METHODS OF GROUND WATER BALANCE EVALUATION
APPLIED IN THE USSR
DEVELOPMENT OF METHODS OF STUDY
OF GROUND WATER BALANCE

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At the present time one of the most important problems of hydrology is the ground water balance evaluation which is a component in the general water balance on land. The term ground water balance is used in the sense of quantitative expression of the connection between the income and expenditure parts of water balance in a zone of complete saturation for a definite territory.

The discussion of this problem at the meetings of the International Association of Scientific Hydrology is of great significance for its further elaboration and for the exchange of the available experience in different countries.

The income part of ground water balance is determined by the value of the infiltration of atmospheric precipitation, condensation of water vapour from the air and the mantle, and the income of various types of ground and surface waters into the aquifers (irrigation, waters of open basins) in horizontal and vertical directions. The expenditure part of the balance includes subterranean flow into open basins and streams and evaporation from the surface of ground waters of shallow aquifers.

The determination of the component elements of the ground water balance for a definite period of time and the prediction of its changes under the influence of natural and artificial factors is important for science and for many fields of practical activity of man.

If for the deeply situated aquifers the relation between the balance elements remains more or less constant in time, the income and expenditure parts of the balance of the aquifers with free surface of ground water continuously change in time. The variable relation of balance elements is especially vividly expressed during the spring snow melting and in the period of abundant atmospheric precipitation, when the income of water into the aquifer exceeds the underground run-off and evaporation. At such periods the accumulation of ground water resources occurs, as well as the increase of their level in aquifers.

The inverse phenomenon is observed in dry periods and in winter when the incoming part of the ground water balance is much less than the expenditure. In these conditions a quick and conspicuous lowering of ground water level in aquifers with free surface is observed, while these changes are slower in deep pressure horizons with distant sources of nourishment.

The works on the determination of the ground water balance elements have long history. Before the Revolution of 1917 in Russia the water balance of land was studied mainly by hydrologists, pedologists, land-reclamation specialists and hydro-technicians.

The Russian scientists (M. A. Velikanov, P. Ya. Polubarinova Kochina, F. P. Savarensky, A. V. Ogievsy, B. V. Poliakov, B. D. Zaikov, V. V. Glushkov and others) have shown the role of ground waters in the general water balance and suggested methods of study of water balance and of its components. The pedologists (G. N. Vysotsky, A. F. Lebedev, A. A. Rode, and others) worked out the method of study of water balance in the aeration zone, in particular for the root-layer of the soils.
The study of the ground water balance has acquired the greatest development in the period after the Revolution in connection with extensive plans of waterworks constructions. The works of hydrotechnicians, hydrogeologists and land-reclamation specialists (A.N. Kostiakov, V.V. Vedernikov, N.N. Pavlovsky, G.N. Kamensky, S. F. Averianov, N. N. Favorin, and others) have provided the problem with a theoretical basis and with methods of practical application to filtration calculations.

The study of the ground water balance in relation to the compilation of forecasts of changes of their regime (during irrigation and irrigation constructions) was developed in the works of the Middle Asia hydrogeologists (M.A. Shmidt, M.M. Krylov, A.F. Sliadnev, and others).

Most of these researchers developed experimental methods of determination of water balance elements.

After the War (since 1943) the Soviet hydrogeologists and specialists in hydraulics (G.N. Kamensky, S.F. Averianov, A.V. Lebedev, P.A. Kiselev, V.G. Thachuk, M.A. Veviorovskaya, V.S. Lukianov, S.K. Abramov, N.N. Verigin, A.I. Silin-Bekchurin, V.M. Shestakov, N.A. Plotnikov, and others) worked on the problem of hydrodynamic method of analysis of the regime of freatic waters, the observations of which widely developed in connection with rapid growth of construction in all fields of industrial activity. On this basis considerably greater possibilities were revealed in the study of the process of formation of freatic waters in natural and in artificial conditions.

Along with the development of hydrodynamic method of study of the ground water regime and balance in the USSR the experimental methods of determination of the basic balance elements are also being developed (V.A. Uryvaev, A.R. Konstantinov, M.M. Krylov, S.F. Sliadnev, and others) such as infiltration of precipitation, evaporation of freatic waters, accumulation of water in the aeration zone and local replenishment of subterranean run-off. The works by M.M. Krylov, A.F. Sliadnev, A.V. Lebedev, D.M. Kats, and others also deal with the development of the lysimetric method which allows a direct study of the process of formation of the stock of freatic waters in natural conditions.

In connection with extensive development of mapping of natural resources of ground waters in the USSR the method of genetic dissecting of the hydrographs of rivers have acquired wide development, as well as the method of the average for many years water balance for the determination of deep water feeding, worked out by B.I. Kudelin and others.

