World Water Resources at the Beginning of the Twenty-First Century

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1.1 PHYSICAL GEOGRAPHY

1.1.1 The area of the Earth’s surface

The total area of the surface of the Earth is 510 million km$^2$. Over 361 million km$^2$ or 71% of this area is occupied by the World Ocean and only 149 million km$^2$ or 29% is covered by land. Water and land are distributed unevenly over the globe. In the Northern Hemisphere land extends over 100 million km$^2$ (39% of its area), while there are 49 million km$^2$ in the Southern Hemisphere (19%). The area of water in the Northern Hemisphere is 155 million km$^2$ (61%), and in the Southern 206 million km$^2$ (81%).

1.1.2 The World Ocean

The World Ocean is divided into four separate oceans by the distribution of the land (Stepanov, 1983): namely the Pacific, Atlantic, Indian and Arctic Oceans, and into numerous seas, gulfs, bays and straits. The Southern Ocean is also identified but is less well defined than the others. Basic information on the oceans and seas (Korzun, 1974b) are presented in Tables 1.1 and 1.2 respectively. The volume of water in the World Ocean is about 1340 million km$^3$.

1.1.3 Continents and islands

During the present geological epoch the Earth’s land consists of six continents: Eurasia, Africa, North America, South America, Australia and Antarctica. The borders between the separate continents are rather arbitrary. The border between Eurasia and Africa passes through the Strait of Gibraltar, along the Mediterranean Sea, Suez Canal, Red Sea, and the Straits of Bab el Mandeb. The boundary between North and South America passes through the Panama Canal. In this Monograph, Eurasia is subdivided into two parts which are considered as independent: namely Europe and Asia. The border between these continents extends from Matochkin Shar, in the north, along Pay Khoy, the Ural Mountains, Mugodzhary, along the River Emba, and the north and west coast of the Caspian Sea and Caucasus Mountains. Information on the continents and largest islands is given in Tables 1.3 and 1.4 (Terehov, 1981).

PRIMARY WATERSHEDS

Primary and secondary watersheds can be identified on the land surface. The primary watershed divides the land into two: the first carrying runoff to the Atlantic and Arctic Oceans (60% of the land area) and the second where runoff occurs to the Pacific and Indian Oceans (40%). The secondary watersheds are those surrounding the basins of the Pacific, Atlantic, Indian and Arctic Oceans and those delineating areas of internal runoff.

The primary watershed extends northwards from Cape Horn along the Andes and the Rocky Mountains to the Bering Strait, then across the eastern plateau of Asia in a westerly direction, and then it turns to run along the eastern edge of Africa to finish at the Cape of Good Hope.

The watersheds of ocean basins are located on individual continents in the following way. In Europe the watershed between the Arctic and Atlantic Oceans passes from the southwest coast of Norway along the Scandinavian Uplands, through the Manselkya Highland, and between Segozero and Onega. The watershed line between the Atlantic Ocean and the area of internal runoff to the Caspian Sea passes between Lakes Onega and Beloye Ozero, along the Valdai Hills, through the Central Russian and the Privolzhskaya Uplands, to Ergeny and the Caucasus Mountains.

In Asia the watershed between the Atlantic and Indian Oceans extends from the south end of the Suez Canal to the source of the Euphrates River. Then the watershed between the Indian Ocean and the area of internal runoff to the Caspian Sea passes between Lakes Onega and Beloye Ozero, along the Valdai Hills, through the Central Russian and the Privolzhskaya Uplands, to Ergeny and the Caucasus Mountains.

In Asia the watershed between the Atlantic and Indian Oceans extends from the south end of the Suez Canal to the source of the Euphrates River. Then the watershed between the Indian Ocean and the area of internal runoff to the Caspian Sea passes between Lakes Onega and Beloye Ozero, along the Valdai Hills, through the Central Russian and the Privolzhskaya Uplands, to Ergeny and the Caucasus Mountains.
Table 1.1. Major hydrological and morphometric characteristics of the World Ocean

<table>
<thead>
<tr>
<th>Ocean</th>
<th>Total area (with islands), km(^2) \times 10(^6)</th>
<th>Area of water surface, km(^2) \times 10(^6)</th>
<th>Area of catchment, km(^2) \times 10(^6)</th>
<th>Water volume, km(^3) \times 10(^6)</th>
<th>Depth, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pacific</td>
<td>182.6</td>
<td>178.7</td>
<td>24.9</td>
<td>707.1</td>
<td>3957</td>
</tr>
<tr>
<td>Atlantic</td>
<td>92.7</td>
<td>91.7</td>
<td>50.7</td>
<td>330.1</td>
<td>3602</td>
</tr>
<tr>
<td>Indian</td>
<td>77.0</td>
<td>76.2</td>
<td>20.9</td>
<td>284.6</td>
<td>3736</td>
</tr>
<tr>
<td>Arctic</td>
<td>18.5</td>
<td>14.7</td>
<td>22.5</td>
<td>16.7</td>
<td>1131</td>
</tr>
<tr>
<td>World Ocean</td>
<td>370.8</td>
<td>361.3</td>
<td>119.0</td>
<td>1338.5</td>
<td>3704</td>
</tr>
</tbody>
</table>

Table 1.2. Major morphometric characteristics of seas

<table>
<thead>
<tr>
<th>Sea</th>
<th>Area, km(^2) \times 10(^3)</th>
<th>Volume, km(^3)</th>
<th>Sea</th>
<th>Area, km(^2) \times 10(^3)</th>
<th>Volume, km(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pacific Ocean</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coral Sea</td>
<td>4791</td>
<td>11 470</td>
<td>Java Sea</td>
<td>480</td>
<td>22</td>
</tr>
<tr>
<td>South China Sea</td>
<td>3447</td>
<td>3 929</td>
<td>Sulawesi Sea</td>
<td>435</td>
<td>1586</td>
</tr>
<tr>
<td>Bering Sea</td>
<td>2344</td>
<td>3 796</td>
<td>Sulu Sea</td>
<td>348</td>
<td>553</td>
</tr>
<tr>
<td>Sea of Okhotsk</td>
<td>1617</td>
<td>1 317</td>
<td>Molucca Sea</td>
<td>291</td>
<td>554</td>
</tr>
<tr>
<td>Sea of Japan</td>
<td>1070</td>
<td>1 630</td>
<td>Seram Sea</td>
<td>187</td>
<td>227</td>
</tr>
<tr>
<td>East China Sea</td>
<td>752</td>
<td>263</td>
<td>Flores Sea</td>
<td>121</td>
<td>222</td>
</tr>
<tr>
<td>Yellow Sea</td>
<td>417</td>
<td>17</td>
<td>Bali Sea</td>
<td>119</td>
<td>49</td>
</tr>
<tr>
<td>Banda Sea</td>
<td>695</td>
<td>2 129</td>
<td>Savu Sea</td>
<td>105</td>
<td>178</td>
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<tr>
<td><strong>Atlantic Ocean</strong></td>
<td></td>
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<tr>
<td>Caribbean Sea</td>
<td>2754</td>
<td>6 860</td>
<td>North Sea</td>
<td>554</td>
<td>52</td>
</tr>
<tr>
<td>Mediterranean Sea</td>
<td>2505</td>
<td>3 754</td>
<td>Baltic Sea</td>
<td>448</td>
<td>20</td>
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<tr>
<td>Gulf of Mexico</td>
<td>1543</td>
<td>2 332</td>
<td>Black Sea</td>
<td>431</td>
<td>555</td>
</tr>
<tr>
<td>Hudson Bay</td>
<td>819</td>
<td>92</td>
<td>Sea of Azov</td>
<td>40</td>
<td>0.4</td>
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<tr>
<td>Baffin Bay</td>
<td>689</td>
<td>593</td>
<td>Sea of Marmara</td>
<td>11</td>
<td>4.0</td>
</tr>
<tr>
<td><strong>Indian Ocean</strong></td>
<td></td>
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<tr>
<td>Arabian Sea</td>
<td>3683</td>
<td>10 070</td>
<td>Timor Sea</td>
<td>615</td>
<td>250</td>
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<tr>
<td>Bay of Bengal</td>
<td>2172</td>
<td>5 616</td>
<td>Andaman Sea</td>
<td>602</td>
<td>660</td>
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<tr>
<td>Arafura Sea</td>
<td>1037</td>
<td>204</td>
<td>Red Sea</td>
<td>450</td>
<td>251</td>
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<tr>
<td><strong>Arctic Ocean</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Barents Sea</td>
<td>1470</td>
<td>268</td>
<td>Kara Sea</td>
<td>903</td>
<td>101</td>
</tr>
<tr>
<td>Norway Sea</td>
<td>1547</td>
<td>2 408</td>
<td>Laptev Sea</td>
<td>678</td>
<td>363</td>
</tr>
<tr>
<td>Greenland Sea</td>
<td>1205</td>
<td>1 740</td>
<td>Chukchi Sea</td>
<td>590</td>
<td>45</td>
</tr>
<tr>
<td>East Siberian Sea</td>
<td>926</td>
<td>61</td>
<td>Beaufort Sea</td>
<td>476</td>
<td>478</td>
</tr>
</tbody>
</table>

