

PROPERTIES OF RIVERS, STREAMS, LAKES AND WETLANDS

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Summary

The author describes the concept of the Earth's hydrosphere, its water bodies, integrated by global and local moisture circulation. He also cites arguments demonstrating the role of water in the origin and development of life on Earth. Physical and chemical properties of water are considered. The significance of changes of water aggregative states for optimum conditions of life on Earth is also shown. The structure of the water molecule at freezing and boiling, its density anomalies, and thermal and dissolving capacities are explained. An overview of absorption and dispersion of solar radiation in water bodies is made. Aquatic life and features of its development subject to natural processes, its ecotype, and modifications of chemical runoff on the boundaries of water ecosystems are considered. Finally, the author formulates the common principles of rational use of water resources, minimizing economic and ecological risks.

1. Physical aspects of water

About 71% of the Earth's surface is covered with waters of the World Ocean, and up to 15% of land is occupied by water bodies (glaciers, lakes, rivers, and swamps). The Earth's hydrosphere contains $1.39 \cdot 10^9$ km³ of water. The World Ocean holds slightly

more than 96% of the hydrosphere in the form of saltwater. The freshwater of the planet comes in the form of glaciers, underground water and ice, meteoric water, lakes, reservoirs, rivers and wetlands. Its volume makes up $0.0367 \cdot 10^9 \text{ km}^3$. This is almost 38 times less than the total water volume. The dominant part of freshwater is concentrated in glaciers and ice sheets ($0.0258 \cdot 10^9 \text{ km}^3$). Only 0.36% of freshwater is collected in lakes and reservoirs. Some of the lakes are brackish, saline and even brine. River flow at any point in time holds only 0.005% of the Earth's freshwater. The freshwater content of swamps and wetlands is much greater and reaches 0.03%. A huge volume of freshwater is in water-bearing geological formations ($0.0234 \cdot 10^9 \text{ km}^3$ of which $0.01053 \cdot 10^9 \text{ km}^3$ are freshwater). Underground ice in the permafrost zone contains 0.82% of freshwater. Atmosphere has 0.04% and living organisms contain 0.003% of the freshwater resource.

Owing to moisture circulation on the Earth, water is permanently moving and is renewed at an extremely low rate. The rate of water renewal is highest for living organisms (a few hours). Only 8 days are necessary for full moisture renewal in the atmosphere. The period of water renewal in rivers and reservoirs are respectively 19 and 52 days. Water rotation period in other water bodies is essentially greater. It is equal to 5 years for swamps and 17 years for lakes. About 1400 years is required for complete groundwater replacement and 2650 years for renewal of the World Ocean. The most invariable water bodies are glaciers and underground ice. Their periods of water renewal reach 9700 and 10 000 years respectively.

Moisture circulation within small areas and the whole planet is carried out both every second and on a long-term time scale. This can create either favorable or extremely severe conditions for life and economic activity. It is appropriate to recollect Antoine de Saint-Exuperit's view on water: "It is impossible to say, that you are necessary for life; you are the life". The academician V.I. Vernadskiy wrote: "water stands apart in the history of our planet. There is no natural body equivalent to water in its influence on the most mighty geological processes. There is no terrestrial substance, mineral and rock, living organism, which did not hold it. The whole terrestrial substance is covered and penetrated by it". The consequences of global water circulation provide strong evidence for the significance of water on the Earth. The amount of water reaching the World Ocean and that received by the land is steady in geological time scales. Moisture balance is not observed in shorter periods of times. The excess of water runoff to the World Ocean over evaporation results in ocean level rise and flooding of the lowlands along the coasts. Conversely, when the ocean level falls, the volume of glaciers increases. Obviously, the instability of the World Ocean level as a planetary factor has an influence on the existence of people, organization of economy, and evolution of water and land ecosystems.

