Development of regional hydrogeological mapping in Russia

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The subject of regional hydrogeology is best described as the subject of regional patterns in groundwater occurrence, formation and evolution. This discipline is a branch of hydrogeology and includes the following components: structural geological zoning, hydrogeological classification of cross-sections, groundwater classification, hydrogeological zoning based on groundwater hydrogeodynamics, hydrochemistry, temperature and other parameters, palaeohydrogeological reconstructions, regional mapping and regional evaluation of groundwater resources.

Regional hydrogeology deals with groundwater formation, occurrence, evolution, distribution, and patterns within big hydrogeological structures in regions, continents and the entire Earth. Regional hydrogeological mapping, being a component of regional hydrogeology, is also an effective tool in studying regional groundwater patterns and resources.

Regional hydrogeological mapping in Russia before World War II

Peter the Great established the Russian Academy of Sciences in 1724. During the eighteenth century, the Academy organized and directed several expeditions to various regions of the country to collect scientific information on natural resources and their potential use. These expeditions explored the Ural Mountains, Siberia, the Volga basin, the Kolsky and Kamchatka peninsulas, the Dnepr basin and the Caucasus region. The expeditions were led by prominent Russian scientists such as academicians V. Zuev, N. Richkov, S. Krasheninnikov, I. Lepekhin and N. Ozeretskovsky. Each expedition spent several years in the field and collected vast amounts of data including information on the occurrence and distribution of fresh and mineral springs, water-table elevations, the relationship between groundwater chemistry and chemical composition of water-bearing formations, and the role of groundwater in karst processes.

Hydrogeological information collected by the expeditions enabled some preliminary regional groundwater zoning. For example, it was found that within the European part of Russia, hardness in shallow groundwater increases in a southerly direction. It was also shown that the distribution of mineral springs is less dense in the interior areas of the Russian Plain than in the surrounding mountainous areas. The widespread occurrence of brackish and salty groundwater in Siberia was also recorded.

The Geological Committee, established in 1882 within the Ministry of State Properties and headed by G. Gel'mersen, initiated systematic large-scale hydrogeological investigations. At the end on the nineteenth century, these investigations were managed by S. Nikitin, now acknowledged as one of the founders of Russian hydrogeology. S. Nikitin conducted extensive studies of geological and hydrogeological conditions in various regions of the European part of Russia, focusing particularly on the Moscow region. From 1884 to 1890, he collected detailed information on the geological setting of Moscow and the Moscow region in order to define the Moscow artesian basin and its recharge area, evaluate the groundwater potential of the main water-bearing formations and determine the chemical composition of the groundwater bodies. These investigations were summarized in two works (Nikitin 1890a, b).

A few years later, S. Nikitin published the monograph (Nikitin 1900) in which he identified that the hardness of the confined aquifers increases with depth and distance from the recharge area. He also delineated the main artesian basins within the Russian Plain and proposed its hydrogeological zoning.

In the early 1900s, the Geological Committee conducted a regional study of the main components of river flow in the

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European part of Russia. The work focused on the baseflow component of the big rivers and was conducted under the guidance of S. Nikitin and N. Pogrebov. The original work on groundwater zoning and groundwater regimes in various climatic areas (Ototsky 1906) was based on the ideas of V. Dokuchaev (Dokuchaev 1899), who studied zoning of soils and the role of the forests in water balance.

In the early twentieth century, systematic regional investigations of groundwater in the permafrost areas of Siberia began. A. L'vov, who worked in Irkutsk (Russia), published a comprehensive summary of groundwater in the permafrost areas (L'vov 1916). The Geological Committee (A. Gerasimov, N. Slavianov, A. Ogil'vi, N. Ignatovich) continued investigations of mineral waters and mineral springs in the Caucasus region. At the same time, N. Tolstihin started a study of mineral waters in eastern Siberia.

By 1925, V. Il'in had summarized all the hydrogeological investigations conducted in the European part of Russia and published regional maps for this territory (Il'in 1925). He came to the conclusion that sustainable groundwater regimes depend on climate, topography and geological setting. Also, in 1925, A. Semikhatov published a monograph in which he described, delineated and mapped the 15 artesian basins in the European part of the USSR (Semikhatov 1925).

The first All-Union Congress of Hydrogeologists was held in Leningrad (today Saint Petersburg) at the end of 1931. A total of 570 delegates from all over the USSR attended this scientific forum and discussed 230 technical presentations. Significant attention at the Congress was given to papers by B. Terletsky, D. Sokolov, V. Zhukov and G. Kamensky that dealt with the methodologies of both site specific and regional hydrogeological mapping. As a result of the Congress, the comprehensive summary entitled *Materials for Characterization of Groundwater Potentials in Various Regions of the USSR* was published (Savarensky et al. 1933).

Many other Soviet hydrogeologists worked successfully in various fields of regional hydrogeology before World War II. A. Semikhatov published a monograph on groundwater in the European part of the USSR (Semikhatov 1934), while F. Savarensky, M. Vasil'evsky, N. Ignatovich, I. Zaitsev classified hydrogeological zones of the USSR in the 1930s. M. Vasil'evsky completed the groundwater classification of the USSR, delineating and mapping hydrogeological basins, provinces and regions (Vasil'evsky 1938; Vasil'evsky et al. 1939), which was the first time this was attempted for the Asian part of the USSR.

