250 years of Russian hydrogeology (1730–1980)

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ABSTRACT

Development of hydrogeology in Russia between 1730 and 1980 is briefly described. The contributions from many distinguished researchers in various fields of hydrogeology are highlighted and comparison of the achievements of the Russian hydrogeologists is made with their respective Western colleagues.

INTRODUCTION

The history of Russian hydrogeology goes back to the 18th century. During this period hundreds of Russian scientists and engineers worked in various fields of hydrogeology and contributed to its development and achievements. Their findings were published in thousands of monographs, papers and reports, but the limited scope of this paper allows only some of the names and publications to be mentioned.

1730–1790

Peter the Great established the Russian Academy of Sciences in 1724. During the 18th century the Academy organised 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 Kol'sky 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. The first of the expeditions was led by S. Krasheninnikov and carried out in 1733–1743; its results were published in 1765 in the monograph entitled *Description of the Land of Kamchatka*. It contained information on the rivers, lakes and the fresh, mineral and thermal springs in Kamchatka.

Hydrogeological information collected by the expeditions enabled some preliminary regional groundwater classification. 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.

1790–1917

As early as in 1791 V. Severgin compiled the inventory of thermal springs in Russia. In 1800 he published the manual entitled *The Method of Mineral Groundwater Testing*. In 1809 he also prepared the first classification of mineralised groundwater based on its chemical composition and temperature, and published a summary on mineral groundwater occurrences in Russia.

G. Abikh studied the geology and hydrogeology of the Caucasus Region in the 1840s through the 1860s. He delineated the main groundwater recharge and discharge areas, found artesian groundwater in Armenia and studied and calculated the baseflow contribution into the Lake Sevan. He also studied the saline lakes in Armenia and numerous mineral springs in the Caucasus Region. He was the first scientist to relate the occurrence of mineral springs with tectonic lineaments.

Ilia Tchaikovsky, the father of the composer Pyotr Tchaikovsky, was a mining engineer who worked in the Ural Region in the 1830s and 1840s. He investigated saline springs and how to extract the salt from the spring waters. Reports were compiled by him for the salt plant owners and the Mining Department in Saint Petersburg.

In the 1850s and 1860s G. Gel'mersen studied artesian groundwater resources as a potential source of water supply for big cities. In 1864 he published the paper entitled *On Artesian Wells*. Based on his results and conclusions, the first deep flowing water well was drilled in Saint Petersburg between 1861 and 1864 under the supervision of A. Inostrantsev. Over the next two decades numerous other deep artesian wells were installed in the capital. In 1884 Inostrantsev published an inventory of these wells which contained all the borehole logs, the hydrochemistry data and some suggestions on the future use of artesian water for drinking and industrial water supply.

G. Gel'mersen and G. Romanovsky were the first geologists to identify artesian groundwater as supply to Moscow. Based on their findings, the first deep artesian well was drilled in Moscow in 1863. The total depth of this well was 459 m and it encountered a thick Devonian water-bearing deposit at a depth of 325 m.

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 19th century these investigations were managed by S. Nikitin, now acknowledged as one of the founders of Russian hydrogeology. He defined hydrogeology as the science of "underground waters, their origin, occurrence, distribution, movement and spring discharge". He stressed that the hydrological cycle is the main principle behind groundwater movement. In another definition of hydrogeology S. Nikitin pointed out that this is the science of "the underground component of the overall hydrological cycle."

I. Sintsov and S. Nikitin compiled the first water well inventory for the whole of Russia. S. Nikitin also 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 until 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 describe the chemical composition of the groundwater bodies. These investigations were summarized in two papers published in 1890: *A Geological Map of Russia, Sheet 57*, and *Carboniferous Deposits and Artesian Waters in the Moscow Region*.

In 1900 S. Nikitin published the monograph *Unconfined and Confined Groundwater in the Russian Plain*. 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 this huge territory and proposed its hydrogeological zoning.