These and many other processes on the Earth are closely connected with the natural and chemical properties of water. Water (oxide of hydrogen, H_2O) is the elementary steady chemical compound of hydrogen and oxygen. Its molecular mass is equal to 18. The share of oxygen thus is 88.81% and the share of hydrogen is 11.19% of its molecule mass. Special conditions are required to form a water molecule from its component parts. At a temperature of 300 °C conjugation of oxygen and hydrogen has a slow character, but at a temperature of 550 °C it happens explosively. Structural breakdown of water molecules is carried out only at higher temperatures. Thermal dissociation

occurs at noticeable magnitude at temperatures above 2000 °C. It reaches a maximum at temperatures higher than 4000 °C. Water is a chemical compound that can be found in a liquid, solid and gaseous state. The aggregative state of water depends on temperature and pressure.

A molecule of water (H₂O) consists of atoms of hydrogen and oxygen. The existence of the three hydrogen (¹H – protium, ²H – deuterium (D), ³H – tritium (T)) and six oxygen (¹⁴O, ¹⁵O, ¹⁶O, ¹⁷O, ¹⁸O, ¹⁹O) isotopes, indicates that water is normally a mixture of various water isotopes. Each kind of water differs in its hydrological, radioactive and biological properties. In fluvial, lake, pluvial, melted, glacial, underground and marine water by far the most common is the “easy” oxygen isotope ¹⁶O; less common is the “heavy” one ¹⁸O, and the oxygen isotope with mass number 17 is very rare. The most common water isotope integrates protium and oxygen isotope ¹⁶O. It forms 99.73% of the water resources of the planet. It is a necessary condition for the existence of life on the planet. Chemically pure water is colorless and flavorless. In natural conditions its clarity is rarely 100%, and it almost always has color. It is also characterized by taste, as it contains various chemical compounds.

The other H₂O varieties form only 0.27% of planetary water resources. For example, tritium waters (HTO) are only 13 to 20 kg in the Earth’s hydrosphere. In the atmosphere its amount is only about 0.07 to 0.10 kg. In oceans its content is less than in continental waters. Each type of natural waters has a specific isotope structure. Pluvial water is enriched by protium. In melted water, on the other hand, the content of heavy isotopes of hydrogen is rather less, and concentration of the oxygen isotope ¹⁸O is greater. This facilitates determination of the origin of any volume of water, and study of the diverse processes of water transformation in the global hydrologic cycle, including continental systems of air circulation and small and large river catchment basins.

Some water isotopes don't support functions of living organisms. On the contrary, they decelerate chemical responses and are physiologically inert. Water with deuterium instead of protium, is named "heavy" water. Heavy water (D₂O¹⁶) was first noticed by G. Luice and R. MacDonald during prolonged electrolysis and distillation of water in 1933. It looked like the usual water which is colorless and flavorless, but freezes and begins to boil at a higher temperature (3.8 and 101.4 °C). The uncharacteristic properties of heavy water are used for deceleration of nuclear reactions and definition of the origin of natural water. The heavy water content in rivers and lakes is characterized by the ratio between protium and deuterium of about 1: 6800, and in seas it is equal to 1:5600. This relation reaches its maximum in the Arctic ice (1:5500), and its minimum in snow cover (1:30 000).

The water molecule can be approximated to an isosceles triangle. There are two atoms of hydrogen in the bottom corners of the triangle and an oxygen atom at its top. The angle H-O-H and the inter-nuclear distances H-H, O-H are important in the aggregative state of water. They reach respectively minimum and maximum values in water vapor and ice. The diameter of the water molecule is equal to 2.76 angstroms. It requires $2.2489 \cdot 10^5$ Joule·mole⁻¹ for its formation. The water molecule has a dipole moment, related to distribution of electrons in the molecule. The electrons on two exterior orbits of the oxygen atom form two poles of negative charge. They are further away from the

hydrogen atoms. The protons of hydrogen atoms are responsible for two poles of positive electrical charges in the water molecule. As a result there is an asymmetry in the disposition of centers of gravity of positive and negative charges in the molecule, or a dipole. Approaching dipole molecules have mutual gravitation. The main points of positive and negative charges gravitate stronger than the repulsion by similar charges. This aspect of H₂O molecules interaction leads to the formation of hydrogen connections. Its durability is more than that of the chemical and less than that of the intermolecular connections. The energy of hydrogen connection varies from 8368 up to 33 472 Joule·mole⁻¹ according to the aggregative state of water.

