B.I. Kudelin: a pioneer of regional evaluation of groundwater resources in Russia

Ernst Zaltsberg

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A talented educator and prolific scientist (with more than 120 publications), an outstanding manager, a person able to foresee mainstream scientific development in relation to societal demands, a visionary of "the big picture" of hydrogeological conditions, and a practitioner able to find a solution for the site specific problem—these are qualities that can rarely be found in one person. Boris Ivanovich Kudelin (Fig. 1), one of the leading figures in the recent history of Russian hydrogeology, possessed all of them in full.

He was born in 1910 in the small village of Kinel-Cherkasy in the Samara region. In 1935, Kudelin graduated from the Moscow Hydrometeorological Institute and for the next ten years worked as a practicing hydrogeologist at various governmental geological agencies.

From 1944 till 1947 he was a post graduate student at the Laboratory of Hydrogeological Problems of the Academy of Sciences where he was preparing a Candidate thesis under the supervision of luminaries of Russian hydrogeology Academician F. Savarenskii and Professor O. Lange. His investigation on groundwater discharge into rivers brought him a Candidate of Sciences (CSc) in 1947. The main findings of this investigation and their practical applications were published in 1949 (Kudelin 1949).

In 1955, Kudelin completed his thesis entitled "Principles of groundwater resources evaluation under natural conditions" and received a Doctor of Sciences (DSc). In 1957 he was appointed professor at the Department of Hydrogeology of the Moscow State University (MGU) and seven years later headed this Department.

Fig. 1 Boris Ivanovich Kudelin in the 1960s

Under his leadership the Department became one of the best educational and scientific establishments in the former USSR. The list of Department members included such prominent hydrogeologists as N. Plotnikov, V. Shestakov, F. Bochever, S. Semenova-Erofeeva; each of them made a significant input in various branches of hydrogeology. Kudelin successfully combined heavy administrative duties, teaching and scientific studies. He taught several courses including general geology, general hydrogeology, methods of hydrogeological investigations, and others.

Kudelin's main scientific achievements

During the 1960s, Kudelin focused his efforts on investigating various aspects of regional groundwater resources evaluation and mapping (Kudelin et al. 1963; Kudelin 1960). He realized that groundwater resources mapping for large territories could not be conducted by using either a hydrodynamic approach or the results of field experimental work. Both produce good results when they are applied to groundwater resources evaluation within relatively small areas. However, their application within large territories would require a tremendous amount of exploration and test work, at incredibly high cost.

Kudelin concluded that evaluation of groundwater resources within the active circulation zone could be based on an assessment of groundwater discharge into the

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E. Zaltsberg (✉)
1101-131 Torresdale Ave, Toronto, ON M2R 3T1, Canada
e-mail: ezaltsberg@rogers.com
Tel.: +1-416-7397963

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rivers. This discharge could be calculated by means of hydrograph separation techniques which allow separation of groundwater runoff from total streamflow.

Depending on the aquifer(s) position within the river valley, he identified four typical schemes of hydraulic connection between the unconfined aquifer(s) and the river. They were as follows:

1. The perfect hydraulic connection between the shallow unconfined aquifer(s) and the river
2. The perfect hydraulic connection between the deeper unconfined aquifer(s) and the river
3. The sporadic (seasonal) hydraulic connection between the unconfined aquifer(s) and the river
4. The lack of hydraulic connection between the unconfined aquifer(s) and the river when the aquifer's bottom is located above the high water level in the river

In general, Kudelin demonstrated that, in the river bank areas, the regime of groundwater runoff fully depends on the streamflow regime. In other words, the river water level defines dynamics of groundwater runoff in these areas.

Using the finite differences method and the long-term water-table monitoring results at observation wells in river-bank areas, Kudelin calculated groundwater runoff for the type 1, 2, and 3 hydraulic connections mentioned in the previous, and compared them with the corresponding streamflow values. Based on such a comparison, he developed and modified the streamflow hydrograph separation technique for each of three types of hydraulic connections and their combinations.

In addition, he developed the hydrograph separation method for rivers that are recharged by both the unconfined and deeper confined aquifer(s). For evaluating groundwater runoff in the unconfined aquifer with no connection with the river, Kudelin utilized Makarenko's approach (Makarenko 1948). The variety of techniques developed allowed Kudelin to conduct separation of the groundwater component from the streamflow hydrograph and to evaluate natural groundwater resources under various hydrological/hydrogeological conditions.

He also developed the scheme of streamflow "bank regulation" during the high- and low-flow periods. In particular, Kudelin demonstrated that during the high-flow period there is no groundwater discharge into the river; in fact, the river recharges into the unconfined aquifer(s) with the type 1, 2 and 3 hydraulic connections with the river. During the following low-flow period, the aquifers are discharged into the river. This discharge includes the amount of water recharged from the river during the preceding high flow period. Kudelin incorporated the effect of "bank regulation" into the hydrograph separation technique for the unconfined aquifers hydraulically connected with the river.

For regional evaluation of deep groundwater resources Kudelin investigated the applicability of the long-term average annual water-balance equation for watersheds under various hydrogeological conditions. Usually, it is presented in the following convenient form:

$$X_0 = Y_0 + Z_0 \tag{1}$$

where X_0, Y_0, and Z_0 are the long-term average annual precipitation, streamflow and total evaporation, respectively.