After Gel'mersen's death in 1885 the Geological Committee was headed by A. Karpinsky who initiated further systematic geological surveys and hydrogeological investigations within the European part of Russia. Under the supervision of the Committee, a wide range of groundwater investigations were conducted in the early 1900s in Ekaterinoslav, Kherson and Samara Provinces in European Russia and in some Asian Provinces as well.

In 1905 the Geological Committee commenced an extensive study of mineral springs in the Caucasus Region led by A. Gerasimov, A. Ogil'vi, and Y. Langvagen who published a fundamental work on the origin of mineral springs and their piping in 1911.

In the early 1900s the Committee conducted a regional study of the main components of streamflow in the 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 Geological Committee supervised hydrogeological investigations for water supply to big cities and the railway network that so depended on steam generation. Exploration of numerous artesian aquifers eventually satisfied demand for drinking water at Saint Petersburg, Moscow, Baku, Taganrog, Voronezh, Novorossiysk, and Sebastopol. In addition, in 1905 N. Pogrebov carried out investigation of the main springs at the Izhorskoye Plateau in order to supplement the water supply of Saint Petersburg. In 1909 he also investigated Shollar springs near Baku in order to evaluate their supply potential.

In 1914 an extensive hydrogeological study was conducted by N. Sokolov and A. Ivanov to find out the reason behind the steady deterioration of the tap water quality in Moscow. This led to detailed hydrogeological survey and mapping of the hydrochemical composition of the main aquifers both laterally and in depth, i.e. in 3D.

Based on ideas of V. Dokuchaev who studied zoning of soils and the role of the forest in water balance, original works on groundwater zoning and groundwater regimes in various climatic areas have been published by P. Ototsky and E. Oppokov. Of special interest is the investigation of A. Lebedev on the role of vapour in groundwater formation (1912). Based on the highly accurate measurements he found that groundwater recharge due to vapour condensation is much less than those due to infiltration of precipitation.

Significant achievements were made in hydrodynamics and well hydraulics. In a paper entitled *Theoretical Study of Groundwater Movement* (1889) N. Zhukovsky derived differential equations describing groundwater movement in porous media.

Investigating groundwater inflow into wells installed into the fractured media, A. Krasnopol'sky found that Darcy's law is inapplicable when the groundwater flow velocity exceeds some specific limit. He published his findings on the validity of Darcy's law and turbulent groundwater flow in *Mining Journal* (1912).

In the early 20th century systematic investigations of groundwater in the permafrost areas of Siberia began. In 1916 A. L'vov, who worked in Irkutsk, published a comprehensive summary on groundwater in the permafrost areas. At the same time the first works on groundwater within oil fields were presented by D. Golubiatnikov and others.

1917–1941

After the 1917 Revolution and the end of the Civil War in 1922, the Geological Committee conducted and coordinated hydrogeological surveys in central Russia, the Volga basin, the Komi area and the Caucasus. The Committee continued extensive investigations of the Moscow artesian basin and V. Khimenkov, A. Ivanov, A. Danshin and V. Zhukov prepared a summary of the geological and hydrogeological data that had been gathered on the basin.

The Committee continued investigations of mineral waters and mineral springs in the Caucasus Region (A. Gerasimov, N. Slavianov, A. Ogil'vi, N. Ignatovich). At the same time N. Tolstihin started a study of mineral waters in Eastern Siberia. The Siberian scientist M. Kurlov proposed a formula for expressing the chemical composition of groundwater (1928), which is still widely used in the hydrogeological literature.

In the 1920s the Institute of Meteorology established the first regional groundwater monitoring network in the European part of Russia, and the Federal Government funded an extensive groundwater monitoring programme over the huge irrigated areas in Central Asia.

