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NATIONAL ENERGY AUTHORITY
HYDRO ENERGY DIVISION

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GROUNDWATER IN ICELAND

Paper presented at the Nordic Hydrological Conference, Nyborg, 6.-8. August 1984

OS-85038/VOD-02
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GRENSÁSVEGUR 9,
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I General description

Iceland is an island in the North-Atlantic Ocean, just below the Arctic Circle and lies astride the Middle-Atlantic Ridge. It is wholly of volcanic origin, consisting for the greatest part of basaltic rocks. The country is approximately 100.000 sq. km. It is nearly oval in shape forming essentially a plateau, at 300 - 1000 m altitude, which is indented by numerous fjords and valleys and capped by many Late-Quaternary volcanic mountains. The higher mountain clusters are crowned by glaciers.

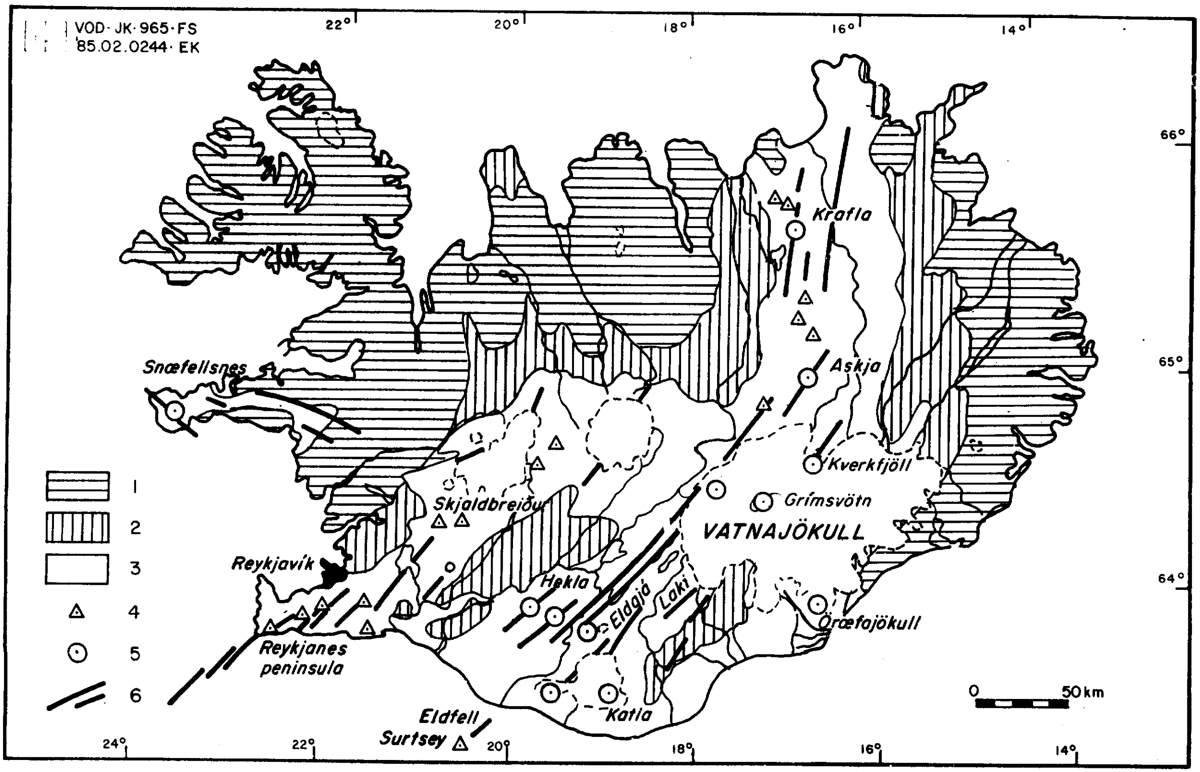

Fig. 1. Geology of Iceland.
Explanations:

1. Tertiary basalt region.
2. Plio-Pleistocene basalts and hyaloclastites.
3. Late Quaternery hyaloclastites and basalts; Holocene lavas and sands.
4. Holocene shield volcano.
5. Active central volcanoes (silicic centres).
6. Eruptive fissures swarms.

The age of the volcanics is Miocene to Recent, the youngest rocks occurring in a presently active Volcanic-Zone across the island (Fig. 1.). The Zonal arrangement in the stratigraphy is thought to be the result of ocean-floor spreading on the Middle-Atlantic Ridge and its prolongation across Iceland. The Tertiary rocks (older than appr. 3 million years) can be described as a pile of tholeiitic and olivine-tholeiitic lava-sheets, interspersed by central volcanoes, characterised by occurrences of acid and intermediate rocks, geothermal alteration and dyke swarms. In most regions this lava pile is with a few exceptions, tilted some degrees, towards the present Volcanic-Zone. The same mode of volcanism is present in the younger formations too. In the Plio-Pleistocene the strata usually dip slightly less than in the Tertiary. Signs of glaciations appear in this formation, including tillite horizons and heaps or horizons of subglacial eruptives in the form of pillow-lavas and hyaloclastites, usually palagonitised ("Móberg" in Icelandic). These subglacial eruptives increase in importance with time, becoming the dominant feature in the Late-Quaternary (less than 0.7 m. years old), and forming table-mountains, ridges and mountain clusters, rising some hundred meters above the surface of the plateau. The volcanism has remained very active in the Holocene, resulting in recent lavas covering wide stretches and extending into the lowlands. A comprehensive review of Icelandic geology is given by SAEMUNDSSON, (1978, 1979).

