GROUNDWATER IN SEDIMENTARY, METAMORPHIC AND VOLCANIC ROCKS

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Contents

Summary

The paper describes the conditions of groundwater formation and its types in areas of recent volcanic activity and in areas under permafrost. The hydrogeological conditions of geologically-structured regions of different types, and groundwater formation in sedimentary rocks of platforms and mountain-folded areas, as well as in volcanic and metamorphic rocks, are considered. The main types of groundwater, their formation and spread, recharge and discharge of groundwater, and the formation of chemical composition and TDS, are considered.

1. Introduction

The genetic type of geologic formation is essential for the conditions of groundwater flow and transport connected with the rock type. It is the genetic type of rocks that determines peculiarities of hydrogeological cross-section structure, type of porosity, values and character of spatial heterogeneity of flow and transport parameters.

The genetic type of geologic formations greatly determines also the geochemical and mineral composition of water contained in rocks, which is of great importance to the conditions of chemical composition of groundwater and to the total dissolved solids (TDS) in the groundwater.

Classification based on the genesis and geologic history of the earth crust structures, which determine mineral-geochemical composition of rocks, distinguishes rocks as: Sedimentary rocks of flat sedimentary basins and intermountain depressions; metamorphic rocks; Volcanic rocks having two subdivisions of intrusive bodies and effusive mass. Hydrogeologic materials concerning the territory of Eurasia, Africa, North America are used in the paper.

2. Groundwater of Sedimentary Rocks

The conditions of formation of groundwater in sedimentary rocks greatly differ between flat regions and intermountain depressions. The differences are determined mainly by tectonics of these structures, degree of lithification and dislocation of sedimentary rocks. To a certain degree they relate to peculiarities of surface relief of these regions.

2.1 Groundwater of Sedimentary Deposits

Groundwater concerned with plates and bound syncline of platforms or large intermountain areas can be attributed to this type. Dominating thickness of sedimentary deposits changes in these conditions within 1-4 km, reaching in some structures 10-12 km or above. To a great extent, sedimentary deposits of these structures maintain primary sedimentary porosity that determines their storage and permeability. Formation of rocks with dominance of fractured porosity is typical mainly of sedimentary carbonate and clay-carbonate rocks (the limestone, dolomite, opoka and others) and of deep (3-4 km and above) parts of structures, where due to high temperature and pressure the processes of lithification of sedimentary rocks (the sandstone, argillite, siltstone and others) take place.

Due to conditions of sedimentation and relatively low tectonic dislocation, hydrogeologic formations of sedimentary deposits typically have layered structure of heterogeneity with aquifer-aquitard consecution. Sand, sandstone, fractured or karstic limestone and dolomite are usually the main types of water-bearing rocks. Typically low permeability rocks are: loam clays, carbonate-clayey rocks, gypsum-anhydride and salt (at their occurrence outside of upper zone of intensive leaching). Due to different litho-facies composition of rocks hydraulic conductivity of adjacent layers can change in several order of magnitude; from 10^{-13} m/s to 10^{-4} m/s or above. The rocks, which are usually considered as water-bearing, i.e. aquifers, have characteristic hydraulic conductivity 10^{-6}-10^{-4} m/s or more. Typical low permeable rocks i.e. aquitards have hydraulic conductivity of the order of 10^{-7} m/s or less.

The so-called confined aquifers, which are confined by aquitards at the top and the bottom (except when the upper aquifer has free groundwater level) are related to the cross-section of sedimentary rocks of this type. When defining regional hydrogeologic zones, geologic structures composed of layered sedimentary formations of significant thickness and spread, the confined aquifers are considered to be artesian basins of different type and structure, see Figure 1 (hydrogeologic cross-section of artesian basins Turanskoy platform)

The depth of their occurrence and intensity of connection between- groundwater and recent surface of basin determine the differences of groundwater conditions of artesian aquifers to a certain extent. Thus in hydrogeologic cross-section of sedimentary formation of basin there can be found three hydrogeologic levels with different conditions of groundwater formation.