Special courses on hydrogeology were available at several Russian Universities from the 1900s. The first Russian textbook on hydrogeology for University students was published in 1922 by P. Chirvinsky, and by the end of the 1920s Bachelor and Master degrees in hydrogeology could be obtained from the Universities of Moscow, Leningrad (now Saint Petersburg), Kiev, Odessa, Tomsk, and Tashkent.

Construction of new industrial complexes in the northern and eastern parts of Russia promoted studies of geological and hydrogeological conditions in these remote areas. During the 1920s M. Sumgin, A. Leverovsky, N. Tsitovich, and V. Sokolovsky studied the hydrogeology of permafrost. In 1922 V. Il'in published a summary of all the hydrogeological investigations conducted in the European part of Russia. At the same time three maps edited by V. Il'in were published: *A Map of Hydrogeological Studies in the European Part of the USSR*, *A Schematic Groundwater Map of the European Part of the USSR* (scale1:2,800,000) and *A Groundwater Map of the Central Industrial Zone* (scale 1:1,000,000). Il'in came to the conclusion that sustainable groundwater regimes depend on climate, topography and geological setting.

In 1925 A. Semikhatov published *Artesian and Deep Unconfined Aquifers in the European Part of the USSR* in which he described the 15 artesian basins in this territory.

In 1922 N. Pavlovsky published the monograph *Theory of Groundwater Movement Beneath Hydrotechnical Constructions and Its Main Applications* and concluded that groundwater flow velocity depends on the properties of the fluid as well as on characteristics of the porous medium. He demonstrated that groundwater flow velocity is proportional to the pressure gradient, the square of the effective diameter of the particles, and the square of the pore diameter and is inverse proportional to the kinematic viscosity of water. For solving problems associated with groundwater movement through and beneath hydrotechnical structures, N. Pavlovsky developed the so called conductive-sheet analogy method.

The First All-Union Congress of Hydrogeologists was held in Leningrad in the end of 1931. 570 delegates from all over the USSR attended this unique 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 dealt with the methodologies of both site specific and regional hydrogeological mapping.

As a result of the Congress, the comprehensive summary *Materials for Characterization of Groundwater Potentials in Various Regions of the USSR* edited by F. Savarensky, M. Vasil'evsky and D. Shegolev, was published in 1933.

Savarensky was a leading figure in Russian hydrogeology during the 1930s and 1940s and was one of the first lecturers to teach hydrogeology in Russia. He started teaching in 1920 at the Institute of Agriculture in Saratov, then at Saratov University and later in various Institutes in Moscow. Savarensky was author of one of the best Russian textbooks on hydrogeology published in 1933 and 1939 which remained "the Bible" for several generations of Soviet hydrogeologists thereafter. He also possessed a tremendous managerial skill for organising research, investigation and study. Savarensky presided over numerous expert Committees and Commissions and was chair of the Hydrogeological Commission of the All-Union Scientific and Technical Society and a member of various Editorial Boards. He was also the author of numerous publications on groundwater resources evaluation. He was one of the first hydrogeologists to stress the need to study man-made factors influencing the environment in general and groundwater in particular, see *The influence of the Kuybishev Reservoir on Geological Processes in the Surrounding Area* (1940, a) and *The Influence of Dams on the Transformation of River Banks* (1940, b).

Many other Soviet hydrogeologists worked successfully in various fields of hydrogeology before World War II. In 1934 A. Semikhatov published a monograph on groundwater in the European Part of the USSR. In 1937 A. Dzens-Litovsky and N. Tolstihin published a comprehensive summary of the occurrence and distribution of mineral waters in the USSR, and monographs and papers on hydrogeology in irrigated areas were published by V. Priklonsky and O. Lange.

F. Savarensky, M. Vasil'evsky, N. Ignatovich, I. Zaitsev defined hydrogeological zones of the USSR in the 1930s. In 1938 M. Vasil'evsky completed the groundwater zoning of the USSR, delineating hydrogeological basins, provinces and regions. This was the first time this was attempted for the Asian part of the USSR.