In Africa the watershed between the basins of Atlantic and Indian Oceans passes from the Gulf of Suez along the peaks of mountains situated besides the Red Sea, along the eastern part of the Abyssinian Highlands, to the east of Lake Victoria between Lake Tanganyika and Lake Nyasa, along the Muchinga Mountains, between the Rivers Congo and Zambezi, Cubango and Cunene, westwards and southwards of Lake Etosha, along
Damaraland, across the hills of the southwest and the southern borders of the Kalahari Desert, through the Drakensberg Mountains to Cape Agulhas.

In North America the watershed between the Arctic Ocean and the Pacific and Atlantic Oceans passes from Cape Prince of Wales along the Brooks Range, through the Richardson Mountains, Seluin, and Rocky Mountains, along the uplands between the Mississippi and Nelson Rivers, northwards of Lake Superior and Lake Huron and along the Labrador Peninsula. The watershed between the Atlantic and Pacific Oceans passes along the Rocky Mountains, around the upper parts of the Mississippi and South Saskatchewan, along the Isthmus of Tehuantepec and to the Panama Canal.

In South America the watershed separating runoff to the Atlantic and Pacific Oceans starts at the Panama Canal and passes along the Andes, through the Strait of Magellan along Tierra del Fuego to its southern tip.

In Australia the watershed between the basins of Pacific and Indian Oceans passes from Cape York along the Great Dividing Range to South East Point (Cape Otway).

Excluding the areas of internal runoff, the Arctic Ocean takes 15% of the runoff from the total land area of the globe, the Atlantic 34%, the Pacific 17% and the Indian Ocean 14%.

**RIVERS**

Depending on the size of the basin they drain, the length and volume of the flowing water, rivers are usually subdivided into very large, large, medium, small and very small. Table 1.5 presents information on the morphology of the principal river basins of the earth.

The largest river in the world is the Amazon with a catchment area of 6915 thousand km², and length 6280 km. Its total annual runoff amounts to about 15% of the total runoff of all the world’s rivers. Among very large rivers are the Congo (catchment area 3680 thousand km² and length 4370 km) and Mississippi (2980 thousand km² and 4700 km). Over the world as a whole there are 20 rivers with catchment areas between 3 million to 1 million km² and 89 rivers with basin areas from 1 million km² to 100 000 km². Most rivers are amongst the medium, small and very small categories. About 80% of the land surface drains to the World Ocean, while the area of internal runoff where the rivers do not reach the ocean accounts for 20% of the land surface. Most of the world’s largest rivers drain to the ocean.

In Europe the area of internal runoff consists of the Caspian Sea basin, which includes the basins of Volga, Ural, and Kura Rivers. In Asia the area of internal runoff is larger and includes: the basin of the Aral Sea (Amu Darya, Syr Darya Rivers) the basin of Lake Balkhash (Ili River) and many rivers flowing into small lakes or disappearing in arid areas (Tedzhen, Murgab, Sary-Su, Turgay, Irgiz and Nura Rivers). There are also the deserts of Alashan, Gobi, and Takla-Makan in Central Asia, while parts of Asia Minor and most of the Arabian Peninsula have areas of internal runoff. There are several closed basins situated in the interfluvial area of the Indus and Ganges.

Almost one-third of Africa drains internally. These are the Sakhara, Libyan, Nubian, Kalahari, and Namib Deserts and semi-deserts, together with the basins of Lakes Chad, Rukwa and Turkana.

In North America the Great Basin (including Great Salt Lake), the deserts of the Mexican Plateau, the Colorado Plateau and the right bank of the Rio Grande have no outlets to the ocean, while in South America the internal runoff areas include the basins of the Lakes Titicaca–Poopo, the Puna de Atakama Desert, the semi-desert plateau of Patagonia and other territories.

In Australia Lakes Eyre, Amadeus, Torrens and Frome are closed, as well as the Great Sandy Desert, Gibson Desert and Great Victoria Desert. Little is known about drainage on the Antarctic continent.

The total area of internal runoff (Korzun, 1974b) amounts to 30.2 million km², including Europe 2.2 million km², Asia 12.3 million km², Africa 9.6 million km², Australia 3.9 million km², South America 1.4 million km² and North America 0.88 million km².
Table 1.4. Principal islands of more than 10 000 km² in area

<table>
<thead>
<tr>
<th>Island</th>
<th>Area, km² × 10³</th>
<th>Island</th>
<th>Area, km² × 10³</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Europe</strong></td>
<td></td>
<td><strong>North America</strong></td>
<td></td>
</tr>
<tr>
<td>Great Britain</td>
<td>230.0</td>
<td>Greenland</td>
<td>2176.0</td>
</tr>
<tr>
<td>Iceland</td>
<td>103.0</td>
<td>Baffin Island</td>
<td>519.0</td>
</tr>
<tr>
<td>Ireland</td>
<td>84.4</td>
<td>Victoria Island</td>
<td>213.8</td>
</tr>
<tr>
<td>Novaya Zemlya Islands</td>
<td>81.3</td>
<td>Ellesmere Island</td>
<td>202.7</td>
</tr>
<tr>
<td>Spitsbergen Islands</td>
<td>62.1</td>
<td>Cuba</td>
<td>105.0</td>
</tr>
<tr>
<td>Sicily</td>
<td>25.4</td>
<td>Newfoundland</td>
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LAKES