Kudelin showed that Eq. 1 could be applied where the watershed comprises the shallow (unconfined) groundwater flow system(s) only. If the watershed comprises either the recharge or discharge area of the deep (confined) aquifer(s) or both areas, Eq. 1 becomes inapplicable and should be replaced with the following equation:

$$X_0 = Y_0 + Z_0 \pm W_0 \tag{2}$$

where X_0, Y_0, and Z_0 are given in the aforementioned, and W_0 is either the long-term average annual recharge or discharge of the deep aquifer(s), or the difference between them.

The value of Z_0 in Eq. 2 should be defined independently rather than from the water-balance equation.

Based on Eq. 2 and its adjustments to the specific hydrogeological conditions within the watershed, Kudelin developed the method for quantitative evaluation of deep groundwater resources. He proved the applicability of this method while studying deep (artesian) groundwater resources in the huge Dnepr-Don artesian basin in the southern USSR (Kudelin 1960). Later this approach was widely used by Russian hydrogeologists conducting groundwater resources evaluation in various regions of the former Soviet Union.

Kudelin's managerial skill

Due to his high scientific reputation and outstanding managerial skill, Kudelin was able to organize a wide-scale study of groundwater runoff and groundwater resources in the USSR. Many Department 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 ambitious 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).

Prior to compiling these maps, hydrogeological regionalization 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 water-bearing complexes/aquifers within the active circulation zone. Depending on the regime of groundwater runoff within these complexes/aquifers and the degree of their

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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 2,128 streamflow gauges with long observation periods had been analyzed and 25,317 streamflow hydrographs had been separated using one of Kudelin's techniques.

For the arid and semi-arid areas with poorly developed river systems, the water-balance method and the results of the previous experimental work were widely used for natural groundwater resources evaluation. As a result, for the first time important quantitative hydrogeological parameters had been mapped for the huge territory and became available for practical use. For example, using the map of groundwater runoff modulus, natural groundwater resources for the whole country or any of its specific regions could be easily calculated. Based on the same map, regional groundwater recharge for the main aquifers could be assessed and used in managing sustainable groundwater withdrawal. Using the map of the ratio between groundwater runoff and streamflow it is possible to evaluate the role of groundwater flow in streamflow and potential changes in streamflow due to extensive groundwater use. It is interesting to know that the whole extensive mapping did not require the implementation of special drilling and testing programs, it was highly cost-effective and conducted in a relatively short time. This unique mapping experience was summarized in Kudelin's monograph (Kudelin 1966).

In 1970, in accordance with the Program of the International Hydrology Decade, the project of evaluating groundwater runoff in the territory of Central and Eastern Europe was initiated by Kudelin. Until his untimely death in 1972, he was in charge of this project including its coordination with several scientific institutions in East European countries. As a result of these international efforts, the map of groundwater runoff in the territory under study (scale 1:1,500,000) and the monograph entitled *Groundwater runoff in Central and Eastern Europe* were published (Zektser et al. 1982).

Being a scientist and practicing hydrogeologist, Kudelin was fully aware that small-scale mapping of groundwater runoff for the entire territory of the USSR was of significant interest to long-term water-resources planning and for the management and solving of many fundamental scientific problems. However, this mapping did not provide detailed hydrogeological information for solving site-specific problems. For this reason, in 1965 he initiated the medium scale (1:200,000) hydrogeological surveying and mapping of groundwater runoff in various regions of the USSR. They were conducted as joint efforts of the MGU's Department of Hydrogeology, the State Hydrological Institute in Saint-Petersburg and the Ural Hydrogeological Expedition. The methodology developed was widely used by the Department of Hydrogeology in conducting further hydrogeological mapping in many areas of the USSR, especially in the Russian Far North and Far East.

In 1960, as a result of budgetary constrains and administrative restructuring, the Laboratory of Hydrogeological Problems of the Academy of Sciences was dissolved. For the following several years, Kudelin vigorously advocated the need for re-establishing the study of various water-related problems within academic institutes. As a result of his lobbying, the Institute of Water Problems of the Academy of Sciences was established in 1967. Kudelin was appointed Head of its Department of Groundwater Resources and Runoff. In this capacity he made a significant input into development of the long-term program of studies/investigations to be conducted by the newly established Institute. He also invited several renowned hydrogeologists (M. Nikitin, N. Ogilvi, V. Kovalevskii and others) to join the Department, which then became the leader in studying groundwater runoff, its formation, distribution, evaluation, mapping, and sustainable use.

Kudelin was either a member or a chief of numerous international and Soviet commissions, committees, scientific councils and editorial boards. He was awarded several prestigious prizes from the MGU, The Academy of Sciences, the Exhibition of Achievements in Economy, and the Moscow Society of Nature Experimenters.

Kudelin's scientific ideas on interaction between surface-water and groundwater are still alive and developed further by hydrogeologists in many countries. This was demonstrated during an international conference that commemorated 100 years since his birth and held in Moscow in 2010. In the conference proceedings a short biographical essay on B.I. Kudelin stands out (Vsevolozhskii and Zektser 2010).

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