Significant achievements were made in further understanding well hydraulics and groundwater dynamics (G. Kamensky and G. Bogomolov, 1932; G. Kamensky, 1933; M. Al'tovsky, 1934). Corrections were introduced into Dupuit's equations, and limits for their practical applications identified. It was found that groundwater withdrawal from a fully penetrating artesian borehole depends not only on the confined aquifer thickness, its hydraulic conductivity and drawdown, but also on the borehole diameter. Factors that define the radius of influence of a borehole (duration of pumping, yield, drawdown, groundwater flow gradient and velocity) were identified and modified equations for calculating the radius of influence developed.

M. Al'tovsky (1934) derived equations for well yield calculation based on the results of a short term pumping test. Meanwhile N. Zhukovsky and A. Kostiakov developed the original theory of groundwater inflow into horizontal wells and galleries and the main achievements in hydrodynamics were summarised in the monograph by G. Kamensky *Principles of Groundwater Dynamics* (1933 and 1935).

Advances in groundwater chemistry were associated with the establishment of the Institute of Hydrochemistry in Moscow in 1921. It was led for many years by O. Alekhin. The Institute published the journal entitled *Materials on Hydrochemistry* in which seminal works by N. Slavianov, N. Tolstihin and M. Kurlov were presented.

Significant funding was provided for studying mineral waters which could be used for medical purposes. In 1936 V. Ivanov, L. Yarotsky, V. Shtil'mark and A. Ovchinnikov compiled a series of hydrochemical maps of mineral waters in the USSR and a summary map of mineral waters in the USSR (scale 1:20 000 000) was compiled by N. Tolstihin in 1937.

In 1933–1936 V. Vernadsky published the monograph entitled *History of Natural Waters*. He considered the various phases of natural waters as components of the global underground hydrosphere and evaluated the role of each phase in the geological and chemical evolution of the Earth and transformations of the Earth's crust. V. Vernadsky subsequently demonstrated the role of natural water in the geological and geochemical evolution of the Earth and highlighted the cyclic development of geological processes and natural water evolution. V. Vernadsky's ideas were fruitful for further development in various fields of hydrogeology including regional hydrogeology, paleohydrogeology, hydrochemistry and others.

Significant achievements were made in studying groundwater movement in fractured rocks. In 1939 D. Shegolev and N. Tolstihin published the monograph *Groundwater in Fractured Rocks* in which they summarized the findings of Russian and Western hydrogeologists. They pointed out the need for studying various geological processes, which influence the occurrence, size and distribution of fractures in rocks as well as the need to study the chemical interaction between the rock and water.

1941–1961

Understanding groundwater flow was a key theme for this period in which the solution of critical differential equations was central. Various scientists were involved, but the work of P. Polubarinova-Kochina, one of the founders of modern hydrodynamics and hydromechanics is perhaps the most famous. Her major work entitled *Theory of Groundwater Movement* was published in 1952 and in a few years several new editions followed along with translations into many languages. This monograph was and still is a handbook for many hydrogeologists throughout the world.

The application of finite difference method allowed site-specific characteristics of an aquifer to be considered. G. Kamensky initially developed this method for one dimensional groundwater flow and later modified it for the two dimensional flow. V. Lukianov constructed and used conductive-solid analogs for simulating groundwater flow within multi-layered water-bearing complexes.

Special emphasis was placed on studying deep aquifers and the role of riverbeds, sea and lake depressions as their discharge areas (K. Makov, F. Makarenko, A. Silin-Bekchurin, and B. Arkhangel'sky). Vertical movement of groundwater through thick clayey deposits was also investigated (N. Girinsky and A. Myatiev).

The extensive development of hydrotechnical works in the European part of Russia made the prediction of groundwater flow retention caused by dam and reservoir constructions of great practical importance. G. Kamensky developed the theory of steady (maximum) groundwater flow retention. Various forecasting equations for retention calculations were developed by G. Kamensky (1943) and N. Bindeman (1951).