Also in the 1930s, significant funding was provided for studying mineral waters which could be used for medical purposes. V. Shtil'mark, N. Tolstihin, A. Dzens-Litovsky and A. Ovchinnikov compiled a series of hydrochemical maps of mineral waters, and a summary map of mineral waters in the USSR (scale 1:20,000,000) was compiled (Tolstihin 1937).

Regional hydrogeological mapping in Russia after World War II

At this time regional hydrogeological mapping was conducted by several leading scientific institutions: the All-Union Geological Institute (VSEGEI) in Leningrad (today Saint Petersburg), the All-Union Institute of Hydrogeology and Engineering Geology (VSEGINGEO) in Moscow, the Moscow State University (MGU) and the Institute of Water Problems (IWP) of the Academy of Sciences in Moscow. The most significant achievements in regional hydrogeological mapping were made in the period from 1965 to 1985.

The comprehensive hydrogeological map for the former USSR (scale 1:7,500,000) was compiled in 1966 by the team of hydrogeologists from the VSEGEI (Zaitsev 1966). The following features were depicted on this map: main hydrogeological structures (artesian basins and hydrogeological massifs), the groundwater type, the groundwater runoff within the active circulation zone, the permafrost areas, ice cover, old river valleys, volcanoes, and geysers. In addition, for the main hydrogeological regions, information on groundwater withdrawal was given. The map included stratigraphical indexes of the main aquifers and typical pumping rates of water-supply wells installed in these aquifers. At several specific locations within each main aquifer/complex, borehole logs were shown. On each borehole log, the groundwater type, the age of the water-bearing rocks, and groundwater chemical composition were indicated. In order to show such a variety of features, the compilers used numerous symbols including colors, shadings, lines, lettering, numbering and others.

The unique hydrochemical map for the former USSR (scale 1:5,000,000) was compiled in Leningrad (today Saint Petersburg; Zaitsev and Tolstihin 1966). It was based on hydrochemical zoning and depicted three main zones: the zone of fresh water with total dissolved solids (TDS) values less than 1 g/L; the zone of saline water (TDS=1–35 g/L); and the zone of brines (TDS more that 35 g/L). This scheme of deciphering fresh waters, saline waters and brines was widely used in the former USSR at that time. Within cross sections, a certain combination of hydrochemical zones was used to set up characteristic hydrochemical belts.

Within artesian basins, the depth of belts was limited by the bottom of the sedimentary cover or the top of the basement. Within hydrogeological massifs, it was limited by the bottom of the active circulation zone. At specific points, typical borehole logs were presented and contained the following information: stratigraphical indexes of water-bearing deposits, the bottom of water-bearing deposit(s), presence of brines, the hydrogeochemical zones and the mineral water's classification number.

Within the artesian basins and folded areas (hydrogeological massifs), mineral-water provinces were delineated. The main mineral-water deposits, mineral lakes and mineral-mud deposits were marked with special symbols. In addition, the groundwater temperature at the bottom of artesian basins was shown with isolines. This map was a state-of-the-art compilation and presentation of an enormous amount of information on groundwater hydrochemistry that had been collected in the former USSR up to that time.

This map is used for solving the following problems:

1. Defining and demonstrating various patterns in groundwater chemical composition with regards to: climatic

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conditions, lithology of and depth to the water-bearing deposits, the type of aquifers/complexes (confined, semi-confined, unconfined), the degree of hydraulic connection between different aquifers/complexes, the distance and velocity of groundwater movement from the recharge zone to the discharge zone, etc.
2. Providing background information for large-scale prospecting of oil, gas and mineral deposits
3. Providing background information for extraction of I, Br and other halogens from groundwater for their industrial use
4. Substantiating the large-scale water-supply projects

Another unique undertaking was an atlas of 22 regional maps for the entire USSR attached to the 50-volume monograph entitled *Hydrogeology of the USSR* (Rogovskaya 1984). All maps for the entire country were divided into four groups, as follows:

1. Maps (scale 1: 7,500,000) showing components of groundwater balance and groundwater resources within the active circulation zone.
2. Maps of groundwater occurrence and distribution (scale 1:5,000,000). They included a map of the vadoze zone which showed the total thickness, lithological composition and hydraulic conductivity of the zone. This sub-set also included maps of shallow and deep (artesian) groundwater occurrence and distribution, which showed the depth of the bottom of fresh and saline groundwaters, permafrost conditions, areas with flowing wells, the groundwater temperature and TDS values of waters at the bottom of the sedimentary cover. The main taxonomic units of cross sections were aquifers and their complexes, water-bearing lenses within aquitards, groundwater in weathered zones and local fractured areas, and aquitards. Typical borehole logs were presented in appendices. Borehole log information included the age and lithological composition of aquifers and aquitards, groundwater chemical and gas composition, and the groundwater temperature at various depths.
3. Maps of groundwater formation. They included maps of hydrogeodynamic structures for the upper and lower structural layers. The upper layer consisted of the vadoze zone and the zone of active circulation; the lower layer consisted of the zone of slow circulation. In addition, this set of maps also included the following: the map of regional aquitards, the map of the shallow (unconfined) groundwater regime formation, hydrochemical maps of the zone of active circulation and the deeper zone, and the hydrothermal groundwater map.
4. Maps of groundwater resources and prospects of their utilization (scale 1:10,000,000) were compiled separately for fresh and brackish groundwater, curative mineral water, industrial mineral water and thermal groundwater. According to the map for fresh groundwater and supporting calculations, fresh groundwater resources in the former USSR amounted to 340 km^3/year.