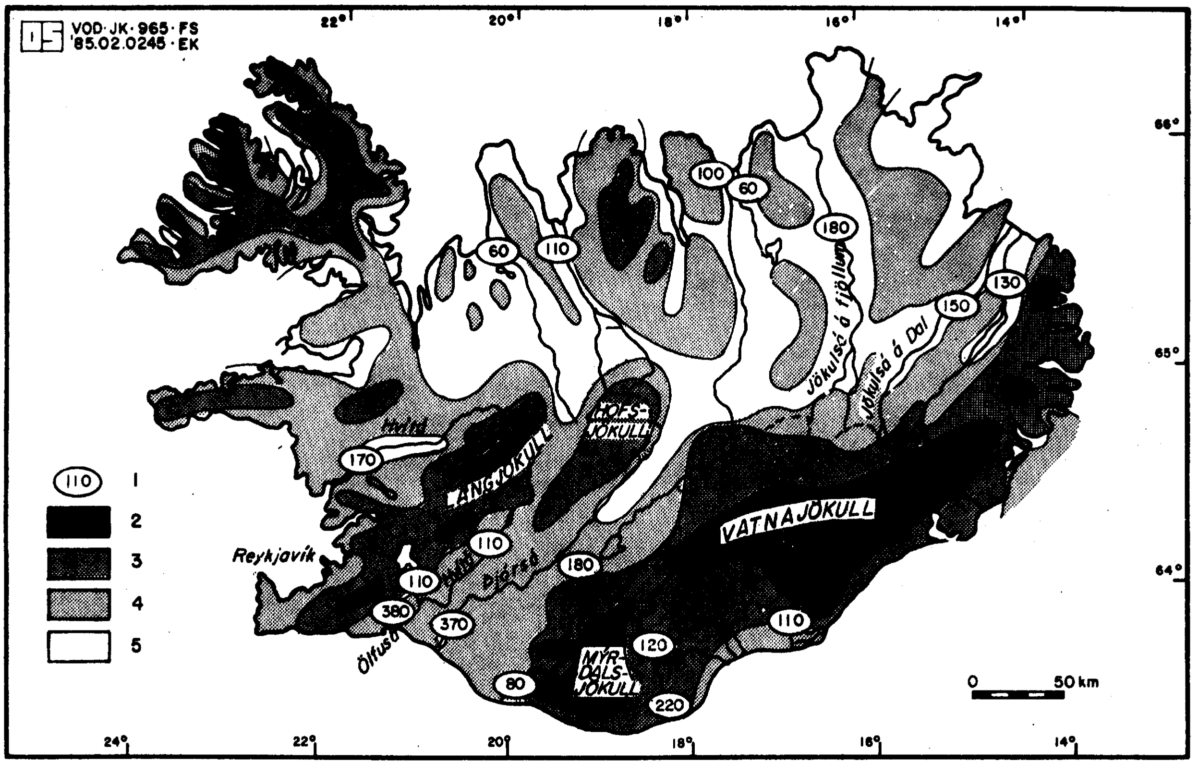

Fig. 2. Mean annual precipitation in Iceland and mean discharge of the greatest rivers.

Explanations:

1. Mean discharge in m^3/s.
2. Precipitation > 3.200 mm/a.
3. Precipitation 1.600 - 3.200 mm/a.
4. Precipitation 800 - 1.600 mm/a.
5. Precipitation <800 mm/a.

The climate in Iceland is oceanic and sub-polar. The south and west coasts, and frequently the north coast, are warmed by a branch of the Gulfstream, while colder sea currents flow along the east coast, and affectng at certain times the north coast also. On the other hand Iceland lies in the path of moisture-laden depressions crossing the Atlantic from west to east giving rise to a very changeable weather and bringing in warm and wet southeast winds, together with cooler but still wet southwest winds. North and northeast winds from depressions passing east or northeast of Iceland are cold but not very wet. The result is, that the southern and eastern highlands experience a precipitation in excess of 2.000 mm/a, while it is generally below 1.000 mm/a in the northern half of the country (Fig. 2). The average July temperature at the west and south coasts is 10-11° C, but 9°C at the north and east coast. In January the average temperature is 0°C at the southwest, south and east coasts, but -1° C at the northwest and north coast (EYTHORSSON AND SIGTRYGGSSON 1971). The temperature falls farther inland.