**METHODS OF GROUND WATER STUDIES**

*Regional study of ground water balance*

The major problem of such researches is the regional evaluation and mapping of natural resources of fresh and slightly mineralised ground waters for large territories.

These researches during the recent years demonstrated a new trend in the field of water balance study.

On the territory of the USSR, where a constantly active hydrographic network exists (covering more than 80% of the whole area of the country) the method of genetic dissection of rivers hydrographs is successfully applied for regional evaluation of natural resources of fresh ground waters. The theoretical basis of application of this method is the following.

Averagely for many years, the amount of nourishment of ground waters from above is equivalent to the amount of ground water run-off into rivers. Therefore, the natural resources of ground waters for a larger part of the territory of the USSR can be expressed by the values of modules, coefficients and by other quantitative characteristics
of ground water run-off wedging into rivers. For the arid and semi-arid zones of the USSR without river network, or with scarce rivers, or with transit rivers which do not drain the ground waters, the method of genetic dissertation of the river’s hydrograph for regional evaluation of natural resources of ground waters cannot be applied. Other methods of calculation are used for these zones.

**Definition of terms**

**Natural resources of ground waters** is used in the sense of the expenditure of ground waters provided by nourishment. Natural resources appear and are continually replenished in the process of the general water circulation on the Earth. In the conditions of exploitation the natural resources comprise the most important element of the balance which undergoes its changes.

**Regional evaluation of natural resources of ground waters** is used in the sense of determination of these resources for considerable territories, for instance whole basins of freatic or artesian waters or their sufficiently large parts. Such evaluations provide mean or total characteristics of resources.

**Intensive water exchange** is used in the sense of the upper level of usually fresh or slightly salt waters under pressure or not with comparatively shallow deposition which are located in the sphere of the draining influence of river systems, lakes, streamless depressions, or flow out in the coastal zone into the sea. Deeper waters are usually located under the draining influence of the hydrographic network, which are usually recognized as the zone of slower water exchange. The recharge periods for the zone of intensive water exchange are different, but in comparison with deeper salt waters they are comparatively small.

In evaluation and mapping the natural resources of ground waters are expressed by the module or by the mean layer of underground run-off. The **module of ground water run-off** characterizes the expenditure (replenishment) or underground run-off in litres per second from the area of 1 km². The **underground run-off layer** characterizes the amount of water running from aquifers during a definite period of time expressed as a layer of water evenly spread on an area (usually in millimeters per year).

The smallest value of natural ground water resources is determined by the **minimal module** (layer) of underground run-off, which is usually determined by stable winter or summer expenditure of rivers in the low-water period. The value of ground water run-off is also expressed by the volume of water in relation to a certain period of time.

Along with the absolute values the ground water run-off is characterized by relative values: coefficient of underground run-off and coefficient of underground nourishment of rivers. **Coefficient of underground run-off** is used in the sense of the relation of value of underground run-off to the value of atmospheric precipitation for the same period. **Coefficient of underground nourishment of rivers** is used in the sense of the relation of value of underground run-off to the value of the total river run-off in percent or fractions of a unit, showing the participation of the underground run-off in the formation of the general river run-off. This value has a great importance for the study of problems of interaction between surface and ground waters. It is calculated for regions where the ground water run-off is formed by river draining of aquifers.

In the evaluation of natural resources of ground waters and their mapping it is useful to give preference to the average many years values (norm) of ground water run-off which is the more stable characteristic.

**Determination of ground water run-off into rivers**

The underground nourishment of rivers is composed of the ground and artesian feeding. The regularities (dynamics) of run-off from separate aquifers drained by the
River valley is determined by conditions of the deposition and feeding of aquifers and by the position of places of expenditure (outflow on the surface) in relation to the river bank.

The following aquifers should be recognized in the study of underground feeding of rivers:

1) Aquifers without hydraulic connection with the river;
2) Aquifers with hydraulic connection with the river;
3) Aquifers with periodic hydraulic connection with the river.

The variety of the indicated conditions in the interrelations of aquifers with the river results in a completely different distribution of the underground run-off into rivers within the year (B.I. Kudelin, 1960).

The major problem is to establish on the basis of the analysis of hydrogeological structure of river basins which of the aquifers (complexes) is the major source of underground feeding of the river and which could be neglected, considering the purpose of the researches and the accuracy of calculations. This facilitates considerably the necessary works and allows to minimize the number of calculation schemes.

At present the whole territory of the USSR can be divided into the following major types of regime of underground run-off into rivers (Kudelin, 1962).

I. Dominantly descending type of regime of underground run-off in mountain countries.
II. Dominantly retaining type of regime of underground run-off in the plains.
III. Mixed (descending-retaining or retaining-descending) type of regime of underground run-off in high ground, flat plains, in intermountain depression.

