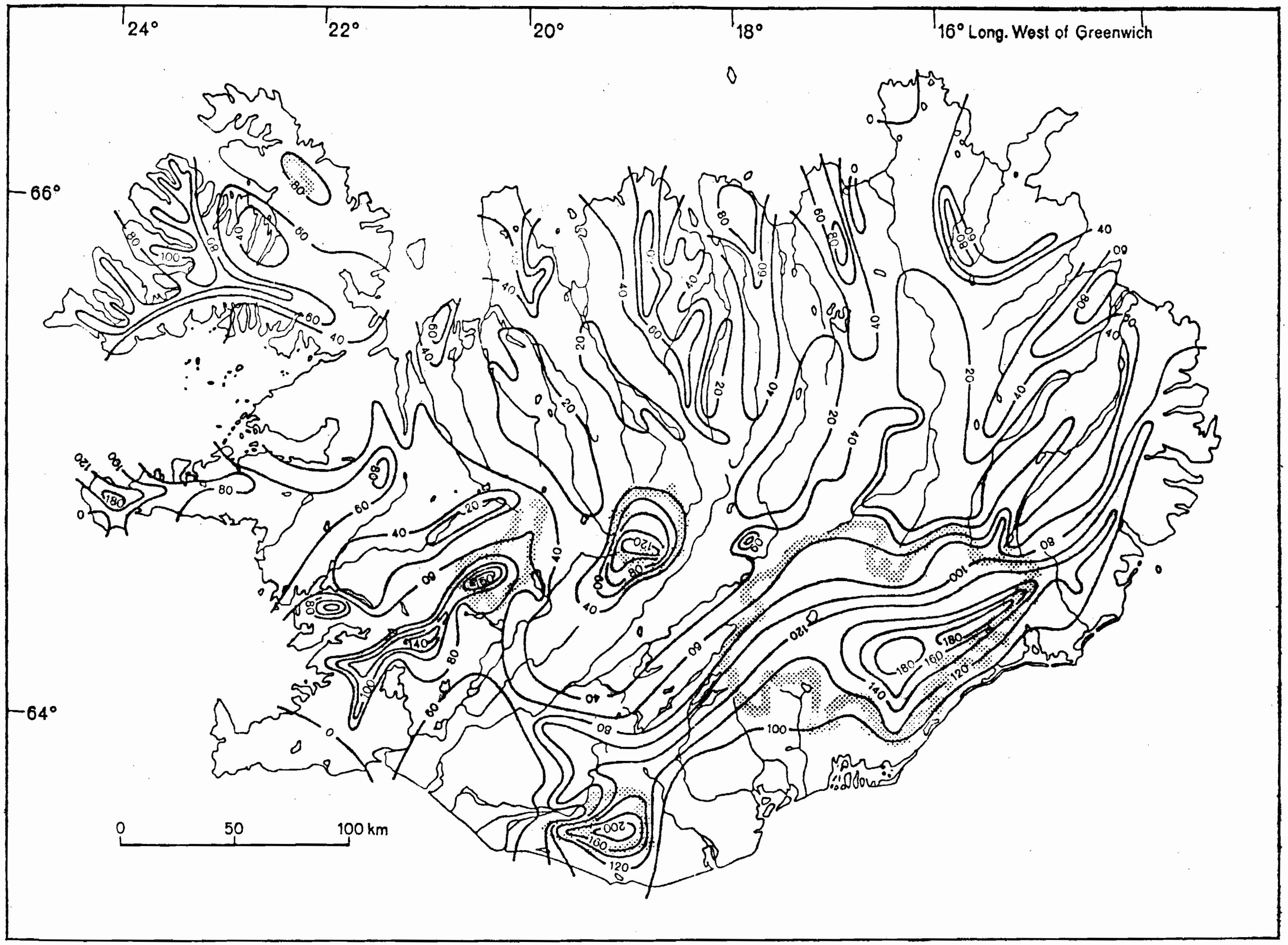


Fig. 12 Run-off map of Iceland, l/s km^2 (S. Rist 1956).

ÁGRIP (ABSTRACT IN ICELANDIC)

Ritgerð þessi er samin sem fylgirit með íslenska hlutanum af Hinu alþjóðlega vatnafarskorti af Evrópu 1:1.500.000 (International Hydrogeological Map of Europe 1:500.000), sem prentað verður og gefið út í Þýskalandi innan skamms ásamt ritgerðinni. Íslenska vatnafarskortið fylgir því ekki þessari útgáfu ritgerðarinnar.

Þetta íslenska vatnsfarskort á sér alllanga forsögu, sem rétt er að drepa lítillega á. Það er tiltölulega skammt síðan farið var að gera sérstök kort sem sýna vatnafar landa svæða. Vatnafarskortin hafa þróast frá almennum jarðfræðikortum á þann hátt, að á þeim er jarðfræðin skoðuð og skilgreind með áhrif hennar á vatnafarið í huga, auk þess sem megináherslan er lögð á að draga saman sem mestar vatnafræðilegar upplýsingar.