This wet and cool climate leads to a very high runoff in Iceland, exceeding 100 l/s km^2 on the southeast highlands and glaciers, although the greater part of the northern half has a runoff below 40 l/s km^2 (RIST 1956). The biggest rivers are all glacier-fed. At least 10 have a mean discharge of more than 100 m^3/s (Fig. 2). As many of them have a steep descend from the plateau they are great potential sources of hydro-power. Because of that the hydrographic network is relatively dense. At present appr. 150 hydrographs are operated by the National Energy Authority.

II Hydrogeology and water quality

The hydrogeological research in Iceland has had practical purposes , i.e. to furnish the public waterworks and industries with clean fresh water and to evaluate the groundwater component of rivers which are intended for hydro-power harnessing, or which are already operated as such. Pure academic research has been minimal. The sporadic beginnings are indeed as old as the geological investigations in Iceland as such. Thorough work on the hydrogeology of Iceland started only a few decades ago (KJARTANSSON 1945, RIST 1956), Its present state is due to developments of the last two decades. The first real hydrogeological map of an extensive area was presented by SIGBJARNARSON (1972), the first intensive investigation of an area was begun in 1975/76 (SIGURÐSSON 1976) and the first reconnaissance survey of a region was started 1978 (HJARTARSON et. al 1981). The preliminary results of these and other research works were summarised by HJARTARSON et al. (1980). Most of these investigations have been carried out by the National Energy Authority. Much more extentive investigations have been conducted on geothermal waters, the ultimate object being the energy content of the water, but not so much the water itself.

The permeability as well as groundwater behaviour of the bedrock is closely connected to the main geological formations. The Tertiary basalts have a low permeability, chiefly because of secondary mineralisation. Where this is lacking, as is the case in the higher parts of the northwest peninsula, the permeability is markedly higher. Rejuvenated fracture zones can also be water-bearing, but they are infrequent. The chief aquifers at the surface in the Tertiary are of sedimentary origin as river gravels and rock-slides. From the latter, springs may issue, hardly ever exceeding 100 l/s and not very often 10 l/s. These aquifers seldom have a great areal extension (a few square km) and are normally relativly thin (less than 10-30 m). The springs are usually caught in dug wells for exploitation. From the river gravels the water is usually extracted through boreholes ranging between 10-50 cm in diametre. The yield is normally 5-20 l/s, but higher yields are known to occur.

The rocks of the Plio-Pleistocene resemble the Tertiary ones in many aspects but are more permeable, although secondary mineralisation can also locally reduce their permeability. Sedimentary intercalations (especially tillites) and horizons of palagonitised hyoloclastites have often a low permeability. The highest permeability is at the contacts between lava sheets or lava sheets and the intercalations or intrusions (FRIDLEIFSSON 1979). This causes an anisotropy, the flow along the bedding planes being much easier than perpendicular to them. Tectonic fracture zones also have an anisotropic effect, being often highly permeable (Fig. 3).