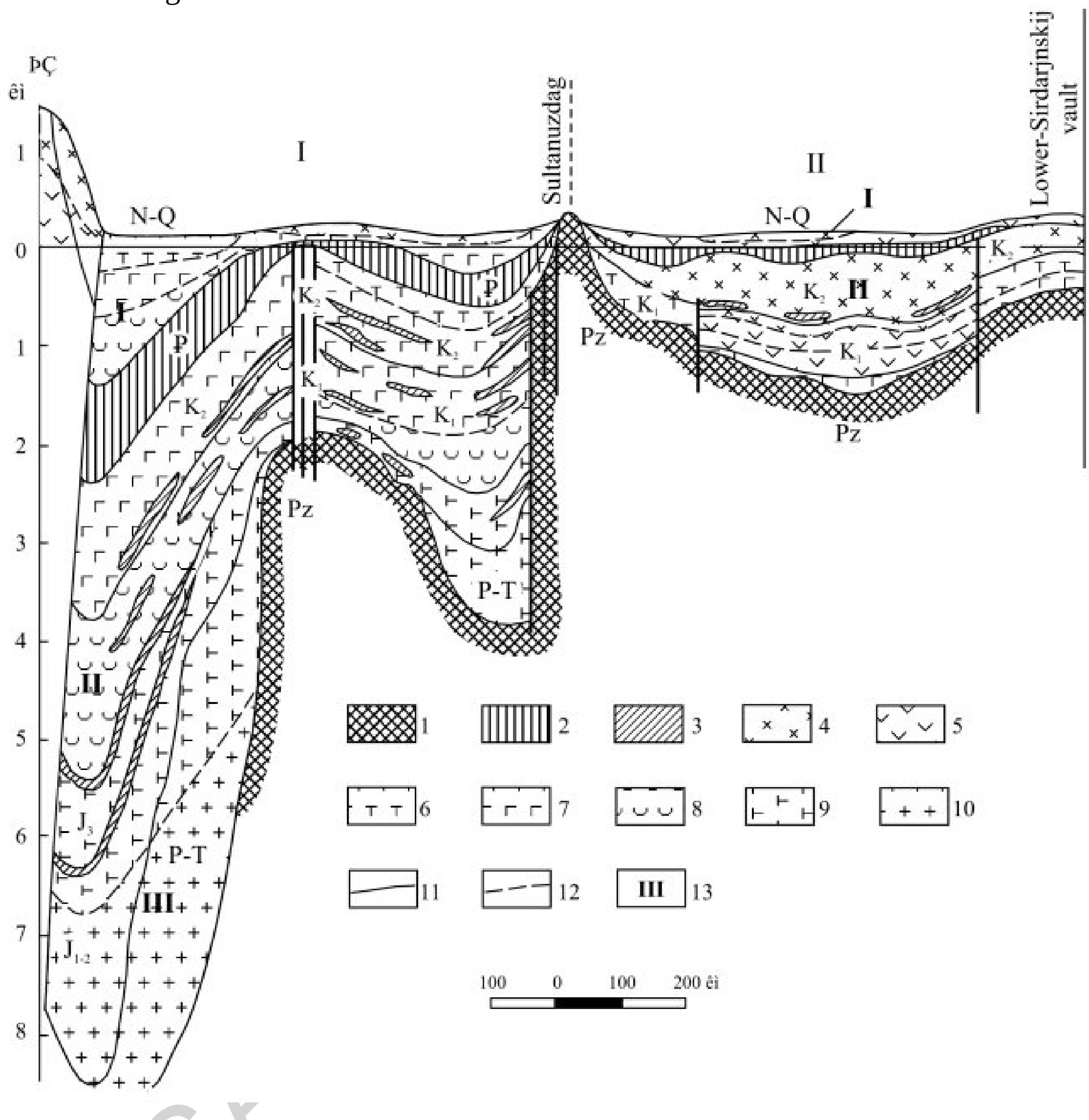

Figure 1. Hydrogeologic cross-section of artesian basins Turanskoy platform

First hydrogeologic level of artesian basin includes the aquifers from the earth surface up to the first regional aquitard. Total thickness of the first level can be 200-500 m or more depending on the properties of cross-section. The level includes the first unconfined aquifer with a free water surface and several confined aquifers with piesometric water heads. In the system of the first level aquifers at relatively uplifted areas, groundwater heads decrease with the increase of the depth of aquifers. At low areas (the river valleys, near-lake lowlands and others) groundwater heads increase with an increase of the depth of aquifers. The groundwater recharge comes from inflow of atmospheric precipitation. The groundwater discharge occurs in the form of springs, discharge into rivers and by evapotranspiration in the areas with shallow groundwater level.

According to the distribution of the heads and areas of groundwater recharge/discharge in aquifers, the first level is the system of local groundwater flows, which structure is determined by the surface relief and by hydrographical system of surface water.
In general values of subhorizontal flow gradient, flow velocities and specific flow discharge at the same conditions (permeability, thickness of aquifers) decrease with increase in the depth of aquifers. The periods of water exchange (the age of groundwater) increase from $n * 10^0 – n * 10^1$ years for the upper aquifer, to $n * 10^5$ for the lowest part of the first level.

Mainly fresh groundwater with TDS less than 1 g/l of bicarbonates, of calcium, magnesium and sodium composition, forms in the aquifers of the first level due to intensive water exchange with the surface water. In lower part of cross-section at the depth of about 200-300m or above in aquifers, groundwater with TDS up to 2-3 g/l or more can be formed. In these aquifers recharge and discharge happen only by subvertical leakages via aquitards, with a composition of sulphates, chlorides and bicarbonates of Ca and Na.

Groundwater of other composition and TDS in aquifers of the first level can be found, for example, in arid zones where the process of continental salinization (50 g/l or above, NaCl composition) takes place and in the areas with spreading in the upper part of cross-section gypsum or intensively plastered rocks, Quaternary sea sediment, terraces of salt lakes and other. Also in the areas of upward flow of deep fluids the chemical composition of groundwater of first level can be affected by this discharge. In modern time due to intensive anthropogenic surface contamination, the chemical composition of groundwater changes.