The dipole moment and the ability to organize hydrogen connections result in the existence of water structure. Water structure is characterized by the relative position and interaction between groups of molecules. The crystalline structure of snow and ice proves its existence. However, presence of groups of water molecules is also possible in a liquid aggregative state. Ideas about the existence of water structure first appeared in the 1930s. The modern statements on this problem are formulated by D. Bernal and R. Fauler (1933), and O.Ya. Samoilov (1946). Accordingly water molecules in ice crystals build a tetrahedral lattice. It is similar to a crystalline lattice of tridymite mineral. Water molecules in this lattice oscillate around their average position. At 0 °C water molecules make up to 10⁵ re-orientations per second in ice crystals. The structure of ice is selected depending on the molecules' disposition in a crystalline lattice *I*-, *V*- and *D*-. All possible transitions and reorientation of molecules are taken into account by the *D*-structure of ice. In a solid aggregative state, a crystalline structure is traced, with large number of hollows in ice. The melting of ice and the increase of water temperature do not cause the destruction of the water structure. Simultaneously distances between the nuclei of the H₂O molecule decrease and distances between molecules increase. Temperature rise results in gradual destruction of a part of the hydrogen connections and the water structure. Even at boiling temperature, about 32.5% of hydrogen connections remain in water. Hydrogen connections and therefore water structure are absent in the gaseous state.

Conversion of water to the solid state (at normal atmospheric pressure) happens at a temperature of about 0 °C. This process is named crystallization and is accompanied by calorification. Freezing of one kilogram of water releases 33.3·10⁴ Joule·kg⁻¹ of heat. Water has an abnormally high freezing-point. Water analogues, i.e. oxides of sulfur, selenium and tellurium (elements from the sixth group of Mendeleev's periodic table), have freezing-points well below 0 °C. The freezing is inversely proportional to the molecular mass of the oxides. Accordingly, water should have the lowest freezing-point. The abnormally high temperature of water crystallization depends upon its chemical structure. The fact that H₂O freezes at 0 °C, ensures the preservation of aquatic ecosystems under the ice cover in rivers and lakes. Solutes in water lower the freezing-point. If concentration exceeds 1 g·l⁻¹, water freezes at a temperature below 0 °C (at normal atmospheric pressure). For example, at mineralization 35 g·l⁻¹, the freezing-point is equal to -1.89 °C.

Freezing of water means seasonal formation of ice and snow cover, prolonged accumulation of glaciers, long-term snow and permafrost. The appearance of water in ice reflects the response of the water body to changes of thermal conditions due to its

interaction with bounding media (air and ground). Supercooling of an upper layer means fast or slow formation of ice crystals. Formation and thickness of ice cover on rivers and reservoirs depend on air temperature and heat storage in the water mass. Positive water temperature under ice cover ensures favorable conditions for aquatic ecosystems. Water bodies also play an important water-supply role. Deep-frozen rivers lose their biological and economic value. Under the ice cover water bodies change their regime into the winter one. Input of underground, more mineralized water in rivers is accompanied by an increase in mineralization and a decrease of dissolved oxygen concentration. Under natural conditions the concentrations of heavy metals and organic matter are reduced in water, thus naturally improving water quality.

The process of transformation of ice into water is called melting. The melting heat is numerically equal to the heat of crystallization. The melting heat of ice is abnormally high in comparison with the other chemical compounds (with the exception of ammonia). It is predetermined by the ice crystalline lattice. The high melting heat of ice has great importance for the climate of our planet. Ice and snow formation is accompanied by heat release, which is used in warming the atmosphere and lithosphere. Conversely, ice melting and the absorption of solar radiation explains the transitional seasons of the year (spring, autumn) in polar and temperate climate.