The need to provide water supply for numerous cities, towns, and newly built industrial complexes initiated new studies in the evaluation of groundwater resources, their mapping, extraction and utilization. M. Al'tovsky developed methods of evaluating the total discharge from several interacted water supply wells and N. Plotnikov introduced a new method of calculating resource potential based on the size of the regional cone of depression.

In 1948–1955 N. Girinsky published on seawater intrusion into confined and unconfined coastal aquifers.

In 1944 the Laboratory of Hydrogeological Problems was created within the USSR Academy of Sciences. F. Savarensky was appointed as the first Director of this newly established scientific body. Under the directorship of F. Savarensky and then N. Slavianov, G. Kamensky, and V. Priklonsky, a team of hydrogeologists including O. Lange, F. Makarenko, A. Silin-Bekchurin, I. Garmonov, and others worked on fundamental theoretical problems of modern hydrogeology. The work included but was not limited to the following subjects: formation of groundwater under various climatic conditions; formation and regularities of regional baseflow; regional and global groundwater zoning; vegetative indicators of groundwater; the role of groundwater in the formation of ore deposits; and formation and utilization of mineral and thermal groundwater. Between 1944 and 1961 the Laboratory played a significant role in development of Russian hydrogeology.

1961–1980

Restructuring of the Academy of Sciences created a new Laboratory for studying geothermal energy and deep hydrogeochemistry under the leadership of F. Makarenko. The distribution of geothermal anomalies and their influence on groundwater chemistry was recorded. The role of groundwater in heat flow was evaluated and areas of geothermal groundwater identified, see *Thermal Waters in the USSR and Their Prospective Use* by F. Makarenko (1963), and other documents from this era.

Other Laboratory works included the chemical evolution of groundwater, chemical loading and the hydrochemical balance within deep aquifers and artesian basins. The Laboratory produced various regional hydrochemical maps and monographs on the hydrochemistry of thermal groundwater, physical and chemical equilibriums in groundwater under various natural conditions, and the regional distribution of groundwater resources.

Works of the Geological Institute of the Soviet Academy of Sciences included investigation of submarine hydrogeological systems; the chemical composition of modern sediments; hydrochemical conditions associated with modern sedimentation; and the interrelation between modern sediments, seawater and thermal springs on the sea bed.

Significant achievements in regional hydrogeology especially in studying and forecasting groundwater regimes and the water balance were made in the All-Union Institute of Hydrogeology and Engineering Geology (VSEGINGEO) established in 1939. In 1957 A. Konoplyantsev headed the groundwater resources, regimes and dynamics department of the VSEGINGEO. Konoplyantsev advocated the need to establish a regional groundwater monitoring network within the vast territory of the USSR and by the end of the 1960s several regional groundwater monitoring agencies had been established.

By 1970, the federal monitoring network consisted of about 30 000 monitoring sites to measure groundwater level, temperature, and chemical composition. All groundwater-monitoring wells were classified as first class (or basic observation wells) and second class (or auxiliary observation wells). The main purpose of carrying out observations in the 20 000 first class monitoring wells was establishing the regional patterns of groundwater regimes and obtaining baseline groundwater data.

The second class monitoring sites, consisting of more than 10 000 observation wells, provided information on groundwater regimes under natural and stressed conditions for site-specific groundwater problems in various environments.

The monitoring agency's responsibilities included not only data collection from first class and second class monitoring sites but also preparation of annual monitoring reports, evaluation of groundwater resources, groundwater mapping and forecasting. All regional monitoring reports were forwarded to the VSEGINGEO where groundwater predictions and maps were compiled for the entire USSR territory. This unique groundwater forecast information service is still operational. In order to process and summarise this huge amount of information, a new approach was needed, and A. Konoplyantsev became one of the pioneers in applying statistical methods to groundwater monitoring results.