In different physico-geographical conditions of the regions the indicated three major types of the regime of underground run-off into rivers could be divided into forms with consideration of regulation:

a) Lake (or artificial);
b) Marsh;
c) Over-ice (permafrost type of underground feeding of rivers).

Depending on the hydrogeological conditions of river basins a certain scheme of dissection of the river's hydrograph is selected.

The first task which appears in the study of underground run-off and the underground component of the river run-off is the hydrogeological zoning of the territory according to types of the underground regime run-off into rivers.

With this purpose a hydrogeological drainage map is compiled on which a legend used in geology shows the age and composition of deposits of aquiferous complexes (horizons) which participate in the formation of underground run-off in the zone of intensive water exchange. According to the recognized hydrogeological regions the typical drainage schemes are plotted which show the relative distribution of aquifers, the character of their interrelations with the river, thickness, composition and age of aquifers, mineralization of water, degree of participation in underground feeding of rivers in the area and the dominant type of regime of underground run-off into rivers.

The drainage map and the typical drainage schemes are plotted in application to the major erosion downcutting of rivers for which the underground run-off is being determined.

The depth of the drainage zone is determined according to:

a) The map of hydrohypses and hydroisopiezies;
b) Comparison of depths of the erosion downcutting with the altitude of aquifers;

c) Position of regional water-resisting;

d) Hydrochemical data on ground waters using the theory of connection between hydrodynamic and hydrochemical vertical zones of ground waters, according to which the greater part of fresh water is located in the zone of intensive water exchange;

e) Results of modelling of drainage processes on analogue models.

The quantitative expression of participation of separate aquifers (complexes) in underground feeding of rivers for maps of underground run-off in scale 1:500000 is marked as "subordinate" (up to 50%) and "basic" (more than 50%).

In river basins with lakes the lake regulation of surface run-off by its accumulation in lake basins is observed. As a result of this the lake rivers show a deviation from the general regularities of formation of river run-off which are characteristic of the given physico-geographical region. In the zone of excess and temperate moisture the influence of lakes on river run-off is of greater importance. By reducing the maximum of floods and high water the lake regulation increases the river run-off in the low-water period. The large water basins redistribute the run-off not only within the year, but also for a long term period.

The complex process of lake regulation hinders the marking on the hydrograph of that part of the general run-off which is formed due to underground feeding of the river. In order to determine the values of underground run-off in the basin of the lake river it is necessary to distinguish from the total run-off the part which is formed by surface run-off of the high water and flood periods and its accumulation in the lake basin. A strict solution of the evaluation of lake regulation can be obtained by the solution of the water balance equation with consideration of the change in the lake volume for the covered periods.

It is impossible to carry out mass determinations of the underground run-off into the lake river by the water balance method, which results in the necessity to calculate it according to empiric formulas.

The analysis of hydrological materials on the lake rivers in the North-East of the USSR carried out together with the analysis of hydrogeological conditions of the studied river basins permits the following basic conclusions about the consideration of the influence of lakes for the determination of the underground run-off into rivers of these regions.

1. The presence of less than 10% of lakes in the river basin has no significant influence on the redistribution of the river run-off according to the seasons of the year. This is confirmed by a complete similarity of the lake river hydrograph with the hydrograph of the river in the same area without lake regulation, as well as by the absence of connection between the relation of spring and summer run-off to the general run-off for the year and the size of the limnetic basin.

2. The determination of the underground run-off into lake rivers, with limnetic coefficient more than 10% and with the limnetic coefficient less than 10% but with distribution of lakes in the middle or especially in the lower part of the river, with consideration of mass calculations for unstudied rivers can be carried out according to the following empiric formula:

\[ q_{no3} = \frac{q_{MuH}}{3\sqrt{\alpha_{03}}} \]

where \( q_{no3} \) is the module of the underground run-off into the river, 1/sec for 1 km²; \( \sqrt{\alpha_{03}} \) is the minimal monthly module of the river run-off, average for the period.
1/sec for 1 km²; \( z_{03} \) is the limnetic coefficient of the river basin in %. The indicated dependence is supported by a comparative analysis of calculations results of underground run-off values according to the empirical formulas of different authors and by more accurate determinations according to the water balance equation of the studied rivers, as well as by comparison with the modules of underground run-off of rivers without lake regulation in the same hydrogeological regions.

The determination of the underground run-off by the method of genetic dissection of the hydrograph of the total run-off for river basins with marshes is connected with the solution of the problem of the regulating influence of marshes on the minimal river run-off. At present most hydrologists come to the conclusion that the marshes in the upper reaches do not increase the minimal run-off which is fully formed in the low water period due to underground feeding.

As to the influence of low marshes on the river run-off the basic source of nourishment of which is the ground water a definite conclusion can be drawn with greater certainty. The run-off from drainage system with considerable areas of low marshes is usually maintained during the winter and summer months. In such basins the formation of low water run-off is also carried out due to underground nourishment.