Lakes are widespread on all continents. There are about 15 million of them, and the total water surface area is about 2 million km² or 1.5% of the land area (excluding the Antarctic). Most of the lakes are small and very small. Across the world there are 88 large lakes with a water surface area exceeding 1000 km². Of these lakes 28 are located in Asia, 13 in Europe, 16 in Africa, 22 in North America, 5 in South America and 4 in Australia. The number of lakes with a surface area greater than 10 000 km² is 19; 1 in Europe (Lake Ladoga), 4 in Asia (Aral, Baikal, Balkhash, Tonle Sap), 4 in Africa (Victoria, Nyasa, Chad, Turkana), 8 in North America (Superior, Huron, Michigan, Great Bear Lake, Great Slave Lake,
Table 1.5. *Major morphometric characteristics of principal world rivers*

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Most lakes are situated in the Northern Hemisphere and are located in glaciated areas (there are many small lakes in the tundra). Many lakes of Europe (e.g. Ladoga and Onega) are situated in large basins, often grabens where the northern sides were eroded by ice. Tectonic depressions, glacial erosion and moraine dams form many lakes in Sweden: Vänern, Vattern, Malaren, for example. There are many lakes formed by glacial dams in the northwest of Russia, and in Finland, Poland, Germany and Canada. A large group of lakes in the south of Finland (e.g. Lakes Saimaa and Päijänne) are divided from the Gulf of Finland by a huge dam made of a double ridge of terminal moraines, known as Salpa-Uselka. The chain of large lakes in North America (Lake Winnipeg, Lake of the Woods, and the Great Lakes: Superior, Huron, Michigan, Erie and Ontario) lie behind morainic...
deposits left by the receding ice, which covered the whole of the north of the North America continent. A group of alpine lakes (Lake Geneva, Lake Maggiore and Lake Garda) are located in the glacially eroded basins at the foot of the Alps.

A number of lakes are located in deep tectonic depressions in mountain areas such as Baikal (1741 m), Khabarsugul (267 m), Issyk Kul (702 m), Nyasa (706 m), and Titicaca (281 m). In the mountain systems of the Tien Shan, the Pamirs and the Altai there are many lakes formed from the blocking of river valleys with rock fragments during earthquakes. Among them are Lake Teletskoye in the Altai Mountains, and Lake Sarezskoye in the Pamirs in the Murghab River valley (this lake was formed in 1911 as a result of the Usoisky River being blocked).

The lakes in high mountain areas are often situated on plateaux surfaces and are mainly of a tectonic origin. Among the large lakes are Lakes Victoria (altitude 1136 m above sea level) and Tanganyika (773 m) in Africa; Titicaca (3812 m) in South America; Kara Kul (3954 m) and Chatyr Kul (3486 m) on the Pamirs, and Issyk Kul (1609 m) on the Tien Shan in Asia. One of the highest lakes is Lake Horpatso, situated in Tibet at an altitude of 5400 m.

The Caspian Sea (−27 m), and the Dead Sea (−392 m) are situated in deep depressions below sea level. The Caspian Sea and a number of other large lakes (Lakes Balkhash, Balaton etc.) are relics of former more extensive water bodies that appeared after the recession of the ice sheets.

Numerous small lakes are formed by wind action (aeolian lakes) in the hot, dry climate of the steppes such as in Western Siberia and Kazakhstan. In regions where limestone, dolomite and gypsum formations dominate the geology, there are karstic lakes, and in areas of permafrost there are thermokarstic lakes. These form when buried ice melts. Lakes of volcanic origin are frequent in Kamchatka, in the Kuril Islands, in the Armenian Highlands, in Middle and Central Asia, and in New Zealand.

Table 1.6 shows the morphological characteristics of the largest lakes. The total volume of water stored in the world’s lakes is 176 400 km³; salt lakes account for 85 400 km³ and fresh lakes for 91 000 km³. The largest volume of saline waters (91% of the total volume) is found in a single water body – the Caspian Sea.

In Asia, the volume of salt lakes is only 3% of the volume of the world total; the volume of fresh waters in Asia is almost 10 times greater than the salt lakes, because of Lake Baikal which holds 27% of the total volume of the world’s freshwater lakes.

In Africa all the large lakes are fresh. Lake Chad situated on the edge of the Sahara, although highly mineralized, is not related to the salt lakes. In North America among the salt lakes is the Great Salt Lake, while in South America Lake Poopo and Lake Titicaca are not salt lakes, but their water cannot be used for drinking.

RESERVOIRS

During the twentieth century the numbers of reservoirs increased markedly. They are used for public water supply, irrigation, hydropower generation and for other purposes. By the late 1980s, Avakyan et al. (1987) estimated there were about 30 000 reservoirs across the world with a volume of greater than 1 million m³. There were 2500 reservoirs with a capacity larger than 100 million m³, accounting for more than 90% (or 5750 km³) of both the total volume and the total surface area of all the world’s reservoirs. According to the estimates available, the total volume of such reservoirs now exceeds 5750 km³, and the total surface area is about 400 000 km².

The large reservoirs constructed during the twentieth century since 1950 have substantially transformed the volume and pattern of fresh water stored on the land surface. They also allowed the development and maintenance of a large number of inter-basin transfer systems (Vugeinsky, 1991).

Of the world’s reservoirs, most are valley reservoirs, which are created by damming the river channel. The biggest valley reservoir in the world in terms of volume is the Bratskoye Reservoir on the River Angara (169.3 km³), and in terms of water surface area the Volta on the Volta River (8480 km²). Since 1950, cascades of reservoirs have been constructed on many large rivers such as the Nile, Yenisei, Colorado, Euphrates, Huang He, Zambezi, Volga, Parana, Mississippi and Missouri.

Reservoirs have also been built by constructing a dam to raise the water level of an existing lake, for example, in Finland, in the northwest of the European part of Russian, and in East Africa. The largest reservoir of this type is Lake Victoria, where the dam at the Owen Falls harnesses a storage of 204.8 km³ and a surface area of 68 800 km².

Along with these two types of reservoirs there are also ones filled in natural depressions by diverting water from a river or by pumping. The largest reservoir in the world of this type is Wadi-Tartar in Iraq having a volume of 72.8 km³ and a surface area of 2000 km².

Reservoirs differ widely in their usage. Hydropower reservoirs are numerous in Africa and South America. In Asia and Latin America there are reservoirs that are used primarily for irrigation. Besides the above usage, many reservoirs on the planet are made for public water supply. In addition there are the reservoirs constructed for navigation, flood protection, fisheries, recreation, timber rafting, and for a variety of different needs. In recent decades multi-purpose reservoirs have been constructed in many parts of the world.

The greatest proportion of the world total volume of stored water is made up from the reservoirs of the USA, Russia, Canada, India and China. Information on reservoirs with a capacity of more than 20 km³ is given in Table 1.7.
Table 1.6. Major morphometric characteristics of principal world lakes

<table>
<thead>
<tr>
<th>Lake</th>
<th>Area, km²</th>
<th>Maximum depth, m</th>
<th>Volume, km³</th>
<th>Country</th>
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Table 1.6. (cont.)

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<th>Maximum depth, m</th>
<th>Volume, km³</th>
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| **Australia** |           |                 |             |                |
| Eyre        | 15 000    | 20              | –           |                |
| Amadeus     | 8 000     | –               | –           |                |
| Torrens     | 5 800     | –               | –           |                |
| Gairdner    | 4 780     | –               | –           |                |
| Georgi      | 145       | 3               | 0.3         |                |
| Taupo       | 611       | 164             | 60          | New Zealand    |

* Salt lake.