The comprehensive hydrogeological map of the former USSR (scale 1:5 000 000) was compiled in 1966 by the team of hydrogeologists from the All-Union Institute of Geology (the VSEGEI) led by I. Zaitsev. 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, icings, old river valleys, volcanoes, and geysers. In addition, information on groundwater withdrawal within main hydrogeological regions was given. It included the stratigraphical indexes of 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 waterbearing 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 of the former USSR (scale 1:5 000 000) edited by I. Zaitsev and N. Tolstihin was compiled in 1966. It was based on hydrochemical zoning and depicted three main zones: the zone of fresh water with total dissolved solid (TDS) values not more 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). Within cross-sections a certain combination of hydrochemical zones set up 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 waterbearing deposits, the presence of halogenated deposits, the bottom of waterbearing deposit(s), the hydrogeochemical zones, and the mineral water's number.

Within the artesian basins and hydrogeological massifs (folded areas) mineral water provinces were shown. 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 state-of-the art compilation and presentation of the enormous amount of information on groundwater hydrochemistry collected in the former USSR by this time.

Detailed groundwater balance studies in the different climatic zones of the USSR were conducted by A. Lebedev at the VSEGINGEO. He developed methods for groundwater balance calculations based on analysis of water table fluctuations. He also compiled numerous maps of groundwater balance components for several basins located in various parts of the USSR. Study of the changes in groundwater regimes and water budgets caused by water infiltration from irrigation systems was made by D. Katz (1967).

B. Kudelin of the Moscow State University was able to organize a wide-scale study of groundwater runoff and groundwater resources in the USSR. Many University staff members (V. Vsevolozhskii, I. Zektser, R. Djamalov, I. Fidelli and others) as well as representatives from other scientific institutions and Regional Geological Surveys participated in this project. During the period 1964–1967 maps of groundwater runoff for the entire USSR territory (scales 1:5 000 000) were completed and published. Every map provided the following information: the average annual value of groundwater runoff or the modulus of groundwater runoff (in $l/s \times km^2$); the ratio between groundwater runoff and streamflow (in percentage); and the ratio between groundwater runoff and precipitation (in percentage). The maps show the quantitative distribution of groundwater flow and enable the evaluation of the groundwater resource potential.

Prior to compiling these maps, hydrogeological regionalisation for the whole USSR was conducted. It was based on consideration of such factors as the occurrence, age, thickness and lithological composition of the main waterbearing complexes/aquifers within the active circulation zone. Depending on the regime of groundwater runoff within these complexes/aquifers and the degree of their hydraulic connection with the rivers, the appropriate scheme for hydrograph separation was chosen for each region. For compiling the map for average annual groundwater runoff the streamflow data at 2128 streamflow gauges with the long observation periods had been analyzed and 25 317 streamflow hydrographs had been separated using one of Kudelin's techniques. The set of maps was awarded several prizes from the Moscow State University, The Academy of Sciences, and Exhibition of Achievements in the Economy. The summary monograph *Groundwater Flow in the USSR* was published in 1966.

In 1967 the Water Problems Institute (IWP) of the USSR Academy of Sciences was established in Moscow. The Institute consisted of several Branches including the Groundwater Resources and Subsurface Runoff Branch. It was headed by B. Kudelin and after his death in 1972, by I. Zektser. Hydrogeologists R. Dzhamalov, V. Kovalevsky, N. Lebedev, and M. Nikitin worked at this Branch for many years and made a sufficient input into Branch's scientific achievements. The main topics which investigated included: distribution of groundwater resources; regional evaluation of groundwater resources; groundwater quality and its dependence on various natural and man made factors; and groundwater protection and conservation.

In accordance with the UNESCO International Hydrological Programme and in collaboration with many Russian and European Institutions, the IWP played a leading role in compiling a map of groundwater flow in the Central and Eastern Europe (scale 1:1 500 000).