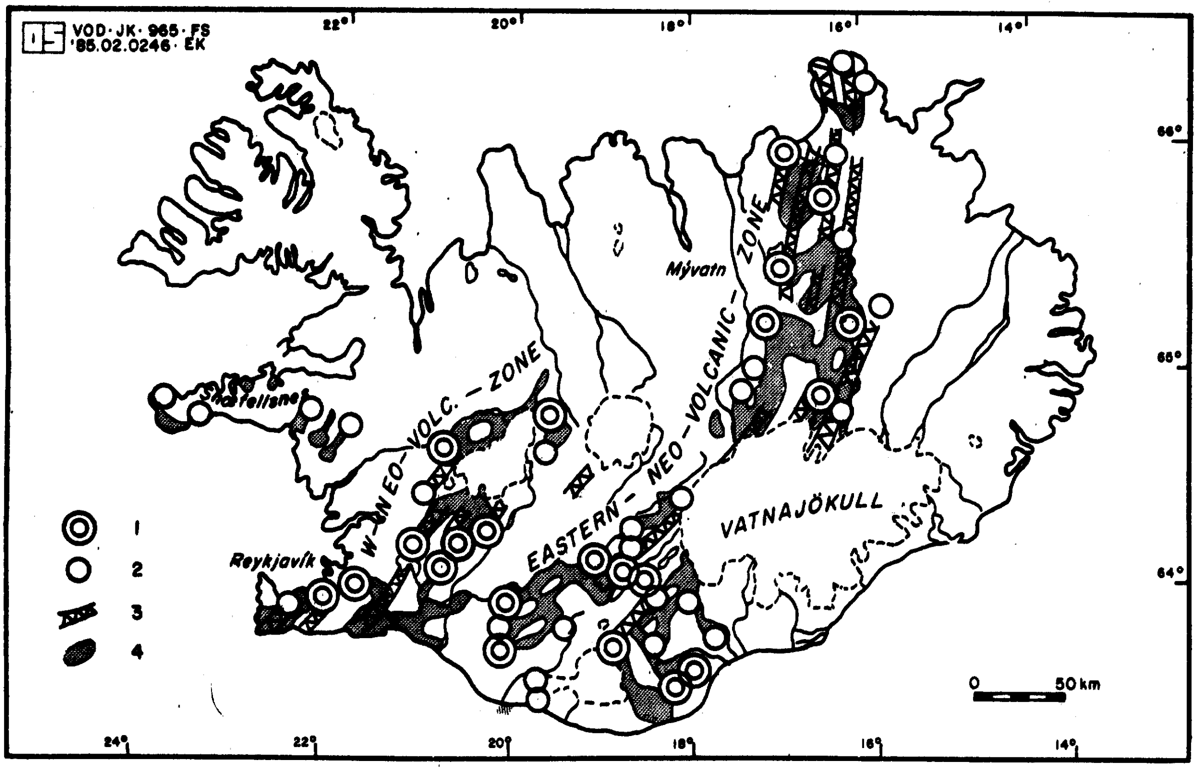

Fig. 3. The main springareas in Iceland.
Explanations:
1. Yield of springarea > 5 m^3/s.
2. Yield of springarea 1-5 m^3/s.
3. Tectonic fissure swarm.
4. Extensive Holocene lava fields.

These anisotropy effects are also very pronounced in the Late-Quaternary to Recent rocks. These rocks can be divided in two main classes: Subglacial rocks (Icelandic "móberg") and lava piles. The subglacial eruptives are on a small scale heterogeneous in lithology, structure and permeability. The pillow lava can be quite well permeable, while the hyaloclastites tend to be much less permeable. On a regional scale (a whole mountain or so) the subglacial eruptives generally have a low permeability compared with the interglacial and postglacial lava piles. The highest permeability in the lava-piles is on the scoriaceous contacts. The horizontal permeability is considered to be as much as 100 times higher than the vertical one. The recent, or even active, fissure swarms in the Neo-Volcanic-Zone create strong, regional anisotropies. Most of the great spring areas in Iceland issue from lava fields, most of them are post-glacial but some are also interglacial, and many are closely connected to the fissure swarms (Fig. 3). Freshwater exploitation from this formation is accordingly based on the springs, where it is possible. Elsewhere drilling of shallow boreholes (less than 100 m) in lava piles as a rule supplies good water, yields up to 50-100 l/s being possible from boreholes with a diametre of 25-30 cm.

The permeability (hydraulic conductivity) of the most important lithological types (formations) has roughly been estimated, see Table 1 which is compiled from may various sources.

TABLE 1.
Permeability of Icelandic bedrock

Lithological type/ rock formations	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

It is worth to note, that the permeability (not the hydraulic conductivity) may be one or two orders of magnitude higher for the hot geothermal water because of its lower kinematic viscosity.

The fresh groundwater in Iceland is low in chemical contents. According to a preliminary unpublished evaluation those contents have three chief sources:

1. Chemistry of the precipitation, mainly marine salts and some industrial smoke particles.

2. Reactions with soils and rocks, increasing the contents of silica and cations.

3. Influx of geothermal water, leading to an overall increase in chemical contents.

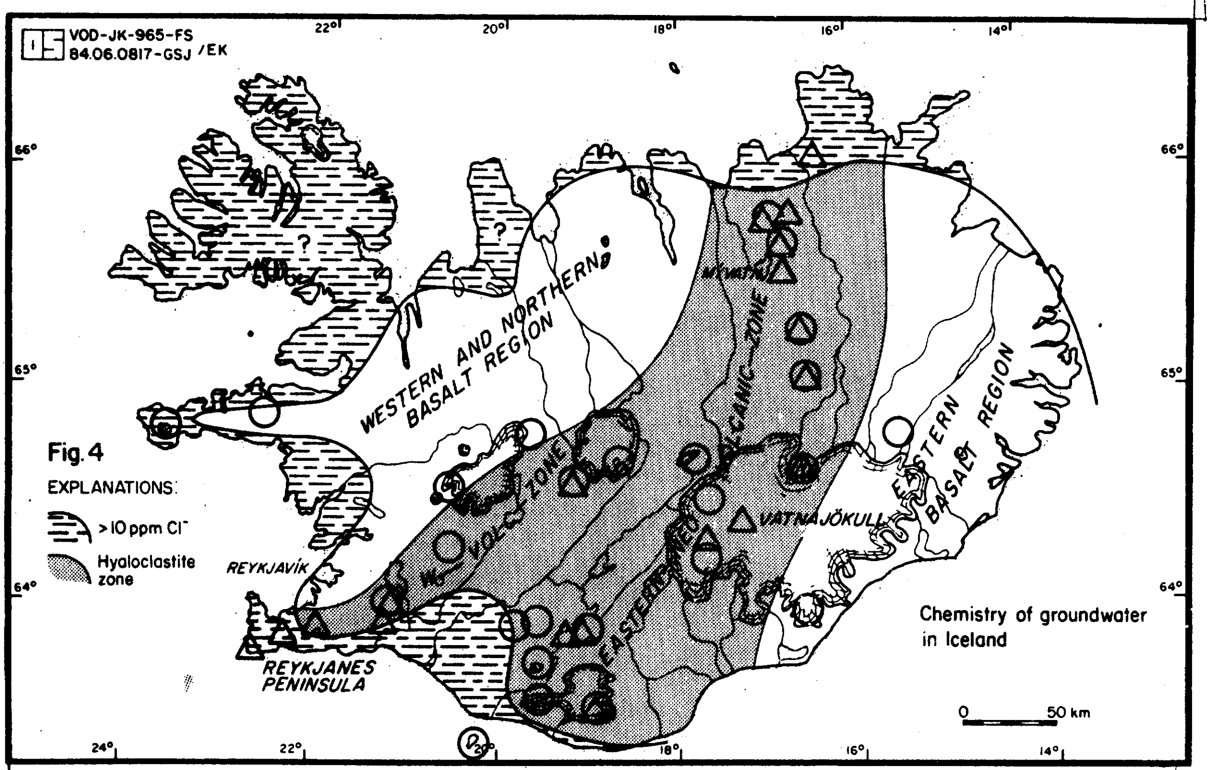

Fig. 4. Chemistry of groundwater in Iceland.

The marine component in the precipitation (Cl^- , - Na^+ , SO_4^{2-}) is strongest at the south and west coast (Fig. 4). The influence from geothermal fields is confined to the Neo-Volcanic Zones, where the increase in silica and cations is overall somewhat stronger, probably because of the freshness and high glass content of the rocks (e.g. hyaloclastites). The ranges for common values of concentrations in fresh groundwater in the inhabitated parts of the country are given in Table 2.

TABLE 2

Chemical contents of groundwater

Components	Range (in ppm)
Cl^-	5 - 15
SO_4^{2-}	2 - 6
Na^+	3 - 15
K^+	0,2 - 1,0
Ca^{2+}	2 - 7
Mg^{2+}	1 - 5
SiO_2	10 - 20
CO_2	15 - 30
total dissolved	30 - 100

Higher values are found in coastal regions, in the vicinity of geothermal fields and in lowlands with extensive peat bogs (carbonate and earth-alkalis). Biologically the groundwater is almost always pure and as yet only very small areas have been polluted through human activities.

The chemistry of Icelandic groundwater has not yet been investigated thoroughly, but a preliminary review indicates, that it will be possible to distinguish between various groundwater basins with its aid. Similiar use can be made of natural isotopes (ÁRNASON 1976, SIGBJARNARSON et.al. 1976).

III Investigation Methods

The relative vastness of the research areas in Iceland, in view of the sparse population, (240.000 inhabitants living on 100.000 sq. km whereof 80% is uninhabitated), does in many cases not allow for more than simple investigation methods. For a long tima a rough hydrogeological classification together with a surficical assessment of the groundwater hydrology was the prevalent method, and must still be resorted to in many cases to-day. In the course of time those methods have become more thorough and of a more quantitative nature. Later on groundwater chemistry and isotopes were added (ÁRNASON 1976). Combination of various surficial methods (hydrogeology, hydrology, chemistry, geophysics, hydraulics) have proved very successful in the last ten years (SIGURÐSSON 1976, SIGURÐSSON et. al 1978). Intensive surveys and modelling are still reserved for groundwater basins of high economic value (INGIMARSSON AND ELÍASSON 1980).

The evaluation of a water basin for exploitation for water works is carried on stepwise, when possible. A field reconnaissance, together with interpretations of existing geological, hydrological and meteorological data is usually the first step. When necessary more sophisticated surficial methods are added like thorough sampling for chemical analyses and borehole-loggings, geophysics and eventually some exploration drilling. The third step involves more drillings, draw-down tests and other pumping tests and eventually geohydrological modelling.

The requirements for an evaluation of the groundwater component of a river for hydro-power purposes are of a more regional nature. They include the measurements of springs (discharge, temperature, eventually chemical sampling) and other surface manifestitions of the groundwater. Comprehensive hydrogeological mapping is also needed (in scale 1:50.000, begun some few years ago) and when necessary exploration drilling. The data thus obtained is used for hydrological modelling and monitoring of climatic changes for the operation of the hydro-power plant system.

No single agency is responsible for the exploitation of freshwater in Iceland, to a noticable harm for the users. Accordingly, no single authority keeps records of the groundwater resources and their utilization. The most thorough information on water works is presumably the one compiled by the scientists of the National Energy Authority,Hydro-Power-Division. No single ministry is responsible for the groundwater in Iceland as a resource, and this has caused a certain state of confusion.