In evaluation of the possible influence of marshes on the river run-off the distribution of marsh masses on the drainage system in respect to the river valleys should also be considered. For river basins, where marsh masses are located on divides and only in the upper reaches are bogged while the area in the vicinity of the valleys are blind creeks (for instance, Vasinganie in the West Siberia), the marsh regulation cannot considerably affect the formation of the underground nourishment of rivers.

On this basis a conclusion can be drawn that in most cases even for considerably swamped river basins certain values of underground run-off are very close to the true ones, provided the evaluation of underground nourishment is made by the method of genetic dissection of the hydrograph without the allowance for swamp regulation in the period of low run-off. According to the calculations of underground run-off for its mapping on the territory of the USSR with a scale 1:5000000 it is assumed that in the low water period on bogged drainage systems the river run-off is formed at the expense of the underground run-off.

The regional evaluation of natural resources of ground waters in the regions of development of perennial permafrost is more complicated than in regions without permafrost. There is still very little experience to solve this problem by the usual reconnaissance and hydrogeological works. The application in this case of the previously described complex hydrological-hydrogeological method is the most practical. The complexity of application of this method lies in a number of peculiarities of this territory which have considerable effect on the formation of the underground run-off into rivers and of the water balance. One of these is the freezing of rivers to the bottom which often does not depend on the size of the drainage system area. Ground water accumulates during the winter period in icings, thus reducing the low water expenditure in rivers, while in spring and summer, when they melt, they increase the underground feeding of rivers and their total expenditure by a certain amount, i.e. a redistribution of underground run-off is observed during the year, which is called the process of underground run-off regulation by icings.

Knowing the area of the icings, their thickness and time of formation, the volume of ice can be determined and, considering the coefficient of the volume expansion of water in freezing, the total debit of springs forming the icings can be calculated. By referring the obtained expenditure to the areas of the basin the module of icings formation is determined. The total value of the winter underground run-off, or the natural resources of ground waters in the drainage zone for the winter period is characterized by the sum of modules of icings formation and the winter river run-off.
\[ M_n = M_3 + M_H \] (2)

where \( M_n \) is the complete module of the underground run-off in the winter period, 1/sec 1 km\(^2\); \( M_3 \) is the winter module of the river (liquid run-off), 1/sec per 1 km\(^2\); \( M_H \) is the module of icings formation, 1/sec per 1 km\(^2\).

If we know the melting period of the icings, the volume of ice melting during the warm season of the year, and the area of the basin, we can obtain the module of the icings run-off into the river.

As the result of the analysis of observation materials a direct dependence was established between the icings areas, volume of ice and expenditures of highly debit springs and approximated empirical formulas were worked out for the calculation of the springs debit forming icings in the critical period:

\[ Q = 93 F_H \] (3)
\[ Q = 129 F_H \] (4)

where \( Q \) is the debit of the spring forming the icing, 1/sec; \( F_H \) is the area of the icing, km\(^2\); 93 and 129 are the empirical coefficients measured 1/sec per 1 km\(^2\).

**Regional evaluation of natural resources of ground waters in arid and semi-arid zones**

The method of dissection of the hydrograph of the river or the utilisation of the low water expenditures of rivers for the regional evaluation of natural resources of fresh ground waters in the zone of intensive water exchange can be applied in the regions with continually operating hydrographic network. The conditions for application of this method are either completely or partly lacking in desert and arid regions. For regional evaluation of natural resources of ground waters in these regions in the USSR the materials, characterizing the value of nourishment from above and the expenditure of the underground run-off, were collected and correspondingly processed.

The following methods of reckoning were applied:

1. Experimental with usage of lysimetric instruments;
2. Calculation of infiltration values according to the variations of the ground water level on the basis of application of equations of unstabilised ground water movement in final remainders;
3. Compilation of water balances on run-off areas;
4. Hydrodynamic calculations of underground run-off. The calculation parameters, included in the Dupuit formula, were determined on the basis of reconnaissance observation materials. This method was widely used in artesian basins, antemountain trains, along river valleys, in trans-adyr and inter-adyr depressions;
5. Calculation of water balance and values of underground run-off into lakes;
6. When possible, the hydrometric calculation methods of accumulation (or loss) of river expenditure were applied in two consecutively located ranges during the low water period;
7. River-bed balance which was used in the conditions of river valleys of the Syr-Daria, Kara-Daria, Kashka-Daria (basic posts of the Chirakchi-tributaries), as well as the Surkhan-Daria, Zeravshan, Chirchik.

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(1) This part was compiled according to the materials of S.Sh. Mirzaev and Yu.P. Guschina for the Middle Asia and U.M. Akhmedsafin and Zh.S. Sadykov for Kazakhstan.
When the rivers drain complex aquifers the method of genetic dissection of the river hydrograph was applied, or the data on the low water expenditure were used with consideration of certain specific conditions of formation of underground run-off into rivers, characteristic to the arid or semi-arid regions.