At a temperature lower than 0 °C and a pressure less than 610 Pascal, water transformation between a gaseous and a solid state is possible. This process is called sublimation. Water vapor can crystallize directly, by-passing the liquid state. Ice sublimation, from solid to gaseous phase, is the main reason for relative runoff decrease from ice melting under solar radiation. The main indications of such ice melting are low night and high day air temperatures. Alternation of evaporation and crystallization in snow cover stimulates gradual increase of snowflake diameter and firn snow formation. The modification of snow porosity and its ability to hold melted water have a great influence on flood formation in spring.

The more usual H₂O transformation into the gaseous state happens through water evaporation and is accompanied by heat absorption. $25 \cdot 10^5$ Joule·kg⁻¹ is necessary to evaporate one kg of water at a temperature of 0 °C. The source of the heat is the internal energy of water molecules. This explains surface cooling under water evaporation. Evaporation is possible at any temperature above 0 °C. The higher the temperature, the smaller the amount of heat needed to evaporate 1 kg of water. The higher the temperature, the deeper the water layers involved in evaporation. Water boiling corresponds to evaporation through the full thickness of the water mass. At a normal atmospheric pressure, boiling starts at a temperature of 100 °C. In mountains (at a reduced atmospheric pressure) this process starts at a lower temperature. Conversely at increased pressure, the boiling point is at higher temperatures. The water boiling-point is abnormally high in comparison with water analogues (sulfur, selenium, tellurium oxides). The boiling point for these compounds is reduced in proportion to their molecular mass. Extrapolation of linear dependence shows that water should have a boiling-point at about -70 °C. The high boiling point is associated with the water structure and the hydrogen connections in the water molecules. Boiling of water is only possible when these connections are broken at a high temperature. This water anomaly determines the unique high thermal capacity of the Earth's hydrosphere, the

thermoregulating role of water bodies, and the heating function of marine and oceanic currents.

In a physical sense, when water evaporations, the number of molecules flying out of water exceeds the number of molecules coming back. The process of their returning is called condensation. The condensation heat is equivalent to the evaporation heat (if other conditions are equal). Water vapor pressure increases with the growth of evaporation rate. The more heat is transmitted to a water mass, the higher the evaporation rate. This regularity is related to the increase of kinetic energy of molecules when water heats up. The rise of water temperature causes increase of the evaporation rate. The evaporation rate depends on the velocity of vapor removal from the surface and hence the wind velocity. The stronger the wind velocity, the higher the evaporation rate. Increased evaporation velocities (with vapor removal from the evaporating surface) is associated with the decrease of condensation rate.

Evaporation and condensation play an important role in water supply for the whole planet, and in global and inland water cycles. These processes have special significance in the arid territories of the Earth, where there is water resources scarcity. Elimination of this famine requires heavy investment in projects of water desalination and redistribution of water resources from regions with surplus to those with scarcity of water. At the same time, there are more economical and ecologically safe methods of water supply in arid zones. These are based on artificial increase of the condensation rate. Such methods were used by our ancestors in the dry subtropics, e.g. in the Crimea. Constructions of specially treated stone were created at some significant height. At night saturated marine air cooled on the stones to a lower temperature and condensed onto an artificially enlarged stone surface. The harvested water was sufficient for the supply of a small settlement. Nowadays there are possibilities of building commercial plants for artificial increase of condensation rate.