The groundwater regime of the first level aquifers is formed by the climatic influence, and that of hydrologic and anthropogenic factors. The most common anthropogenic changes of the groundwater regime of the first level aquifers are associated with the exploitation of groundwater, mine drainage, management of surface water resources, irrigation, etc. Most observable changes of natural groundwater heads and temperature regimes are found in urban areas, industrial regions with enterprises of chemical and oil and gas industry and other.

The second hydrogeologic level of artesian basins unites the aquifers, in which sediment crops out or lies near the surface at peripheries of the basin and at structured uplifts of internal area. In central submerged part of the basin these aquifers are overlaid by regional aquitard and lie at depths of 1.5-2km or more. Depending on geology of the basin the thickness of the second level is usually 1.5-2 km or more. Hydrogeologic cross-section of this level includes a system of relatively isolated areas of interconnected aquifers composed by different sedimentary rocks. Toward the periphery to the basin centre, the total thickness of the second level increases while simultaneously the total thickness of aquifers decreases and, accordingly, the thickness of aquitards increases. The decreasing of permeability occurs in the same direction.

Maximum values of permeability are typical for areas, where aquifers lie near the earth surface (particularly for fractured and karstic rocks).

The piezometric hydraulic heads of groundwater of this level is usually fixed near the earth surface. At lowered areas (the large river valleys, seaside lowlands and other) the hydraulic head of this groundwater is often fixed above the land surface (well-spring or spouting).
Groundwater recharge of the second level is realized by inflow of atmospheric precipitation and leakage from overlying aquifers at peripheries of the basin, and also by inflow of groundwater from adjacent region from relatively higher altitudes.

Existence of bound and outward areas of recharge leads to the artesian groundwater flow pattern, which partly discharges into local drains, partly forms the regional flow directed to internal area of the basin.