It should be noted that in a number of regions of the arid zone the modern state of study of the underground run-off did not allow to express its value in the form of isolines of mean annual modules; therefore the maps show on the area of distribution of definite aquifers the ranges of variations or the mean values of modules of underground run-off.

Compilation of maps of underground run-off

According to the data obtained for the territory of the USSR, complexes of maps of underground run-off were compiled in the scale 1:5000000.

The basic principle of compilation of such maps is the consideration of regularities of its spatial distribution on the territory of the USSR in dependence on the complex of all natural factors affecting the conditions of its formation. In compilation of maps the typical drainage schemes were applied, which characterize the hydrogeological profile of the zone of intensive water exchange on all major structure-hydrogeological units of the territory, and the hydrogeological description of conditions of formation of underground run-off.

In order to make allowance for the hydrological regime when compiling maps of underground run-off, the maps of separate water balance elements were used: norms of river run-off, precipitation and evaporation values.

The map of underground run-off from the zone of intensive water exchange is given in isolines of mean perennial modules in litres per second per 1 km$^2$, and it is basic. It was compiled according to the calculation data of values of underground run-off according to the methods indicated above.

The calculated values of modules, obtained according to hydrometric ranges, related depending on the general conditions of formation of the underground run-off to the centers of river basins or to the point of the river basin, which according to the hydrogeological situation can be the average weighted center of value of the obtained module.

The map was marked with calculated modules for all hydrometric ranges. When drawing the isolines the preference was given to points for which the values of the modules were obtained according to the calculated ranges of basins with the area of 1000-50 000 km$^2$ (for plains) and from 100 km$^2$ and more (for mountains).

The interval values of the module between separate isolines, their "step", was determined on the basis of the analysis of oscillations of the module's values for all the calculated points on the area of the given region. At considerable variations of the values of the modules on small distances a larger "step" of the isolines was used while with small changes it was smaller. Thus the "step" of the isolines for separate parts of the territory of the USSR changes from fractions of 1/sec per 1 km$^2$ for plains in southern regions approaching to the climate of semi-arid and arid zones, to 3-5 1/sec per 1 km$^2$ and more for mountain regions.

The same principles of constructing isolines on maps were followed in the arid regions as well.

In order to compile the map of coefficients of underground run-off as percentage of precipitation the calculated data were used on mean perennial underground run-off and mean perennial value of annual amount of precipitation over a basin or calculated area.

The isolines of coefficients of underground run-off were constructed with consideration of the whole complex of physico-geographical conditions, and in the first place the hydrogeological peculiarities of the territory.
The maps of underground run-off as percentage of the total river run-off were compiled on the basis of observation materials which were the data on all hydrometric ranges with determination of perennial values of mean annual modules of underground run-off. The value of the ratio of underground run-off into river to its total run-off was calculated according to the average perennial values (norm) of average annual modules and was expressed in percent.

The utilization of maps of underground run-off

The compiled maps of the underground run-off allow to solve the following practical problems:
1. Determination of natural resources of ground water over the territory;
2. Determination of the nourishment value (replenishment) of ground waters during regional evaluation of exploitation resources of ground waters;
3. Determination of underground run-off as a component of the water balance of the territory;
4. Determination of the interrelation between surface and ground waters.

The method of genetic dissection of the river's hydrograph is used for regional evaluation of natural resources of ground waters.

The drainage zone of ground waters of the river usually covers several aquifers. The drainage map and the typical schemes of drainage clearly show the state of participation of separate aquifers (complexes) in the formation of underground run-off into the river.

Using the map of isolines of mean perennial modules of the underground run-off, the natural resources of ground waters (expenditure of underground run-off) can be calculated for any given area according to the formula

\[ Q = 0,001 \cdot M \cdot F \] (5)

where \( Q \) is the expenditure of ground water, \( m^3/sec \); \( M \) is the module of underground run-off, \( l/sec \) (taken from map); \( F \) is the area limited by the water-divide line, given cross-section of the stream and conditional lateral lines of flow, \( km^2 \).

When on a given area several isolines of underground run-off modules are shown, then the calculation of the expenditure of underground waters is carried out according to the formula

\[ Q = 0,001(M_{n1}F_1 + M_{n2}F_2 + ... + M_{nn}F_n), \] (6)

where \( M_{n1}, M_{n2}, ..., M_{nn} \) are the modules of underground run-off taken from the map of isolines; \( F_1, F_2, ..., F_n \) are the areas (determined by planimetry) tending to the given isoline according to which the value of the underground run-off modules were obtained, \( km^2 \).

The values of minimal natural resources (expenditures) of ground waters are calculated according to any given area, using the values of minimal modules of the underground run-off.