1 The hydrosphere surrounding the Earth includes liquid, solid and gaseous forms of water. The hydrological cycle transports this water about the Earth exchanging energy and moving materials as part of the process. The hydrosphere unity is determined by not only its continuity but also the constant water exchange between all its elements. The hydrosphere includes all types of natural waters – oceans, seas, rivers, lakes and glaciers, underground, atmospheric and biologically combined waters. The lower limit of the hydrosphere is assumed to be at the level of Mokhorovichich surface, and the upper limit practically coincides with the upper atmospheric limit (Blyutgen, 1972). Sea, lake, river, glacier, underground and atmospheric waters are all interrelated and water moves from one situation to another as the hydrological cycle progresses (Glushkov, 1929; Vernadsky, 1967).

The Earth’s hydrosphere is one of the oldest mantles of this planet and it appeared between 3.5 and 4 billion years ago (Klige et al., 1998). It developed together with and in close relationship to the lithosphere, the atmosphere, and then with life itself. Up to the present the mechanisms of the origin of water on the Earth have not been completely explained (Kotwicki, 1991). However, the degasification theory seems to be the most likely explanation (Rubey, 1951; Vinogradov, 1959; Artyushkov, 1970; Condie, 1989). According to this theory the basic mass of the hydrosphere formed as a result of the processes of melting and degassing the Earth’s mantle and it was determined by geophysical processes operating at depth.

The mechanism is assumed to be that water vapour, the carbon compounds CO², CO and CH, ammonia, sulphur and its compounds H₂S and SO, acid halides HCl, HF, HBr, boric acid, hydrogen, argon and some other gases came to the Earth’s surface during lava degassing (Monin and Shishkov, 1979; Holland, 1989). The largest part of the volcanic gases condensed and was transformed into water, forming the hydrosphere.

Acid vapours HCl, HF, HBr, ammonia, sulphur and its compounds, and a considerable part of the CO₂ dissolved in drops of condensed water and fell as acid rain to the Earth’s surface. These acid flows ran to low places (oceanic depressions) on the Earth’s primary surface, at the same time reacting with underlying rocks and taking out of them the equivalent amount of alkali and alkali earths. Oceanic water appeared to be saline from the very beginning, and land waters fresh as a result of the leaching occurring in

1 There are different interpretations of term “hydrosphere” and viewpoints on its origin (Hydrosphere, 1960; Belousov et al., 1972; Chebotarev, 1978; Monin and Shishkov, 1979; L’vovich, 1986; Kotwicki, 1991; Hydrosphere, 1993a, b).
Table 1.7. Principal reservoirs in the world with the capacity of more than 20 km³

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Continent</th>
<th>Country</th>
<th>Basin</th>
<th>Year of filling up</th>
<th>Dam backwater, m</th>
<th>Full volume, km³</th>
<th>Use†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Owen Falls</td>
<td>Africa</td>
<td>Uganda, Kenya, Tanzania</td>
<td>Victoria–Nile</td>
<td>1954</td>
<td>31</td>
<td>204.8</td>
<td>HFI</td>
</tr>
<tr>
<td>(Lake Victoria)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Bratskoye</td>
<td>Asia</td>
<td>Russia</td>
<td>Angara</td>
<td>1967</td>
<td>106</td>
<td>169.3</td>
<td>HNTWFR</td>
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<tr>
<td>Nasser</td>
<td>Africa</td>
<td>Egypt</td>
<td>Nile</td>
<td>1970</td>
<td>95</td>
<td>169</td>
<td>IHA N F</td>
</tr>
<tr>
<td>Kariba</td>
<td>Africa</td>
<td>Zambia, Zimbabwe</td>
<td>Zambezi</td>
<td>1959</td>
<td>100</td>
<td>160.3</td>
<td>HNIFA</td>
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<tr>
<td>Volta</td>
<td>Africa</td>
<td>Ghana</td>
<td>Volta</td>
<td>1965</td>
<td>70</td>
<td>148</td>
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<tr>
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<td>N. America</td>
<td>Canada</td>
<td>Manicouagan</td>
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<td>Caroni</td>
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<td>Wadi-Tartar</td>
<td>Asia</td>
<td>Iraq</td>
<td>Tigris</td>
<td>1976</td>
<td>–</td>
<td>72.8</td>
<td>S I</td>
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<td>WAC Bennet</td>
<td>N. America</td>
<td>Canada</td>
<td>Peace</td>
<td>1967</td>
<td>183</td>
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<td>Zeiskoye</td>
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<td>Russia</td>
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<td>La Grande 3</td>
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<td>Canada</td>
<td>La Grande</td>
<td>1981</td>
<td>93</td>
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<td>Ust-Ilimskoye</td>
<td>Asia</td>
<td>Russia</td>
<td>Angara</td>
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<td>Russia</td>
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<td>1959</td>
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<td>Brazil</td>
<td>Tocantins</td>
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<td>Caniapiscau</td>
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<td>Keban</td>
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<td>62</td>
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<td>Iroquois</td>
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<td>USA, Canada</td>
<td>St. Lawrence</td>
<td>1958</td>
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<td>Brazil, Paraguay</td>
<td>Parana</td>
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<tr>
<td>Loma de la Lata</td>
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<td>Don</td>
<td>1952</td>
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Table 1.7. (cont.)

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<tr>
<th>Reservoir</th>
<th>Continent</th>
<th>Country</th>
<th>Basin</th>
<th>Year of filling up</th>
<th>Dam backwater, m</th>
<th>Full volume, km³</th>
<th>Use</th>
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<tr>
<td>Kenney</td>
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<td>Asia</td>
<td>Russia</td>
<td>Khantaika</td>
<td>1975</td>
<td>50</td>
<td>23.5</td>
<td>HN</td>
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<td>Fort Peck</td>
<td>N. America</td>
<td>USA</td>
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<td>1937</td>
<td>76</td>
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<td>Xinanjiang</td>
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<td>China</td>
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<td>Parana</td>
<td>1974</td>
<td>85</td>
<td>21.2</td>
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<td>Yacyreta</td>
<td>S. America</td>
<td>Argentina, Paraguay</td>
<td>Parana</td>
<td>1991</td>
<td>41</td>
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<td>H N I</td>
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<td>Furnas</td>
<td>S. America</td>
<td>Brazil</td>
<td>Grande</td>
<td>1965</td>
<td>96</td>
<td>20.9</td>
<td>H A</td>
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<tr>
<td>El Chocon</td>
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<td>Limay</td>
<td>1975</td>
<td>65</td>
<td>20.2</td>
<td>H I A</td>
</tr>
</tbody>
</table>

*H, hydropower; N, navigation; W, water supply; I, irrigation; F, fishery; T, timber rafting; R, recreation; A, accumulation; S, struggle with inundations.*

*In 1970 the filling of the reservoir was stopped. The project reservoir capacity was not attained.*

the upper zone of the Earth’s crust, remaining saline only in deep areas.

Some scientists (Shoemaker, 1984; Alvarez, 1987) do not agree with this theory on the origins of the hydrosphere. They consider that the Earth has experienced during its history numerous collisions with comets that were potential sources of water.