2. Chemical aspects of water

Water is chemically pure only in exclusive cases. Naturally it always contains greater or smaller amount of dissolved and suspended matter. Mineralization is the amount of dissolved mineral substances in water. In fresh waters, it is measured in $\text{g}\cdot\text{l}^{-1}$ or $\text{mg}\cdot\text{l}^{-1}$. For other types of waters, concentration of dissolved matter is measured in practical salinity units (PSU). The range of chemical compounds in water is very diverse, as there is variation in the content of the principal ions, dissolved gases, biogenic and organic substances, and microelements. In general water components have natural or anthropogenic origins. Each kind of water body has characteristic properties: salinity, alkalinity, hardness, acidity, corrosive properties, etc. These determine life conditions of aquatic ecosystems, and the scope for water resource use for people and economic development. Natural and anthropogenic factors have an influence on water quality, which depends on both mineralization, dissolved and suspended matter. At constant mineralization and chemical composition, water quality can be reduced by anthropogenic or natural diminution of water content, or increase of suspended sediments (turbidity).

Fresh waters are subdivided into four groups according to their mineralization.

Mineralization of rivers is considered to be small, medium, high and very high, if the substances' concentration in water is respectively less than 0.2; 0.2 to 0.5; 0.5 to 1.0 and $> 1.0 \text{ g}\cdot\text{l}^{-1}$. Most rivers have small and medium water mineralization. Spatial variability is most evident in small rivers. The difference between maximum and minimum mineralization for rivers with drainage area from 1 to 100 km² reaches 100 to 1000% in comparison with the zone water mineralization. Mineralization of medium size and large rivers is of the same order. Water mineralization varies along the large rivers. It is connected with the heterogeneity of factors of chemical weathering in various parts of catchment areas, and dilution of more mineralized rivers by tributaries with less mineralization.

The mineral substances, dissolved in water, are divided into macro- and micro-components. Macrocomponents (the main ions) include calcium, sodium, magnesium, and potassium cations and Cl^- , SO_4^{2-} , HCO_3^- , CO_3^{2-} anions. The macrocomponents comprise around 90 to 95% of all substances in fresh water and up to 99% of saline waters. In natural conditions the main concentration of ions in water is determined by dissolution and leaching of mountain and sedimentary rocks, and disintegration and oxidation of plant and animal substances. Changes of water mineralization and especially anion concentration also depend, however, on the kind and the intensity of human impact. The content of cations in water is determined by their migration ability (rate of dissolution) and biological significance (degree of absorption by living organisms). Natural water bodies are divided into the following types: fresh, brackish, or saline. Certain combinations of anions and cations in water distinguishes hydrochemical water types, e.g. hydrocarbonate-calcium or chloride-sodium. Passing from humid to arid zones the hydrocarbonate-calcium water is replaced by the chloride-sodium one.

Microcomponents are the chemical elements whose concentrations are essentially less than $1 \text{ mg}\cdot\text{l}^{-1}$. Microcomponents are composed of cations such as ions of lithium, rubidium, cesium etc., and anions such as bromine, iodine, fluorine, boron, and ions of heavy metals (e.g. copper, zinc, nickel, silver, lead), and radioactive and some other elements.

Water contains various gases such as nitrogen, oxygen, argon and carbon dioxide. Gases, dissolved in water, are of the various origins. The gaseous fraction of gases gets to the water from the atmosphere. Processes that take place in rivers and reservoirs are of great value for changes of gas concentration in water. Oxygen concentration in summer is largely controlled by photosynthesis. In the meromixis, the oxygen deficit is explained by its absorption by living organisms and organic oxidation. Sometimes the remaining organic oxidation leads to the anaerobic conditions and to the formation of carbon dioxide, methane, ammonia and hydrogen sulfide in water.

Nutrients in water are of great value for water ecosystems. There are chemical elements tightly connected with aquatic communities, and supply of these nutrients are often limiting factors for plant growth. The main nutrients are silicon, nitrogen, phosphorus and iron. Nitrogen and phosphorus concentration are usually of key importance. Nitrogen in water occurs in the form of ammonium, nitrate and nitrite ions and organic compounds (suspensions, colloids, and molecules). Transformation of nitrogen causes

liberation of ammonia, but this is oxidized to nitrites and nitrates by bacteria. The nitrites and nitrates are then assimilated by animals and plants. With an oxygen deficit, the process proceeds in the opposite direction.