IV Exploitation

Water has always been an inexpensive and easily available commodity in Iceland, with the result, that the consumption per capita is probably one of the highest in the world. In the urban area of Reykjavík and its suburbs (population 130.000) the consumption is estimated to be 500-700 l per day and capita. In some settlements with intensive fish industries it is thought to be as high as 1.500 l per day and capita (Fig. 5). This waste of water is not necessary because of any natural conditions, it has its causes in the general and common attitude of the Icelanders towards costs and price of water: Water has been inexpensive and abundant in Iceland, and it is a common view that it will remain so indefinitely; the water is not paid for proportionate to the consumption but through a property tax; necessary costs are not always treated as such, but this may play a disturbing role in communal politics. Thus the present mode, to leave the water supply completely in the hands of communal authorities has not proven itself to be satisfactary, from a point of view of national interest.

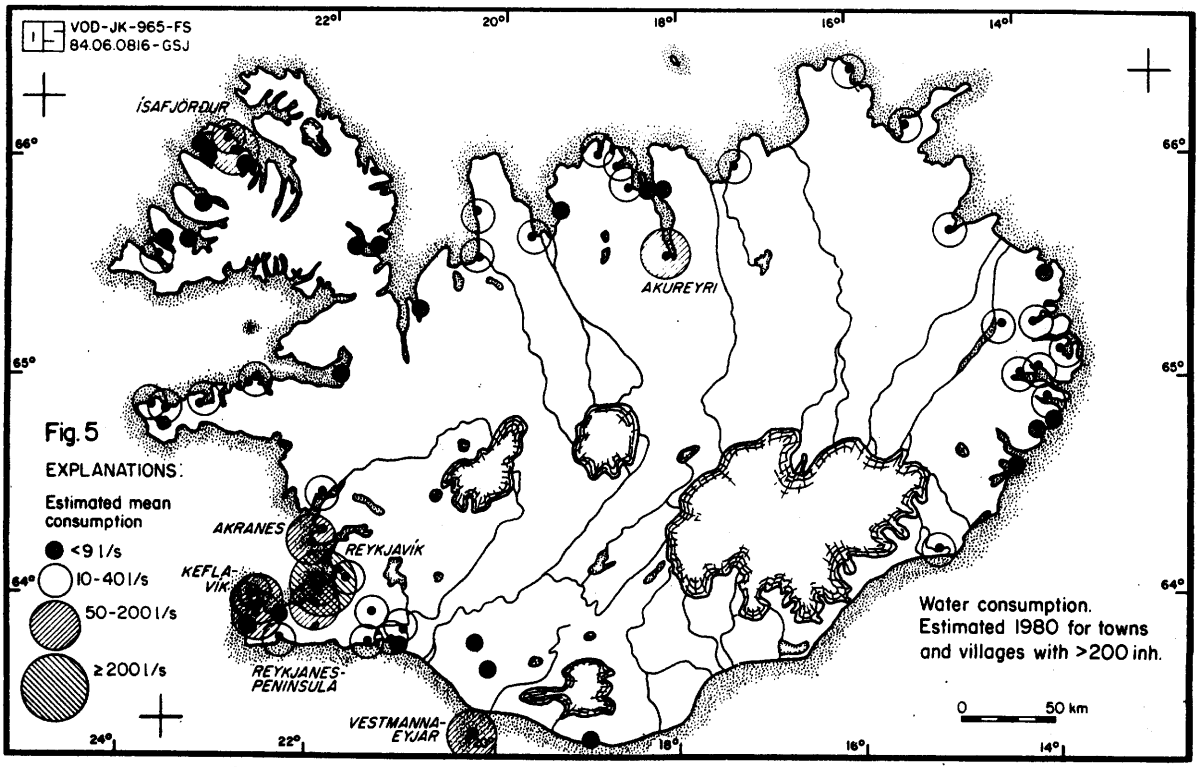

Fig. 5. Water consumption.

A second cause at these unsatisfactory conditions is to be seen in the historical developement. With the rapid increase in the urban population in the 20th century, the quantitative demands for supplied water also increased. These demands were often met in the cheapest way possible and then equally often with the result that the quality of the water deterioriated as the quantity increased. In later years amendments of those conditions have been intensified with good results.