Eitt af því, sem mönnum hætti löngum til að telja óþrjótandi hversu sem af væri ausið, var vatnsforði jarðarinnar. Það var ekki fyrr en um 1950, að enn sannaðist fyrir mönnum hið fornkveðna, að allt eyðist sem af er tekið, jafnvel vatnið. Þá stóðu þeir líka víða frammi fyrir augljósum afleiðingum rányrkjunnar, vatnsbirgðirnar voru á þrotum, grunnvatnsborðið komið niður úr öllu valdi og yfirborðsvatnið megnað og spillt. Viðbrögðin voru bæði snör og snögg og hörð. Áhugi á vatnafræði óx mjög svo og skilningur á nytsemi þessarra fræða. Þetta leiddi til örrar þróunar og alþjóðlegs samstarfs.

Á 13. þingi UNESCO var samþykkt að efna til alþjóðlegs vatnafræðiáratugs sem standa skyldi frá 1965-1975. Tilgangurinn var að stuðla að alþjóðasamvinnu í vatnafræðirannsóknum og þjálfun sérfræðinga og tækniliðs í vísindalegri vatnafræði. Þannig skyldi öllum þjóðum gert fært að meta vatnaauðæfi sín og nýta þau á sem hagkvæmastan hátt í samræmi við síaukna vatnsþörf vegna fólksfjölgunar og þróunar í iðnaði, landbúnaði og fiskveiðum.

Um 1960 höfðu verið gerð vatnafarskort í stórum mælikvarða af afmörkuðum svæðum hér og hvar um heim, en þau voru ósamræmd og gerólík innbyrðis. Nefndin "Commission for Hydrological Maps" var stofnuð 1959 og eins og nafnið bendir til skyldi hún fyrst og fremst fást við samræmingu og framþróun vatnafarskorta. Árið eftir var hafinn undirbúningur að Hinu alþjóðlega vatnafarskorti Evrópu, í samstarfi við IAH og UNESCO. Þetta kort er fyrsta vatnafarskortið í smáum kvarða af stórum lendum sem gert er. Það kostaði vitaskuld geysimikla undirbúningsvinnu og tilraunir, að finna kortatákn og kortlagningaraðferð sem tryggði samfellda túlkun á hinum ýmsu og oft gerólíku svæðum álfunnar.

Fyrsta skref þessa undirbúnings var samning alþjóðlegra skýringa við vatnafarsskort. Fyrsta útgáfa þeirra kom út hjá UNESCO 1962. Þjóðverjinn prof. dr. H. Karrenberg (núverandi formaður ritstjórnarnefndarinnar eða "Committee of Scientific Editors of the International Hydrogeological Map of Europe 1:1.500.000") lagði jafnframt fram tvö uppköst af vatnafarskorti sem byggð voru á þessum skýringum. Eftir miklar umræður og gagnrýni voru skýringarnar endursamdar og Karrenberg birti þriðja uppkastið 1965 og það fjórða 1966 sem að lokum hlaut almenna viðurkenningu. Það var prentað og gefið út 1970 sem fyrsta kortablaðið í Evrópukortinu. Jafnframt var gefin út endurskoðuð útgáfa af alþjóðaskýringunum. 1971 voru þær þýddar á íslensku af Kristni Einarssyni og gefnar út af OS-ROD í samráði við Landsnefnd IHD. Ráðgert er að út komi 30 kortablöð alls. Hverju kortablaði fylgir allnákvæmur skýringatexti til að fylla upp í þá mynd sem hinn smái skali kortsins fær dregið fram.

Vinna við Íslandshluta þessa korts hófst haustið 1976 og var að mestu lokið 1978. Upphaflega var ætlunin að Ísland yrði á blaði með Færeyjum og hluta af Noregi. Seinna varð það að ráði að skilja Noreg frá, en hafa einungis Ísland og Færeyjar á kortinu.

Gerð íslensks vatnafarskorts er ýmsum annmörkum háð. Í fyrsta lagi hafa aldrei verið gerðar neinar samfelldar vatnafræðilegar athuganir með tilliti til kortagerðar hérlendis. Í öðru lagi verður vatnafarskort að byggja á jarðfræðikortum en slík kort eru af skornum skammti til af landinu öllu. Í þriðja lagi eru tákn, grunnmunstur (skraferingar) og litir kortsins miðuð við alþjóðlega kortlagningu sem oft á tíðum er erfitt að fella að hinum sérstæðu jarðfræðilegu og vatnafræðilegu aðstæðum hérlendis.

Þrátt fyrir þetta erfiði hefur kerfið reynst vel í öllum aðalatriðum við kortlagningu Íslands. Nauðsynlegt var þó að innleiða nýjar merkingar, m.a. fyrir jarðhita, eldvirkni og jökulhlaup.

Með þessari kortlagningu hefur verið dregin saman á einn stað og samræmd, dreifð og sundurleit þekkingarbrot samtíðarinnar af vatnafari Íslands. Vangaveltur sem upp komu í kjölfar kortavinnunnar leiddu af sér nokkur nýmæli, svo sem flokkun veita (aquifers) og stemma (aquicludes) í íslenskum jarðlögum, flokkun linda og þankabrot um uppruna salts vatns í jörðu og ölkeldna. Einnig er sýnd efnafræðileg flokkun á íslenska grunnvatninu, heitu og köldu, söltu og súru.