Estimates of the amount of water formed in this way at early stages of the evolution of the Earth vary from 4% to 40% (Chyba, 1987) and some suggest even higher proportions (Hoyle, 1978) of the volume.

Present-day geological studies have shown that the hydrosphere existed during most geological periods (Markov, 1960; Strakhov, 1963). According to calculations (Timofeyev et al., 1988) the Earth’s mantle contains $28 \times 10^9$ km³ of water, which supports degasification as the origin of the hydrosphere.

During the early history of the Earth degasification was more intensive. The basic mass of the hydrosphere would probably have formed during the first hundreds of millions of years. Oceans appeared rapidly during this time (Kuenen, 1950).

However, Revelle (1955) was of the opinion that the oceans appeared late and quickly. According to Schopf (1980), the major volume of degasification occurred between 4.6 and 2.5 billion years ago, and according to Sorokhtin (1974), the maximum rate of growth took place during the Lower Riphean.

New studies (Staudacher and Allegre, 1982; Hydrosphere, 1993a, b) show that the Earth degasified rapidly during the 50 million years after it originated. The results of further studies in this area have been generalized by Holland (1989) and Kump (1989).

During the Archean Period the Earth’s surface relief was subdued and water covered an area of about 500 million km² (Klige, 1992). There was a warm and humid climate without distinct latitudinal zones and with alternating periods when minor warming and cooling occurred together with glaciation (Monin and Shishkow, 1979). In the Proterozoic Era, photosynthesis became active with the development of live matter in the hydrosphere (Alpatiyev, 1983).

The gradual increase in the land area with the growth of the thickness of the Earth’s crust and the development of mountains exerted a considerable effect on the hydrological cycle. At this time conditions were more arid and ice sheets developed in distinct climatic zones, the hydrological cycle between the oceans, atmosphere and land grew more active and a river network developed (Drozdov et al., 1981).

In the Palaeozoic Era the hydrological cycle became more complicated due to changes in the ratio between the area of ocean and land. During this period the ocean reached its greatest size in the Ordovician. Marine deposits show that this was the most powerful transgression in the history of the Earth. The land area was 72 million km² or 50% of its present size. The sea level rose by more than 250 m and 83% of our planet was covered by water (Klige, 1980). In contrast, the area of the land was greatest during the Mesozoic when the sea level was 100 m lower than at present.

Simultaneously with the decrease in the size of the ocean and an increase in the elevation of the continents, as a result of the development of mountain-forming processes, climatic conditions became more arid, runoff decreased, and a considerable part of the water became locked up in ice sheets and glaciers. At this time the character of the water cycle came close to the one that exists today.

By the Mesozoic the gaseous composition of the atmosphere had changed greatly, as a result of the increase in the amount of carbon dioxide and oxygen due to the development of vegetation and animal life. There is evidence of boreal, humid and subtropical climates on land in the late Triassic (Razumikhin, 1976).

The recent great oceanic transgression started at the end of the Jurassic Period and reached its maximum in the Cretaceous Period. Since then the ocean has, in general, regressed and the land area has increased (by about 35 million km²), and this has been accompanied by powerful mountain-building of the Alpine
Table 1.8. Water content in the hydrosphere

<table>
<thead>
<tr>
<th>Type of water</th>
<th>Area of distribution, (\text{km}^2 \times 10^3)</th>
<th>Volume, (\text{km}^3 \times 10^3)</th>
<th>Water layer, m</th>
<th>Fraction of total volume of hydrosphere, %</th>
<th>Fraction of fresh water, %</th>
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<tr>
<td>World Ocean</td>
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<td>1 338 000</td>
<td>3700</td>
<td>96.5</td>
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<tr>
<td>Ground water (gravity and capillary)</td>
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<td>23 400</td>
<td>174</td>
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<tr>
<td>Predominantly fresh ground water</td>
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<td>10 530</td>
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<td>16.5</td>
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<td>16 227.5</td>
<td>24 064</td>
<td>1463</td>
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<td>2 340</td>
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<td>Mountainous regions</td>
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<td>Fresh</td>
<td>2 058.7</td>
<td>176.4</td>
<td>85.7</td>
<td>0.013</td>
<td>--</td>
</tr>
<tr>
<td>Salt</td>
<td>1 236.4</td>
<td>91.0</td>
<td>73.6</td>
<td>0.007</td>
<td>0.26</td>
</tr>
<tr>
<td>Swamp water</td>
<td>822.3</td>
<td>85.4</td>
<td>103.8</td>
<td>0.006</td>
<td>--</td>
</tr>
<tr>
<td>River stream water</td>
<td>2 682.6</td>
<td>11.5</td>
<td>4.28</td>
<td>0.0008</td>
<td>0.03</td>
</tr>
<tr>
<td>Biological water</td>
<td>148 800</td>
<td>2.12</td>
<td>0.014</td>
<td>0.0002</td>
<td>0.006</td>
</tr>
<tr>
<td>Water in the air</td>
<td>510 000</td>
<td>1.12</td>
<td>0.002</td>
<td>0.0001</td>
<td>0.003</td>
</tr>
<tr>
<td>Total volume of the hydrosphere</td>
<td>510 000</td>
<td>1 386 000</td>
<td>2718</td>
<td>100</td>
<td>--</td>
</tr>
<tr>
<td>Fresh water</td>
<td>148 800</td>
<td>35 029.2</td>
<td>235</td>
<td>2.53</td>
<td>100</td>
</tr>
</tbody>
</table>

a With no account of underground water of the Antarctic, approximately estimated at 2 million \(\text{km}^3\), including predominantly fresh water of about 1 million \(\text{km}^3\).

The hydrologic cycle is complex and involves the movement of water in multiple forms, including liquid, solid, and gaseous states. The hydrosphere, which encompasses all water on Earth, is a critical component of the global water cycle. The distribution of water is uneven, with the majority held in the World Ocean, while continental glaciers, groundwater, and soil moisture also play significant roles.

1.2.2 The contemporary hydrosphere

There are no large disagreements in the estimates of the volume of the present hydrosphere (Korzun, 1974a; Kotwicki, 1991; Hydrosphere, 1993a, b), since it is determined, basically, by the enormous volume of water contained in the World Ocean. The volume of the hydrosphere is most frequently estimated to be 1370 million \(\text{km}^3\) and this figure is practically equal to the water volume in the World Ocean. However, as more information becomes available about the relief of the ocean bottom, particularly for the Arctic Ocean, where underwater ridges have been discovered, there have been reductions to a total of 1338 million \(\text{km}^3\), i.e. a reduction of 32 million \(\text{km}^3\) (Frolov, 1971). The total volume of the hydrosphere, according to current data (Korzun, 1974) is 1386 million \(\text{km}^3\) (Table 1.8). Fresh water in all its states makes up only 2.53% of the total, of which 1.74% is in the ice sheets of the Antarctic and the Arctic and in mountain glaciers.

In addition to free (gravitational) water, the lithosphere contains a large amount of physically and chemically combined water. The average content of the physically and chemically combined waters amounts to 3.5% of the rock weight, i.e. some 0.84 \(\times\) \(10^2\) g (Derpgolts, 1971). Combined water does not participate actively in the hydrological cycle, at least at recognizable time-scales, and is not taken into account in this present study.