In the 1930s through the 1950s new concepts of aquifer compressibility and elasticity were developed in the USA by Theis (1935), Jacob (1940, 1946) and Boulton (1954) and eventually introduced into the Russian hydrogeological literature. They have since been successfully applied by Russian hydrogeologists for problem solving. The significant input into development of modern groundwater dynamics and its practical application in evaluating groundwater resources have been made by V. Babushkin, G. Barenblatt, N. Bindeman, F. Bochever, I. Gavich, V. Gold'berg, E. Kerkis, A. Lebedev, N. Ogil'vi, I. Zhernov, and others.

V. Shestakov was one of Russian hydrogeologists who made a smooth transition from Darcy-Dupuit-Boussinesq-based classical groundwater dynamics into modern hydrogeodynamics and modelling that opened new possibilities and means for solving the wide range of complicated practical problems.

He developed, verified and successfully applied various mathematical methods in many areas of hydrogeology such as the design of lateral drainage systems, calculation of the regional drawdown caused by pumping in interacting wells, pumping from multi-aquifer groundwater systems, pumping from wells located in river valleys, interpretation of pumping test results.

In the numerous textbooks and articles on hydrogeodynamics Shestakov highlighted the importance of the following crucial issues: schematization of hydrogeological conditions as the first step in transition from field investigation and description of the site to its mathematical simulation; heterogeneity within the aquifer, aquitard and vadoze zone and its incorporation into hydrogeological models; and groundwater modelling as the necessary component and tool in hydrogeological research and studies.

In 1974, V. Shestakov and V. Mironenko published the monograph *Principles of Hydrogeomechanics* which was one of the most important contributions to understanding of interaction between water and the water-bearing media of that era.

V. Mironenko led the development of mining hydrogeology and groundwater dynamics. His early research involved evaluation of the efficiency of horizontal drainage wells, various aspects of dewatering of mineral deposits, an assessment of the stability of quarry and pit slopes with regard to dewatering operations, and rock deformation due to the influence of extensive dewatering. Gradually his interest switched to contaminant hydrogeology, groundwater protection, and environmental hydrogeology. In the early 1970s Mironenko pioneered the use of modern computer techniques, especially numerical modelling, in solving complex hydrogeological and environmental problems.

In the 1960s and 1970s many monographs and papers on hydrochemistry were published. As in the past, the scientific interest was focused on groundwater origin and formation (A. Silin-Bekchurin, A. Khod'kov, E. Posokhov, S. Smirnov, and others), and on regional hydrochemistry (K. Pit'eva, S. Shvartsev, E. Pinneker). Fundamental works were published on geochemical methods for ore deposits exploration (A. Brodsky, A. Germanov, A. Ovchinnikov, V. Borovitsky, V. Kiryukhin, and S. Shvartsev). Special attention was given to the groundwater geochemical features which could be used for oil fields exploration (V. Sulin, V. Krotova, and others). Hydrochemistry of mineral waters in various regions of the USSR continued to be studied and summarised in works by A. Perel'man (1968), A. Ovchinnikov (1970), N. Tolstihin and E. Posokhov (1977).

In the 1960s and 1970s many groundwater exploration studies were carried out. For example, in the mid-1960s about 1.5 million groundwater exploration boreholes were drilled annually. Between 1971 and 1975 groundwater abstraction was developed to supply more than 650 big cities including Tbilisi, Erevan, Tallinn, Vilnius, Irkutsk, Frunze; significant achievements were made in developing the principles and methods of groundwater resources evaluation and groundwater safe yield calculations. Among numerous publications in this field, the comprehensive monographs by F. Bochever and N. Verigin (1961), F. Bochever (1968), and L. Yazvin (1972) should be mentioned. In the early 1970s first detailed studies on groundwater protection were published by V. Gold'berg, F. Bochever and A. Oradovskaya (1972).