In regional evaluation of exploitation resources of ground water the value of nourishment (replenishment) of ground waters is determined according to the maps of mean perennial or minimal modules of underground run-off, which characterize the total value of feeding of all aquifers of the drainage zone. The possible water collecting

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(1) The map of coefficients of underground run-off and the map of underground run-off in percent of the total river run-off are combined on one sheet.
area of drawing waterworks is also considered. If it is necessary to determine the feeding value of one aquifer, then with stage distribution of aquifers the total feeding value (module of underground run-off), as indicated earlier, is divided on the basis of the hydrological analysis in proportion to the product of water percolation capacity of individual aquifers multiplied by pressure gradient.

\[ M_{n,t} = \sum_{i} M_{n} K_{i} m_{i} J_{i} \]  

(7)

where \( M_{n,t} \) is the module (layer) of underground run-off of the characterized aquifer (complex), 1/sec per 1 km²; \( M_{n} \) is the general module (layer) of underground run-off of the drainage zone (taken from map);

\[ \sum_{i} K_{i} m_{i} J_{i} \]

is the sum of products of percolation capacity of separate aquifers (complexes), forming the drainage zone, multiplied by the pressure gradient; \( K_{i} m_{i} J_{i} \) is the product of percolation capacity of the characterized aquifer (complex) multiplied by pressure gradient.

The determination of the volume of underground run-off in compilation of the water balance of the USSR or any region is made according to the map of mean perennial modules of underground run-off by the methods described above.

The solution of the problems on interrelation between surface and ground waters and the determination of the role of underground run-off in the general river run-off are carried out on the basis of the analysis of hydrogeological and hydrological conditions and maps of underground run-off as percentage of the general river run-off.

Detailed study of ground waters balance (according to data of stationary observations of their regime) (*)

The fundamental principles of the hydrodynamic method were suggested in 1950 by G.N. Karnensky. They are concerned with application of equations of unstable movement of freatic waters in final remainders to the calculation of values of their nourishment according to the data of regime observations along the ranges of observation holes. In 1950-1951 A.V. Lebedev, P.A. Kiselev have improved this method for compilation of the full balance of ground waters for elements of flow, and for drawing water works and river divides on the whole. The essence of the method is given in the following.

For the element of the freatic current limited on the plane by middle lines, normal to the direction of movement and drawn between neighbouring holes and limited on the profile by the first water resistant and water table, in the final remainders the following equation is proper

\[ \mu \Delta H = \frac{Q_{1} - Q_{2}}{F} \Delta t + w \Delta t, \]  

(8)

where \( \mu \) is the water yield or deficiency in saturation of soils within the changes of water level; \( \Delta H \) is the change of level of freatic waters during the time period \( \Delta t \) in the element of the flow; \( Q_{1} \) and \( Q_{2} \) is the inflow and outflow of freatic waters correspondingly flowing and outflowing from the element at a unit of time; \( w \) is the intensity of feeding

(*) The present report is not concerned with experimental methods for determination of separate water balance elements, because these problems were discussed at the symposium in the Netherlands in 1966.
of freatic waters from above; $\Delta t$ is the calculated time interval; $F$ is the area of the 
element of flow in the plan.

Usually the chronological plot of the level variations shows such time intervals $\Delta t$ during which a continuous and regular increase or decrease of level is observed. This period of time is usually related to monolaterally directed processes of infiltration or 
evaporation from the level of ground waters (from pressed capillary margin).

If the time period $\Delta t$ covers both indicated processes, then the value obtained by 
calculation $w\Delta t$ characterizes the resulting infiltration $w_1\Delta t$ (observed during 
the period of time $\Delta t$) and evaporation from the surface of ground waters $u\Delta \theta$ (for the 
time $\Delta \theta$). In this case $\Delta t = \Delta t + \Delta \theta$ while the feeding value is 

$$w\Delta t = w_1\Delta t - \tau u\Delta \theta.$$  \hspace{1cm} (9)

By dividing the annual cycle into a number of indicated time periods $\Delta t$ for each of 
them according to the measurement data of levels in neighbouring holes the mean 
water expenditures $Q_1$ and $Q_2$ are calculated, as well as the changes of freatic water 
resources $\mu \Delta H$ (usually according to the average hole from the three neighbouring on 
the range).

In order to calculate the water expenditures $Q_1$ and $Q_2$ the Dupuit or Kamensky 
formulas are applied, which at comparatively small (several hundreds of meters) 
distances between the holes show deviations less than 10% of the calculations results 
according to the formulas describing the unstable filtration regime.

In the case of two-dimensional movement of freatic waters, non-horizontal 
water-resistant and inhomogeneous structure of aquifers the corresponding 
formulas of ground waters dynamics are applied with the purpose of more precise 
calculation of values $Q_1$ and $Q_2$. In the presence of freatic waters flow into the inter-
layer pressure horizons in the right part of the equation (8) the value of flow $-\varepsilon \Delta t$ is 
also considered (where $\varepsilon$ is the intensity of flow) depending on the filtration properties 
of the dividing slightly permeable rocks (their filtration coefficient) and the pressure 
gradient of the vertical filtration.