Hydrogeologic studies of many artesian basins in Eurasia have shown that border part of the basin can be divided into three zones with different character of groundwater flow in the aquifers of the second level. In the first zone flow changes along the flow path chaotically and abruptly according to the position of local areas of recharge and discharge of the groundwater. This zone is an internal area of modern recharge of artesian water. The width of this zone changes from several kilometres to 150-200 km and depends on geological structure of the peripheries of basin and modern relief.

Within the second zone the rapid decreasing of total groundwater flow of the second level takes place due to sub-vertical upward leakage to the upper aquifers. The position of this zone is usually determined by the existence of the modern basin surface of the areas with relatively low level of surface and groundwater. Thereby, the border zone of the second hydrogeologic level groundwater discharge is formed directly at peripheries of the basin, near regional area of recharge. According to existing estimations within this zone the discharge is up to 60-90% from artesian water recharge. It indicates that modern groundwater cycle (recharge – run-off - discharge) is mainly formed in border part of the basin. The underground inflow to internal area of basin (the third zone) is characterised as a rule, by relatively small flow. Within this third zone of the second level, feebly marked regional flows of groundwater are formed, related with the main orographic elements of modern surface (the continental divide of sea basins, river valleys I and II order).

The chemical composition and TDS of the second level groundwater is determined by general flow pattern as mentioned above. Within internal area of recharge (the first zone) in conditions of sufficiently intensive water exchange due to local recharge and inflow from adjacent region well marked zone with low TDS (less than 1 g/l) in groundwater of bicarbonates of calcium and magnesium composition is formed. The thickness of this zone in different basins changes from 300-500 to 1000m or more. With deposits already formed in the second level, of gypsum -anhydride within the first zone, in the second level the forming of $CaSO_4$, $MgSO_4$, and Na2SO4, $CaCl_2$ and NaCl composition, with TDS up to 3-5 g/l or above is possible.

Within the second zone due to decrease of groundwater flow the gradual (toward the internal area of basin) increase in groundwater TDS up to maximum values takes place, typical for internal area of basin.

The TDS and chemical composition of groundwater of second level of basin internal area is determined by the genetic type and mineral-geochemical composition of aquifers and aquitards deposits. At dominance of continental terriogenous sediments of continent or of sea with normal TDS, the TDS in the groundwater reaches 20-35 g/l with NaCl and Na_2SO_4, composition (West-Siberian basin). Groundwater TDS reaches up to 200-250 g/l or above with NaCl and Na_2SO_4, composition in conditions of carbonate rocks and gypsum-anhydride formations (the Moscow basin). In the second level, by leaching salt deposits the NaCl brines of TDS 300-350 g/l are formed. Metamorphosed brines of NaCl and $CaCl_2$ composition with the TDS up to 500-600 g/l or more are formed in deep parts of internal area of the basin (the Angara-Lensky, Yakut basins).

The temperature of the groundwater of the second level reaches 40-80°C or above in internal area at depths 1.5-2 km in basins of different type. Outside the border zone, composition of microcomponents and dissolved gases is determined by the conditions of interaction with deeper water of the third level and crystalline rocks of basin foundation.

The third hydrogeologic level of artesian basin unites the aquifers, which usually occur at depths more than 2-2.5 km that in modern conditions do not have connection with surface of the basin. Due to processes of consolidation and cementation, the sediments of this level are characterised mainly as fractured, with pore-fractured permeability (tectonic and lithogenetic fracturing). The values of porosity are less than 10% and hydraulic conductivity changes within 10^{-6}-10^{-7} m/s. At the same time, according to some data at these depths primary sedimentogeneous or secondary porosity of 15-20% and hydraulic conductivity of about 10^{-5} m/s of the sedimentary rocks are observed.

The interaction of groundwater of the third level with overlaying aquifers is realized by leakage through separating aquitard. The inflow from modern areas of recharge (the periphery of basin) is insignificant or it is absent. The water balance and hydraulic head in aquifers of the third level are determined mainly by endogenic factors: inflow of deep fluids from crystalline rocks of basin foundation, illision of pore water under the geostatic and geodynamic (the tectonic of movement) consolidation of clay deposits, the processes of dehydration of clays and rock-forming minerals.