Phosphorus in water is presented in both inorganic and organic compounds. Its concentration is determined by the direction and intensity of interchange between living organisms and inorganic forms of phosphorus.

Economic activity greatly effects phosphorus and nitrogen concentrations in surface and underground waters, and it can affect iron content. In well vegetated wetlands, however, the strong acids present (e.g. carbonic acid), react with iron to form humic compounds. The natural colloidal iron content in such water can be quite high.

Analysis of natural waters involves not only dissolved minerals, but also organic compounds—primarily compounds of carbon, oxygen and hydrogen. Their existence in water is largely determined by the vital functions of living organisms, i.e. their metabolism. According to their origin organic compounds are divided into autochthonous (formed in the water body) and allochthonous (coming from an inflowing river or the catchment area). Dissolved organic compounds increase the mobility of some heavy metals, as well as influencing dissolved oxygen content and water flavor.

An important factor in aquatic ecosystems is the hydrogen ion concentration. They appear as a consequence of dissociation of hydrogen and hydroxyl ions ($\text{H}_2\text{O} \rightleftharpoons \text{H}^+ + \text{OH}^-$). As the hydrogen ion concentration is small in water, it is convenient to use its logarithm with a reversed sign ($\text{pH} = -\lg[\text{H}^+]$). pH is a measure of degree of disturbance in water. In the equilibrium state, the product of concentration of hydrogen and hydroxyl ions (at a temperature of 22 °C) amounts to $1 \cdot 10^{-14}$.

Their concentrations in water are equal. For such conditions $\text{pH} = 7$, and the medium reaction is neutral. At $\text{pH} > 7$, the equilibrium is broken due to the increase of hydroxyl concentration, and the water becomes alkaline. Otherwise water is characterized by an acid reaction. Acidity and alkalinity are of key importance for water quality and living conditions of ecosystems. In general, volcanic, mine, marsh and underground waters are acid, with pH of 2–3, 3–4, 4–6 and 6–7 respectively. An alkaline reaction is typical for rivers, lakes, seas and oceanic waters. For rivers and fresh lakes pH is in the range 6.2 to 9.2. For saline lakes, seas and oceans the pH is in the range of 7.8 to 10.5.

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Biographical Sketch

Alekseevskiy Nikolay Ivanovich, Russian, was born in 1950 in the North Caucasus region. His parents were agricultural workers. In 1968 he graduated from special courses of a teacher institute in Stavropol and began work in the school as a teacher of physical culture. From 1969 to 1972 he was in the army. He graduated from the Moscow State University (MSU) in 1978 and in 1981 gained a Ph.D. on "Channel processes in the mouth of rivers with high sediment runoff" from the Department of Geography. In 1994 he defended his doctor's thesis on "Formation and movement of river sediment". Since 1981 he has been working in MSU as a scientist, assistant professor, and professor at the Faculty of Geography (Department of Hydrology). He is now Chief of the Department of Hydrology at the Faculty of Geography (MSU). He has been a full professor since 1995. His sphere of scientific interests is theory of channel processes, river sediment, physical, chemical and biological processes in water bodies, and problems of eco-hydrology and water quality. He has had more than 110 scientific publications devoted to different aspects of his science area including some monographs ("Formation and movement of the river sediment", "Movement of the sediment in different parts of the catchment and sea coast zone" (with A.E.Michinov), "Hydrology of Terek and Sulak river deltas (with V.N.Mikhailov, M.V.Mikhailova, A.U.Sidorchuk), and "River sediments and channel processes" (with R.S. Chalov and other). As a full professor of MSU he teaches courses: "Hydrology", "Hydraulics of water streams", and "Problems of Hydrology". He is in charge of post-graduate students; three masters were defended under his supervision. He is married, with a daughter.