The 50-volume monograph *Hydrogeology of the USSR* was published between 1960–1976. Each volume describes in full the hydrogeology of a specific region of the USSR. It contains descriptions of climatic and geological settings, areal and vertical distribution of main aquifers and water-bearing complexes, the hydraulic characteristics, hydrochemistry and groundwater temperature data, sources of groundwater contamination and their influence on groundwater quality, evaluation of groundwater potentials, and current and future groundwater use and management. The summary volume consists of five books and an atlas of various regional hydrogeologic maps. The current use of different types of groundwater is thoroughly evaluated and the long term forecast of their future utilization is given.

CONCLUSIONS

1 The development and achievements of hydrogeology in Russia were always based on and closely associated with geology, and with geological surveying and mapping. One of the most prominent Russian hydrogeologists, Professor N. Tolstihin repeatedly told his students "Nobody can pretend to be a good hydrogeologist without being a good geologist". Geology was and still is the main component of hydrogeological training, study and research in Russia.
2 A multi-theme approach was typical for hydrogeological investigations in Russia. The groundwater origin, occurrence, distribution and chemical composition were studied alongside geological, hydrogeological, hydrological, climatic, topographic, soil and other natural conditions.
3 Regional investigations and studies were a significant component of the hydrogeological development in Russia. These were conducted by the Academy of

Sciences, the Geological Committee, the Federal and Republican Ministries of Geology, the Water Problems Laboratory, the All-Union Institute of Hydrogeology and Engineering Geology, the All-Union Geological Institute and other Institutions. As a result, such problems as regional evaluation of groundwater potentials, regional mapping, regional characteristics of groundwater regimes and balance, and regional groundwater forecasting were studied in depth, and Russian achievements in these fields were impressive.

4 Solving fundamental scientific problems was always a significant component and driving force behind Russian hydrogeology. For the period from 1960 to 1980 only, several hundred monographs were published in Russia dealing with a variety of topics including planetary and regional hydrogeology, hydrodynamics, hydrochemistry, hydrogeomechanics, groundwater in the permafrost areas and groundwater modelling.

5 Russia claims to host the largest number of Universities and Institutions teaching hydrogeology. As a result, the Russian hydrogeological community consists of several thousand professional hydrogeologists most of whom have a MSc degree.

6 The isolation of Russian hydrogeologists from their Western colleagues from the early 1930s to the late 1980s stimulated original investigations and studies to satisfy immediate needs of the industry, agriculture and urban and rural developments. Many achievements of Russian hydrogeologists working on in such fields as regional evaluation of groundwater resources, regional groundwater mapping and forecasting, evaluation of groundwater regimes and balances, regional and planetary hydrogeochemistry remained unknown for many years in the West. The political barriers created by the Cold War were counterproductive for the development of both Russian and Western hydrogeology. Nowadays the personal contacts and exchange of ideas and literature is common practice.

7 Considering 250 years of Russian hydrogeology in its broadest context, for much of the time Russia was more advanced than Western countries in large scale investigations and studies of evaluation and distribution of groundwater resources, groundwater mapping and forecasting, groundwater regimes and balance, and interaction between groundwater and surface water. Russia was also a pioneering country in establishing the national groundwater monitoring network and development of regional groundwater forecasts. The typical Russian approach was always first to get the big hydrogeological picture and use this to help solving site specific problems, rather than to collect piece meal site specific information to compile a big picture. The numerous regional studies and investigations resulted in a large amount of fundamental scientific monographs and papers being produced on various aspects of hydrogeology. Unfortunately, many of them remain unknown to the Western hydrogeological community to this day.

8 In the 1930s, 1940s and 1950s, Russia was behind the West in the field of modern groundwater dynamics. In the 1960s and 1970s Russian hydrogeologists were also behind their Western colleagues in applying numerical methods and modern computer techniques for solving complicated groundwater problems including those in the field of contaminant hydrogeology. However, starting from the late 1970s, Russian groundwater specialists were again in the front line of the international hydrogeological community with regards to their scientific achievements and its practical applications.

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