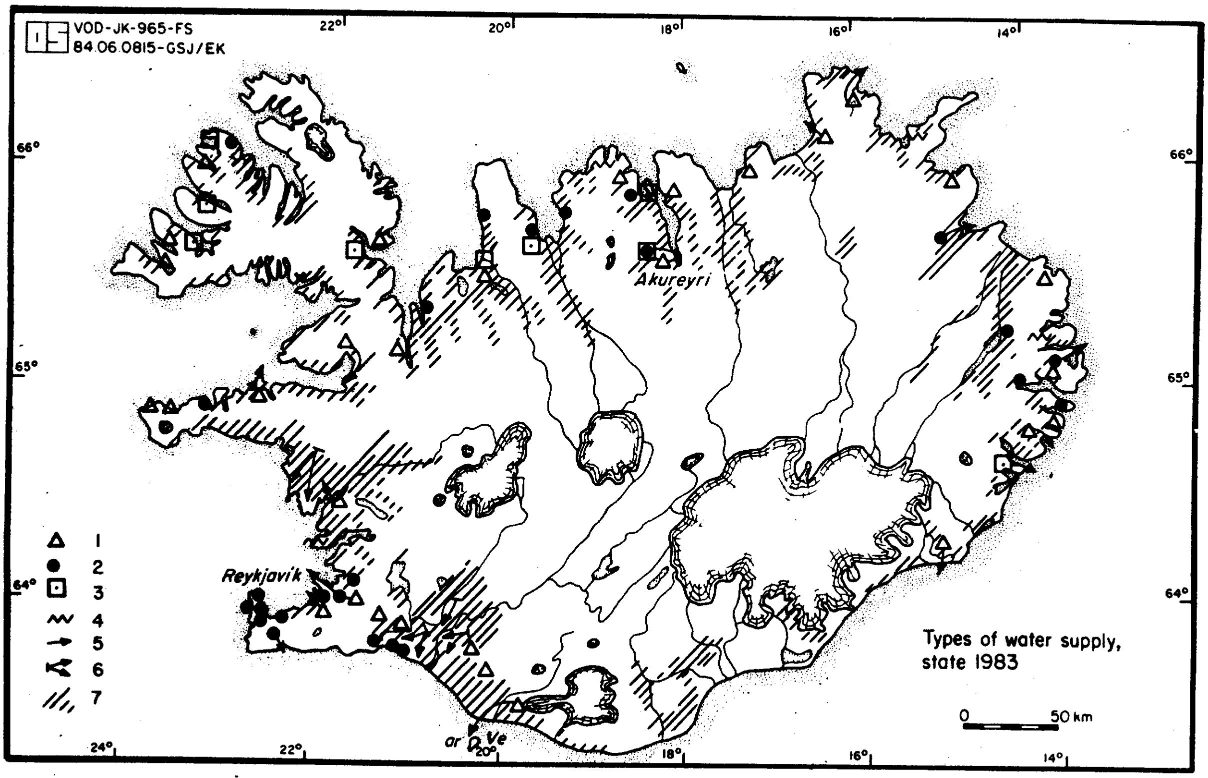

Fig. 6. Types of water supply, state 1983.
Explanations:

1. Natural springs.
2. Boreholes.
3. Dug wells in sediments.
4. Surface water.
5. Pipeline.
6. Rural waterworks.
7. Rural areas.

The type of wells for the waterworks is chiefly dictated by the hydrogeology (Fig. 6). In the Tertiary regions springs in rock-slides and boreholes in river gravels are the most common types. The springs are usually caught in dug, shallow wells, where great precautions are taken not to disturb the natural conditions unnecessarily. The boreholes in the loose sediments are usually drilled with a cable-tool drill, and have a diametre of 15-60 cm. The boreholes have a whole casing down to below the supposed water-level at maximal drawdown.

In some settlements with old waterworks and where it is difficult and expensive to obtain fresh water with other means, surface water has been used. It has nowhere been possible to obtain in that way clean and pure water all the year around, a fact that sometimes been consealed by the communal authorities in question. The chief reason is the tremendous amount of mud the surface waters carry with them in the not so infrequent thaw- and rain-floods.

A special treatment of public water is not generally practised in Iceland. In most cases it is also unneccessary i.e. where groundwater is used. As yet no installed filter-works are known to have been adequate where surface water is used, to clean the muddy flood waters successfully.

In the Quaternary regions springs which issue directly from the bedrock (e.g. lava-fields, fissures), or after flow for a short distance through sediments, are the chief source of supply, together with boreholes in the permeable bedrock (postglacial and interglacial lava). Various drill-equipments are used, according to the varying