In order to determine the value $\varepsilon \Delta t$ in the flow element besides the holes for freatic 
waters an observation hole is established in the underlying inter-layer horizon.

After substituting the values $\mu \Delta H$, $Q_1$, $Q_2$ and $\varepsilon \Delta t$ in (8) the value of feeding from 
above $w\Delta t$ is determined, which with positive value and keeping to the principles 
given above for division of the annual cycle into a number of time periods $\Delta t$, relates 
to the value of infiltration of atmospheric precipitation from above. The negative 
values $w\Delta t$ correlate to the total expenditure of freatic waters to the aeration zone and 
atmosphere, including the transpiration of vegetation. Often such values of freatic 
waters feeding are conditionally called the total evaporation of these waters from the 
level of ground waters.

The algebraic sum of all components of the ground water balance for the flow 
element produces the annual balance (in presence of penetration of freatic waters into 
inter-layer horizons) in the form:

$$\Sigma \mu \Delta H = \Sigma \frac{Q_1 - Q_2}{F} \Delta t + \Sigma w_1 \Delta t - \Sigma u \Delta \theta - \Sigma \varepsilon \Delta t.$$ \hspace{1cm} (10)

The value $\Sigma [(Q_1 - Q_2)/F]\Delta t$ is an expression of the local replenishment of the hori-
ental underground run-off, but assumed with a reverse sign, i.e. the value. 
$-\Sigma [(Q_2 - Q_1)/F]\Delta t$. When averaged according to the water-collecting area, if the basin 
is limited by a water-dividing line, this value (in mm of water layer) gives the average 
layer of the underground run-off.
The next stage of researches is in finding the correlation connections between the infiltration values $\Sigma w_1 \Delta t$, evaporation of ground waters $\Sigma \mu A_\theta$, on the one hand, and the major factors which define them, on the other hand. For instance, almost always such a factor is the depth to the water $Z$ (m).

With this purpose the calculation indicated earlier concerning the values of freatic waters nourishment $w_\Delta t$ is carried out for other elements of the flow with three consecutive holes in range along the water movement by using the relative data about level variations and $\mu$ parameter. Usually in order to obtain reliable connections between the values $w_\Delta t$ (mm) and $Z$ (m) it is sufficient to have, with all other equal conditions, 5-6 calculating elements of the flow with 3 holes in each, if the depth to the water on their area changes from 0.5-1.0 to 5-6 m.

If the map of the depth of situation of ground water, compiled according to the average data is available with the help of the indicated feeding values correlation $w_\Delta t$ with depth to the water $Z$ it is easy to compile the maps of infiltration of atmospheric precipitation to the freatic waters and their expenditure for total evaporation according to seasons.

Such maps, if supplemented by another map showing changes of ground water resources $\mu A_\theta$ easily compiled in presence of observation holes, allow to approach the evaluation of conditions of formation and values of underground run-off according to regions and for the whole basin.

The value $\Sigma (Q_1 - Q_2)/\mu A_\theta$, calculated by (10) (if the other terms of equation are known), is also easily mapped. According to the map of the value $\Sigma (Q_1 - Q_2)/\mu A_\theta$ not only the average layer of the underground run-off for a certain season is determined, but also typical conditions are defined of the water exchange between the aeration zone and the freatic stream.

The algebraic summing and the determination of summarized values of infiltration $\Sigma w_1 \Delta t$ evaporation of ground waters $\Sigma \mu A_\theta$ and other elements of balance according to seasons and months is carried out according to the calculated areas (elements of the flow), regions (recognised by the complex of hydrogeological conditions) and for the whole basin.

The last stage of researches is confined to the coordination of monthly and seasonal values of ground water nourishment with other components of water balance on the surface of the ground and in the aeration zone. Thus, for instance, for natural conditions the value of ground water feeding, determined according to the experimental data on a definite area, is equal to:

$$ (w_\Delta t)' = X - E + K_1 + Y_1 - Y_2 - D_1 - D_2, \quad (11) $$

where $X$ is atmospheric precipitation; $E$ is the total evaporation from the surface; $K_1$ is the condensation of vapour on the surface and in the aeration zone; $Y_1$, $Y_2$ is the inflow and outflow of surface waters; $D_1$, $D_2$ is the accumulation of water sources on the surface and in the aeration zone (taken from the surface to the highest level of the capillary margin for the observation period).