The whole atlas was an example of high-quality regional hydrogeological mapping with regards to theoretical knowledge applied, methodology used and the amount and diversity of information provided.

Hydrogeological maps compiled by Zaitsev (1966) and Rogovskaya (1984) are still widely used for the following purposes:

1. Establishing the scientific basis for further more-detailed mapping and investigations
2. Quantitative evaluation of shallow and deep groundwater resources in the entire country and its large regions
3. Conducting sustainable groundwater development in the large basins/regions
4. Providing background information for conducting the large-scale industrial, construction, water supply and mining projects
5. Conducting preliminary impact assessment of various large-scale projects

Under the supervision of B. Kudelin (MGU) and in cooperation with many other scientific institutions, maps of groundwater runoff for the entire USSR (scales 1:5,000,000 and 1:2,500,000) were compiled in the 1960s and 1970s. Each map provided: the average annual groundwater flow (in L/s per km^2); the minimal groundwater flow, or base flow; the ratio between base flow and streamflow (in percentage); and the ratio between base flow and precipitation (in percentage). The maps showed the quantitative distribution of groundwater flow and enabled the evaluation of the groundwater resources potential for both specific regions and the entire country (Kudelin 1966). Considering regional hydrogeological mapping as the basis for further large-scale mapping, it is important to stress that the usual Russian approach is to get "the big picture" first and then develop more detailed mapping/investigations. The Western approach is quite different and includes collecting the various piecemeal (site specific) sources of information and then combining them into "the big picture". Although both approaches have advantages and disadvantages, the Russian approach seams more efficient and eventually cost effective.

In this regard, it is interesting to overview the development of regional hydrogeological mapping in the USA in the second part of the twentieth century. In the 1960s, regional hydrogeology in the USA and Canada was mainly focused on effects of topography and geology on regional flow systems (Tóth 1963; Freeze and Witherspoon 1967). In 1978–1995, the US Geological Survey conducted the Regional Aquifer System Assessment (RASA) program with the objective to establish a framework of background information on the geology, hydrogeology, and geochemistry of the nation's 28 most important aquifer systems.

By the year 1999, this program was crowned by compilation of a National Groundwater atlas (scales 1:7,500,000, 1:5,000,000 and 1:2,500,000), which presented a summary of the USA's major groundwater

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resources. Despite this being an important step forward in developing regional groundwater mapping in the USA, the atlas contains much less information than that presented on Russian maps compiled by Zaitsev (1966) and Rogovskaya (1984). Moreover, the atlas does not provide the complete “big picture” of hydrogeology in the USA but rather a description of hydrogeological conditions and evaluation of groundwater resources in 13 separate regions of the country.

Among other interesting projects related to regional hydrogeological mapping, evaluation of groundwater resources in Minnesota (USA), conducted in the 1990s and 2000s, should be mentioned (Shmagin and Kanivetsky 2002; Peterson et al. 2008). However, this project dealt with regional mapping within the one state only.

In 1980–2010, works on regional hydrogeological mapping in Russia continued although not with the same intensity as in the previous years. A map of groundwater runoff in Central and Eastern Europe was compiled, and a monograph describing map compilation methodology was published (Konopliantsev et al. 1982). More recently, several works on regional and global groundwater resources and their mapping have been published (Zektser and Everett 2004; Zektser and Dzhamalov 2007).

During recent years, significant attention has been given to the problem of regional groundwater vulnerability to pollution and groundwater protection (V. Gol’dberg, V. Mironenko, V. Rumynin, I. Zektser, G. Vartanian). One example of this work was a set of ecological geological maps edited by A. Smyslov (Smyslov 1996) and awarded the State prize in 2002. It included an ecological-hydrogeological map (scale 1:10,000,000) which summarized extensive information on groundwater susceptibility to pollution from various sources and the areas of existing groundwater contamination in Russia.

Conclusions

Regional hydrogeological mapping is an important tool in long-term water-resources planning, managing sustainable water resources, studying regional groundwater patterns and groundwater prospecting for various purposes. Regional investigations, studies and mapping were a significant component of the hydrogeological development in Russia. These were conducted by the Academy of Sciences, the Geological Committee, VSEGINGEO, VSEGEI and other institutions and ministries. As a result, such problems as regional hydrogeological mapping, regional evaluation of groundwater potentials, regional characteristics of groundwater regimes and balance, regional groundwater zoning were studied in depth. Russian achievements and experience in these fields were (and still are) significant and worth making known to the Western hydrogeologial community.

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