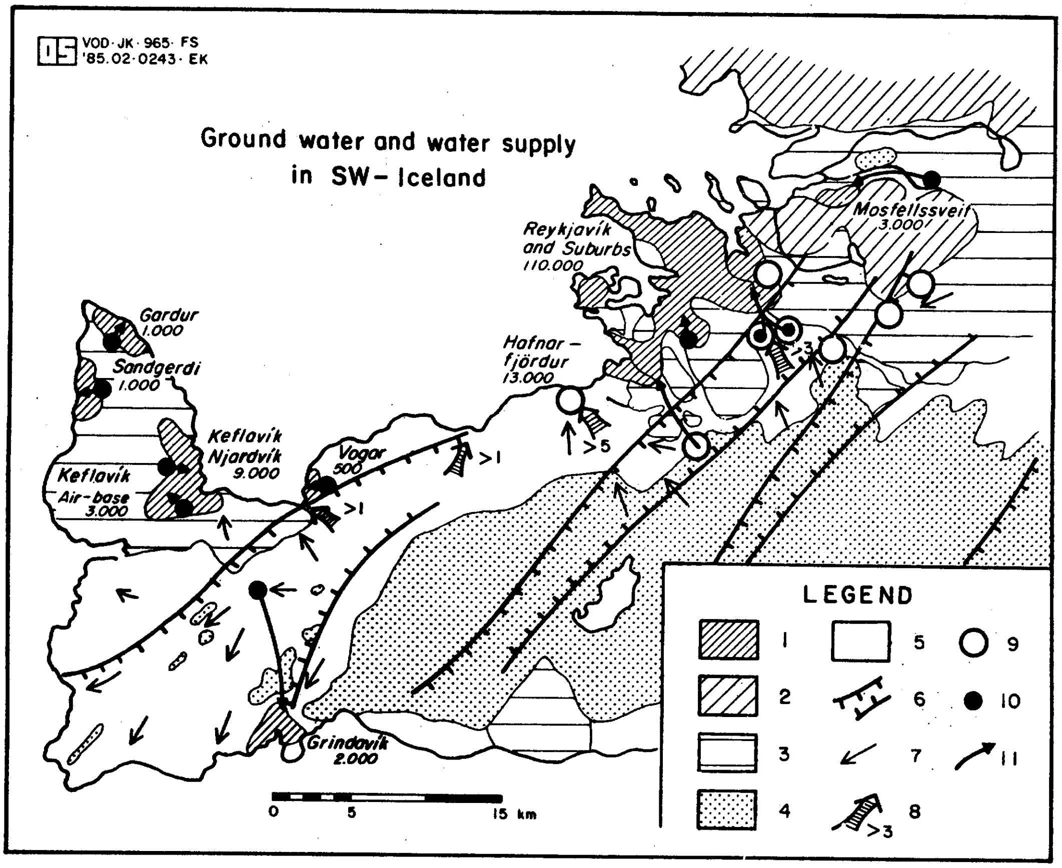

Fig. 7. Groundwater and water supply in SW-Iceland.
Explanations:

1. Urban settlement area. Numbers relate to population.
2. Early Quaternary volcanics and intrusives.
3. Interglacial basalts.
4. Glacial volcanic mountains (hyaloclastites and pillow lavas).
5. Post-glacial basaltic lavas.
6. Tectonic fissure swarms.
7. Direction of groundwater flow.
8. Coastal outflow, estimated discharge in m^3/s.
9. Natural spring areas.
10. Sites of water extraction.
11. Pipelines.

The wells usually lie outside the settlements, in the thinly populated country side or even in uninhabitated parts of the country. The danger of contamination is, therefore, not great. Fencing off the wells area and closing the wells is usually regarded as a sufficient preventive measure. In view of the scanty vegetation, thin soil covers and highly permeable aquifers, this is certainly in some cases inadequate. Freshwater preservation is only a problem on a major scale in the SW-corner of the country, where 60% of the population are living on 2% of the total area (Fig. 7). In the western part of Reykjanes-Peninsula a thin freshwater layer (appr. 50 m) is floating on sea water (SIGURDSSON 1985). Cases of seawater intrusions through overdraft are known. The investigations going on in that area have contributed essentially to the developement of more adequate explotation methods.

The water is seldom transported over long distances, 20-30 km being at present the maximum length of pipelines to the towns and villages. Because of the climatic conditions the pipes are usually dug and ploughed into the soils. Great use is made of pipes of plastics or other non-corrosive and flexible materials. Storage tanks are as a rule insufficiant thus requiring higher capacities of well pumps and pipelines than would be necessary by adequate storage capacities. Pumping costs are high, one cause being the above mentioned lack of storage. Another cause is a wrong choice of pumps because no draw-down tests have been performed in the misunderstood intention to lower investment costs. A third cause is damaged pumps due to rapid pressure changes, where the pumps are connected directly to the pipelines and the distribution net. A fourth cause is a deficient construction of wells because of a lack of proper advice.

Some rural regions are supplied with water from central water works, despite the long distances to be covered. Much use is made of slim plastic pipes, ploughed down in the soft soils.

V Agencies in groundwater exploration and development

There is no central agency responsible for freshwater matters in Iceland. The water supply is a communal concern in the urban areas, but else a private business. Scientific advice has been given by the National Energy Authority, Hydro Power Division and private firms, which also contribute the technical advice and construction plans. No official approval is necessary for the installment and operation of those waterworks.

Possibilities for scientific training in groundwater sciences are limited in Iceland. The University of Iceland in Reykjavík gives undergraduate courses in geology and hydraulics, but geohydrology, hydrogeology and freshwater exploitation are not dealt with extensively. On the other hand it is worth to mention the very successful operation of the UN Geothermal Training Programme in Reykjavík, a branch of the United Nations University, providing lectures and training courses for students from all continents.

VI Cooperation with underdevoloped countries and other states

Icelandic agencies participate in various international organisations, dealing with groundwater and related matters. Cooperation with the Nordic countries has been carried out for practical purposes on a limited scale. The experience in Iceland of investigations and exploitation of groundwater under rough conditions and in a thinly populated country could however be highly valuable for some of the developing countries, especially in regard of the hydrogeology of volcanic rock. To-day some preliminary discussions are going on regarding these matters.

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