THE WORLD OCEAN

Table 1.8 shows that the World Ocean holds by far the largest part of total volume of water on the planet. However, in recent
Table 1.9. Present-day glaciation of continents and islands of the Earth

<table>
<thead>
<tr>
<th>Region</th>
<th>Area of glaciers, km²</th>
<th>Water volume, km³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arctic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Greenland</td>
<td>1 802 400</td>
<td>2 340 000</td>
</tr>
<tr>
<td>Franz Josef Land</td>
<td>13 735</td>
<td>2 530</td>
</tr>
<tr>
<td>Novaya Zemlya</td>
<td>24 420</td>
<td>9 200</td>
</tr>
<tr>
<td>Severnaya Zemlya</td>
<td>17 470</td>
<td>4 620</td>
</tr>
<tr>
<td>Arctic Islands</td>
<td>226 090</td>
<td>83 500</td>
</tr>
<tr>
<td>Canadian Archipelago</td>
<td>148 825</td>
<td>48 400</td>
</tr>
<tr>
<td>Spitzbergen (Western)</td>
<td>21 240</td>
<td>18 690</td>
</tr>
<tr>
<td>Small Islands</td>
<td>400</td>
<td>60</td>
</tr>
<tr>
<td>Total</td>
<td>2 028 490</td>
<td>2 423 500</td>
</tr>
<tr>
<td>Europe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iceland</td>
<td>11 785</td>
<td>3 000</td>
</tr>
<tr>
<td>Scandinavia</td>
<td>5 000</td>
<td>645</td>
</tr>
<tr>
<td>Alpes</td>
<td>3 200</td>
<td>350</td>
</tr>
<tr>
<td>Caucasus</td>
<td>1 430</td>
<td>95</td>
</tr>
<tr>
<td>Total</td>
<td>21 415</td>
<td>4 090</td>
</tr>
<tr>
<td>Asia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pamir-Altai</td>
<td>11 255</td>
<td>1 725</td>
</tr>
<tr>
<td>Tien Shan</td>
<td>7 115</td>
<td>735</td>
</tr>
<tr>
<td>Dzungarian Ala Tau, Sayan Mountains</td>
<td>1 635</td>
<td>140</td>
</tr>
<tr>
<td>Eastern Siberia</td>
<td>400</td>
<td>30</td>
</tr>
<tr>
<td>Kamchatka, Plateau of Koryak</td>
<td>1 510</td>
<td>80</td>
</tr>
<tr>
<td>Hindu Kush</td>
<td>6 200</td>
<td>930</td>
</tr>
<tr>
<td>Karakoram Pass</td>
<td>15 670</td>
<td>2 180</td>
</tr>
<tr>
<td>Himalayas</td>
<td>33 150</td>
<td>4 990</td>
</tr>
<tr>
<td>Tibet</td>
<td>32 150</td>
<td>4 820</td>
</tr>
<tr>
<td>Total</td>
<td>109 085</td>
<td>15 630</td>
</tr>
<tr>
<td>North America</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alaska (Pacific Coast)</td>
<td>52 000</td>
<td>12 200</td>
</tr>
<tr>
<td>Inner Alaska</td>
<td>15 000</td>
<td>1 800</td>
</tr>
<tr>
<td>USA</td>
<td>510</td>
<td>60</td>
</tr>
<tr>
<td>Mexico</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>67 522</td>
<td>14 062</td>
</tr>
<tr>
<td>South America</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Venezuela, Colombia, Andes, Tierra del Fuego</td>
<td>7 100</td>
<td>2 700</td>
</tr>
<tr>
<td>Patagonian Andes</td>
<td>17 900</td>
<td>4 050</td>
</tr>
<tr>
<td>Total</td>
<td>25 000</td>
<td>6 750</td>
</tr>
<tr>
<td>Oceania</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Zealand</td>
<td>1 000</td>
<td>100</td>
</tr>
<tr>
<td>New Guinea</td>
<td>14.5</td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td>1 014.5</td>
<td>107</td>
</tr>
<tr>
<td>Africa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kenya, Mount Kilimanjaro, Ruwenzori</td>
<td>22.5</td>
<td>3</td>
</tr>
<tr>
<td>Antarctica</td>
<td>13 980 000</td>
<td>21 600 000</td>
</tr>
</tbody>
</table>

years, studies have appeared (Sofer and Skirstymonskaya, 1994; Wallace, 1996) that show volumes which differ from the data here by between 0.7% and 10%. Including the water stored in the bottom silts of the oceans causes the 10% difference.

The World Ocean has accumulated $3.06 \times 10^{25}$ Joules of heat (Stepanov, 1983). Every year it takes up almost twice as much solar energy as the land, and this factor determines its important role in the planetary heat exchange. The major portion of this energy is employed in evaporating over 500 000 km³ per year of water, which ensures global water exchange.

**GLACIERS AND ICE SHEETS**

The largest volume of fresh water is stored in the planet’s glaciers and ice sheets. The total area of the present glaciation exceeds 16.2 million km² (Kotlyakov, 1997). The mean ice thickness on this area is 1700 m, and the maximum is more than 4000 m (in Antarctica). The distribution of ice sheets and glaciers and the water stored in them is given in Table 1.9. The data on glacier thickness and water storage are approximate. To estimate the mean thickness of ice data were used from the few measurements from ice drilling and seismic sounding (Korzun, 1974b). These data were applied by analogy to other glaciers taking into account their morphological features. The accuracy of the assessment of that water storage in the Antarctica, for example, is about ±3.0 million km³. The total water volume in the ice across the globe is estimated to exceed 24 million km³ (Korzun, 1974b). Most of the water stored in the ice cover is concentrated in Antarctica (almost 90%), while the remainder is found in Greenland (almost 10%) and in mountain glaciers.

Glaciers are giant “water reservoirs” and “coolers” greatly influencing the climate and water regime of the Earth (Kotlyakov, 1979). Their state and the changes from this state over time are an important indicators of global climatic and hydrological changes – past, present and future. Cooling and warming and the advance and recession of glaciers result in the change of all the elements of the hydrological cycle: precipitation, runoff and evaporation, and the volume of water stored on land and in the ocean. During glaciation a large amount of water becomes locked up as snow and ice on the land. As a result the volume of runoff decreases, the World Ocean level falls by tens of metres, uncovering extensive areas of the continental shelves. With the decline of glaciation, river flow increases, the volume of water in the ocean becomes larger, the level rises and the land area diminishes.

**UNDERGROUND ICE**

Areas of permafrost extend over northeast Europe and the north and northeastern parts of Asia, including the Arctic islands; they cover northern Canada and the fringes of Greenland and
Antarctica, as well as higher parts of South America. The total area of permafrost is about 21 million km², some 14% of the land area. In the Southern Hemisphere (Antarctica, South America) permafrost covers about 1 million km². The depth of permafrost ranges from 400 to 650 m. Underground ice within this range is found as vein formations and strata. The water stored as underground ice can be estimated only approximately due to lack of data and few studies (Grave, 1968) but the most likely figure is 300 thousand km² (Korzun, 1974b). In the permafrost areas 150–200 km³ of water occurs in the form of river ice.

The annual snowfall over the Earth is about $1.7 \times 10^{13}$ tonnes, and this snow covers an area of between 100 and 126 million km². The distribution of snow varies considerably from year to year depending on climatic conditions.