As a result in sedimentary rocks of the second level a specific "layer-block" flow system is formed. Within a united stratigraphic element of cross-section, considered as an aquifer permeable and relatively isolated blocks of different sizes, concerned with litho-facies particularities of construction of layer, zones of intensive fracture fracturing, crown and steep slope of positive structures of second-third order (pleated and lithogenesis fracturing). The system of local intrastructural flows of groundwater related with the structural plan of crystalline foundation of the basin and lower part of sedimentary rocks forms in "aquifers” of third level. The main type of fluid flow is, probably, subvertical upward flow to aquifers of second level.

Water balance of relatively isolated blocks can be greatly different from block to block (inflow from adjacent blocks, flow from crystalline foundation, water due to consolidation and dehydration of clays, etc.). Because of that, pressure, gradients, the main flow direction, chemical composition and temperature of groundwater can be greatly change on relatively short distances.

The TDS and chemical composition of groundwater of sedimentary deposits of third level of basin are determined mainly by mineral-geochemical complex of water contained rocks. As a rule water of aquifers of this level is characterized of the highest TDS in the basin (see table 1). However in a number of cases, relative decreasing of TDS is observed at the depth about 1.5-2 km or more. This decreasing could be related to changing of the chemical composition of rocks and possible peculiarity of hydrodynamics of some blocks.

Name artesian basin	Depth, km	TDS of groundwater, g/l	Chemical composition	Microcomponents, maxim concentration, g/kg
Moscow	3-3.5	240-270	Cl-Ca, Na	Br – 1950 I – 7 Sr – 1000
Pechora	4.0-4.5	250-300	Cl-Na, Ca	Br – 900 I – 46
West-Siberian	3.0-3.5	15-120	Cl-Na Cl-Ca, Na	Br – 187 I – 28
Angara-Lensky	3.0-4.0	до 500 и более	Cl-Ca, Na Cl-Na, Ca Cl-Mg, Ca	Br – 6000 I – 200 Sr – 7000

Table 1: (Chemical composition and TDS of groundwater of the third level in some artesian basins of Russia).

Dissolved gasses in groundwater of third level are represented mainly by methane (CH_4 – up to 95% or more), heavy hydrocarbons, nitrogen, carbon dioxide, helium and argon. The temperature of groundwater of lower part of cross-section (3-4 km) depending on type of the basin and depths of occurrence changes from 50^o-60^o to 100^o-120°C or more.

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Biographical Sketch

Vladimir Alekseevich Vsevolozhsky was born on the 31st October 1931, in Moscow. From 1955 he entered the Geology faculty of the Moscow State University by M.V.Lomonosov. His specialty is as a geologist–hydrogeologist.

Since 1960 he worked at Geological faculty of MSU in the post of hydrogeologist, chief of a geological party, assistant, senior lecturer, and professor. Since 1988 he has headed the department of hydrogeology of Geological faculty MSU.

His interests in scientific research lie in the areas of regional hydrogeology, evaluation of stores and resources of groundwater, research of regional hydrogeodynamics of artesian platform basins, etc.

In 1966 he defended a candidate thesis on the subject of: "Forming of underground run-off in the southern part of the West-Siberian plate." His 1987 doctoral thesis was "Underground run-off and water balance of platform structures."

From 1971 to 1983 he was the responsible executor and one of the managers (deputy editor-in-chief) of the International working group. He initiated the work on an evaluation and mapping operation of underground run-off in Central and East Europe, and is a fellow of the International Association of the Hydrogeologists. He is the author more than 120 published scientific works, including author and co-author of 6 monographs and 4 maps of underground run-off in territories of the USSR/Russia and Central and East Europe in scales of: 1:1 500 000 to 1:500 000.

Under V.A.Vsevolozhsky's scientific guidance 11 candidates and 2 doctoral theses were prepared and successfully realized.