**UNDERGROUND WATER**

The volume of gravitational water contained in the pores, fissures and fractures of the water-saturated strata of the Earth’s crust represents the natural storage of water underground. The geographical distribution of ground water is closely related to the geological structure of the Earth’s crust. It also depends considerably on the climatic factors: precipitation, condensation and evaporation, and particularly on the infiltration. Since runoff also depends on these factors, there is a strong relationship between ground water and runoff: ground water draining to rivers are included in the volume of runoff, being its most stable contribution to the hydrograph, especially during dry periods and drought.

The reliable estimation of ground water storage is very difficult (Garmonov et al., 1974). The water content of water-bearing strata can be obtained approximately by multiplying the volume of water-bearing table by a water loss factor and effective porosity. The natural storage of ground water is determined down to the absolute depth of 2000 m – the depth of the isobath which indicates approximately the distribution of the Earth’s continental crust.

Three zones of ground water movement can be distinguished vertically:

1. A zone of active water exchange is located above the local base level and is highly dynamic. Movement of water in this zone increases with height above the base level. Here the character of the water is most closely related to the nature of the overlying soil and to the rock strata containing them and also to climatic factors. The effective porosity of this zone is about 15%.

2. A zone of less active water exchange is located below this first zone down to sea level. This zone is situated below local base levels and the water here is only affected by large rivers which may have deep channels. Drainage of ground water in this zone is also related to basins and depressions.

Table 1.10. *Natural ground water resources in the upper layer of the Earth’s crust by hydrodynamic zones*

<table>
<thead>
<tr>
<th>Continent</th>
<th>Zone</th>
<th>Ground water resources, $\text{km}^3 \times 10^6$</th>
<th>Total resources of ground water, $\text{km}^3 \times 10^6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>1</td>
<td>0.2</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>Asia</td>
<td>1</td>
<td>1.3</td>
<td>7.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>Africa</td>
<td>1</td>
<td>1.0</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>North America</td>
<td>1</td>
<td>0.7</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>South America</td>
<td>1</td>
<td>0.3</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>Australia and Oceania</td>
<td>1</td>
<td>0.1</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.9</td>
<td></td>
</tr>
</tbody>
</table>

* For explanation of zones see text.

Where these lie under the sea the discharge of water from this zone occurs into the sea. Less movement provides for higher mineralization of ground waters, however here they are basically fresh or weakly mineralized. The nature of the waters in this zone is determined by the occurrence of aquifers and aquicludes and their juxtaposition in the form of depressions, troughs, synclines and monoclines forming artesian basins. The effective porosity of this zone is 12%.

3. A third zone lies in the crust from sea level to the absolute depth – 2000 m. The waters of the upper part of this zone are only influenced by the biggest rivers at depth, and by large-scale features such as depressions in the relief of land and the ocean. In the upper part of this zone, water is fresh or weakly mineralized, with saline water and brines below. The effective porosity is 5%.

The mean altitude of each continent was used for calculating the total volume of ground water stored in the Earth’s crust (Korzun, 1974b). The total storage of ground water to the 2000 m level in the Earth’s crust was estimated to be 23.4 million km³ (Table 1.10). With 3.6 million km³ in the first zone, 6.2 million km³ in the second and 13.6 million km³ in the third, rivers are fed mainly from water stored in the first zone.
LAKES AND RESERVOIRS

There are 145 large lakes across the globe with an area of 100 km$^2$ and holding 168 thousand km$^3$ of water (Korzun, 1974b) (Table 1.11). This is 95% of the total volume of all the world’s lakes, giving a total volume of lake water of 176.4 thousand km$^3$. Of this total 91 thousand km$^3$ is fresh water, and 85.4 thousand km$^3$ is salt. The hydrology of about 40% of the world’s large lakes has not been studied and their volumes are estimated approximately. Some studies (L’vovich, 1986; Wallace, 1996) exaggerated estimates of the water stored in lakes and these vary from 200 000 km$^3$ to 278 000 km$^3$. The hydrosphere includes water held in reservoirs. Their total volume exceeds 6000 km$^3$ and they regulate about 15% of the Earth’s total runoff.

WATER STORED IN SWAMPS, CHANNEL NETWORKS, SOIL, LIVING ORGANISMS, PLANTS AND THE ATMOSPHERE

Swamps and bogs are widespread across the Earth with a total area of approximately 2.7 million km$^2$ or about 2% of the land area. The most swampy continent is South America (Table 1.12). The total volume of water in the world’s swamps and bogs is estimated to be about 11 470 km$^3$ (Korzun, 1974b). This value has been obtained on the assumption that the mean thickness of the peat bogs is 4.5 m, their volume is 12 070 km$^3$, and that they are 95% water.

The hydrosphere also includes the water stored in the river channel network. The total volume of this water – 2120 km$^3$ – was estimated by the State Hydrological Institute (Korzun, 1974b) taking into account the volume of runoff and the lengths of the main rivers and their tributaries (Table 1.13). According to L’vovich (1986) this volume is 1200 km$^3$. In spite of the very small volume of water in the river channels, it is this water which is continuously renewed and which is most important for human use.

The soil moisture is an integral part of the hydrosphere. This water occurs mainly in the top 2 metres of the soil. The total volume of soil moisture is estimated to be approximately 16 500 km$^3$ (Korzun, 1974b). This figure assumes that soil moisture is 10% of the 2-m layer, and that the area of soil containing moisture covers 55% of the land area or 82 million km$^2$. L’vovich (1986) estimated the total volume of soil moisture to be 83 thousand km$^3$; however he did not state the method used to estimate it.

Biological water (the water included in living organisms such as plants and animals) is an active link in the hydrologic cycle. Part of the water that evaporates from the land and enters into the atmosphere is due to transpiration of soil moisture by vegetation. Alpatjyev (1969) gives the volume of living matter in the biosphere as $1.4 \times 10^{12}$ tonnes. The water content of living matter is about 80% (Derpgolts, 1971), i.e. $1.12 \times 10^{12}$ tonnes or approximately 1120 km$^3$.

The water contained in the atmosphere, as water vapour, water drops and ice crystals, is an important part in the hydrosphere, possibly the most active part. The total volume of moisture in the atmosphere, according to the different estimates (Korzun, 1974b; L’vovich, 1986; Wallace, 1996), varies from 12 900 km$^3$ to 14 000 km$^3$.

---

### Table 1.11. Water resources in the principal lakes of the Earth

<table>
<thead>
<tr>
<th>Continent</th>
<th>Number of lakes</th>
<th>Total area, km$^2 \times 10^3$</th>
<th>Water resources, km$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fresh</td>
</tr>
<tr>
<td>Europe</td>
<td>34</td>
<td>430.4</td>
<td>2027</td>
</tr>
<tr>
<td>Asia</td>
<td>43</td>
<td>209.9</td>
<td>27 782</td>
</tr>
<tr>
<td>Africa</td>
<td>21</td>
<td>196.8</td>
<td>30 000</td>
</tr>
<tr>
<td>North America</td>
<td>30</td>
<td>392.9</td>
<td>25 623</td>
</tr>
<tr>
<td>South America</td>
<td>6</td>
<td>27.8</td>
<td>913</td>
</tr>
<tr>
<td>Australia and Oceania</td>
<td>11</td>
<td>41.7</td>
<td>154</td>
</tr>
<tr>
<td>Total</td>
<td>145</td>
<td>1300</td>
<td>86 500</td>
</tr>
</tbody>
</table>

### Table 1.12. Area of bog over the Earth

<table>
<thead>
<tr>
<th>Continent</th>
<th>Bog area, km$^2 \times 10^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eurasia</td>
<td>925</td>
</tr>
<tr>
<td>Africa</td>
<td>341</td>
</tr>
<tr>
<td>North America</td>
<td>180</td>
</tr>
<tr>
<td>South America</td>
<td>1232</td>
</tr>
<tr>
<td>Australia and Oceania</td>
<td>4</td>
</tr>
</tbody>
</table>

### Table 1.13. Water volume in river channels of the Earth

<table>
<thead>
<tr>
<th>Continent</th>
<th>Water volume in river channels, km$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>80</td>
</tr>
<tr>
<td>Asia</td>
<td>565</td>
</tr>
<tr>
<td>Africa</td>
<td>195</td>
</tr>
<tr>
<td>North America</td>
<td>250</td>
</tr>
<tr>
<td>South America</td>
<td>1000</td>
</tr>
<tr>
<td>Australia and Oceania</td>
<td>25</td>
</tr>
</tbody>
</table>
1.2.3 Global water exchange in the hydrosphere – the hydrological cycle

The waters of the hydrosphere are in constant, usually cyclic, motion under the effects of solar radiation, the energy released from the Earth’s interior and gravitational forces. Due to geological processes about 1 km³ of water a year is released from the mantle through degasification and this rises gradually to the Earth’s surface. As a result of convection in the mantle, part of this matter can emerge through breaks in ocean rift zones related to oceanic ridges (Monin, 1977). The global process of water exchange provides some stability in the distribution of waters between the land, the oceans and the atmosphere. This equilibrium is relative and can change in time, and these changes can lead to corresponding changes in hydrological and climatic conditions.

Water evaporating from the surface of reservoirs, soil and vegetation enters into the atmosphere as water vapour where it is dissipated upwards by turbulent diffusion and is transported by air currents from one place to another. With a temperature decrease, water vapour is condensed, transforming it to a liquid or solid. During rainfall from clouds, part of the water returns to the Earth’s surface (inland cycle), and part of it returns to reservoirs in the form of runoff. Some precipitation can fall into the ocean.

Water evaporated from the surface of the oceans and seas mostly (90%) falls back into the sea, short-circuiting the cycle. A smaller part of it (10%) participates in the major cycle, being transported through oceanic circulation to the land where, as rainfall, it can be involved in a number of smaller versions of the complete hydrological cycle when surface and ground water and ice drainage reaches the World Ocean, closing the complete cycle. Part of the water is combined and decomposed by plants.

Part of the water contained by the Earth is in chemical compounds, such as crystal hydrate, sorbate and many other forms which are found in porous deposits in the Earth’s crust. This chemically combined water can be removed from the total water exchange for thousands of years. The crustal rocks lose water during the process of metamorphization and subduction under the effects of high pressure and high temperature. This water rises through rock pores and appears on the Earth’s surface (Vinogradov, 1973).

The global hydrological cycle is not a closed system. Solar energy and energy from space, together with cosmic dust, meteorites and meteors, arrive from space. The Earth in its turn gives back part of its energy to space and dissipates hydrogen and helium to it (Alpatjyev, 1983; Kulp, 1951). This exchange of matter and energy brings about 0.01 km³ of water per year (Derpgolts, 1971; Alpatjyev, 1969) from space to the Earth. At the same time part of the hydrosphere is lost due to the dissipation of light gases, and their escape beyond the limits of the Earth’s gravitational field, amounting to about 0.1 km³ per year (from 0.03 to 0.27 km³: Yuri, 1959; Pavlov, 1977; Alpatjyev, 1983).

Every year human influences grow and cause more and more changes to natural processes, including the hydrological cycle. These changes bring about alterations to the water balance and to water resources and their availability. The rapid growth of population, the development of industrial production and the rise of agriculture have resulted in the increased use of water, reaching a global total of about 4 thousand km³ per year (Shiklomanov, 1997) by 1990. Some 80% of this water is used for agriculture, primarily for irrigation, and this causes more evaporation and an intensification of the hydrological cycle.

Human activities have also changed the character of ground water. Although there are some examples of artificial recharge of aquifers, more often the water table has been lowered to provide water for drinking. Every year up to 20 thousand km³ of ground water is abstracted (Plotnikov, 1976), which results generally in the reduction of aquifer storage and the lowering of ground water levels, and in some cases in land subsidence.

The construction of reservoirs has led to the slowing down of the movement of river waters (Kalinin, 1974). Slowing the movement of water can influence its quality particularly by the accumulation of pollutants. Because the World Ocean water is contaminated by oil products, this leads to the reduction of evaporation from the water surface by about 10% (Duvanin, 1981) and this contributes to the reduction in the rate of exchange of water between the ocean and the land surface.

Of course water in the hydrosphere is connected by the hydrological cycle; however the rates of movement and residence times are very different for water in its different states (Table 1.14). Table 1.14 shows that biological waters included in plants and living organisms are renewed most rapidly – perhaps over a period

<table>
<thead>
<tr>
<th>Water of hydrosphere</th>
<th>Period of renewal</th>
</tr>
</thead>
<tbody>
<tr>
<td>World Ocean</td>
<td>2 500 years</td>
</tr>
<tr>
<td>Ground water</td>
<td>1 400 years</td>
</tr>
<tr>
<td>Polar ice</td>
<td>9 700 years</td>
</tr>
<tr>
<td>Mountain glaciers</td>
<td>1 600 years</td>
</tr>
<tr>
<td>Ground ice of the permafrost zone</td>
<td>10 000 years</td>
</tr>
<tr>
<td>Lakes</td>
<td>17 years</td>
</tr>
<tr>
<td>Bogs</td>
<td>5 years</td>
</tr>
<tr>
<td>Soil moisture</td>
<td>1 year</td>
</tr>
<tr>
<td>Channel networks</td>
<td>16 days</td>
</tr>
<tr>
<td>Atmospheric moisture</td>
<td>8 days</td>
</tr>
<tr>
<td>Biological water</td>
<td>several hours</td>
</tr>
</tbody>
</table>

Table 1.14. Periods of renewal of water resources on the Earth
of a few hours. Plants transpire this water. Atmospheric water, which forms due to evaporation from any water surface, is renewed on average over 8 days. Water stored in the channel network is also renewed on average over a period of 16 days. The soil water is renewed over a period of a year and is spent mainly for evaporation and partly on runoff. Water stored in swamps has a 5-year residence time.

Most lake water is renewed on average over a period of 17 years. However different lakes have different renewal times. For example, for Lake Baikal this time is 380 years. All other types of natural waters (glaciers, ground waters, ocean waters etc.) are renewed more slowly, possibly over periods of thousands and even tens of thousands of years. The largest period is for the ice in the tundra and in Antarctica, which may be renewed only over several hundreds of thousands of years (Kotlyakov, 1984).

The time data presented here for the exchange of natural water in the global hydrological cycle (Korzun, 1974b; L'vovich, 1986) are very approximate and typical of the lower limits of the exchange process (Kalinin, 1972).