Undoubtedly, the values $(w_\Delta t)'$ calculated according to (11) can differ from the values $(w_\Delta t)$, determined by the method of final remainders on the basis of regime observations. The discrepancy of these values by more than 15-20% can indicate to certain unforeseen elements of water balance or to errors in other experimentally obtained balance elements. In keeping to the indicated accuracy (or convergence) of values $w_\Delta t$ by (11) and by the method of final remainders it is easy to establish those basic factors which regulate the process of nourishment and expenditure of ground waters in different directions.

Thus as the result of application of the described method of detailed study a possibility is provided for a more thorough research of the process of replenishment of
ground waters differentially by regions, evaluate resources of these waters and obtain
the basic characteristics of the water balance which are important for regime regulation
of these waters.

Certain differences in the calculation methods of feeding values $w \Delta t$ introduce the
analytical solutions of differential equations of unstable movement (S.F. Averianov,
V.S. Shestakov, A.V. Lebedev). At the same time the practical application of these
solutions considerably facilitates the calculation of the values $w \Delta t$, because they do not
demand the presence of three holes along the current for one-dimensional movement
of waters; besides $\mu$ parameter they are limited by the data on the coefficient of level-
conductivity.

**Peculiarities of ground waters balance and regime formation in conditions of exploitation**

The analysis of ground water balance with an allowance for the water expenditure,
used during exploitation, as well as the changes of precipitation infiltration and evapo-
ration of ground waters in reducing their level indicates to the specific character of this
balance during water exploitation. The described control can be carried out for the
exploitation area, for the whole aquifer or for part of it.

For the whole aquifer or for several of them such an analysis can be carried out
according to the module of underground run-off and its comparison with the ground
water run-off module formed in the process of exploitation.

The analysis of ground water balance with consideration of exploitation expenditure
can be carried out by approximated balance equations. During such analysis of ground
water balance the possible change of their composition during exploitation should be
considered with allowance of contamination or with consideration of water replenish-
ment which changes the composition of the ground waters in exploitation.

In the USSR when selecting sources of water supply preference is given to ground
waters.

The character and conditions of violation of natural balance and regime of ground
waters can be classified by the following features.

A. Replenishment of exploitation expenditure in the ground waters balance:
1. With replenishment of exploitation expenditure;
2. With partial replenishment of exploitation expenditure;
3. Almost without replenishment of exploitation expenditure;
4. With replenishment of exploitation expenditure after a long period of time, of the
   order of several years or even decades.

B. Nearness of feeding source and size of regulating capacity of aquifer.

Nearness to water drawing of the feeding sources and the size of regulating capacity
of aquifer sometimes determine the possibility and character of replenishment of
exploitation expenditure of ground waters and their balance in conditions of exploita-
tion.

According to the indicated features the following conditions can be distinguished in
the formation of the regime and balance of ground waters during exploitation:

1. Ground waters where the exploitation area is located within the region of feeding
   source by atmospheric precipitation. In this case during the exploitation of ground
   waters, with expenditure recharged by infiltration of atmospheric precipitation,
   first a considerable decrease of ground water level occurs on the exploitation area
   (with partial activity of gravity resources), and then annually in connection with
   periodical infiltration of atmospheric precipitation the decrease and increase of
   level correspondingly occurs;
2. In the conditions of nearly area of reliable ground waters feeding by infiltration of waters of open currents (with infiltration of bank drawing waterworks) during the first short period of exploitation the decrease of levels occurs on the drawing area and then the increase and decrease of ground water level occurs with corresponding change of horizon of surface waters;

3. Deep pressure waters where the exploitation area is located at the distance of several tens of kilometers from the feeding area. In this case during ground waters exploitation the elastic water sources become active.

During the analysis of the balance and regime of ground waters of a certain level in exploitation certain phenomena should be taken into account, such as:

1. Change (certain decrease) of the infiltration value of precipitation during decrease of water level;

2. Change (considerable decrease) of the value of total evaporation from the level of ground waters deposited close to surface at the same decrease of level;

3. Possible change of the chemical composition of ground waters due to the decrease of level and change in geochemical situation in the aeration zone (for instance, enhancement of oxidation process of dispersed sulphides, etc);

4. Possible change of hydraulic interrelations of the used aquifer with adjacent horizons and with surface streams, etc.

The first of these factors somewhat decreases the replenishment of ground waters due to atmospheric precipitation. But the second factor with shallow waters can greatly increase the ground waters feeding from above.

All the enumerated phenomena and factors can be taken into account in the water and salt balance of the used aquifers.

CONCLUSIONS

The study of the ground water balance on the whole and of the comprising elements, in particular, offers an important problem to hydrogeology. These researches should be developed on the basis of improvement of regional and special methods of ground water balance evaluation. Successful development of this problem can be carried out on the basis of consideration of such important factors as inflow of porous solutions into aquifers, overflow of water from one artesian basin into the other, and exchange of waters between different aquifers through water resistant layers when the thermodynamic parameters are changed. Researches should be extended in the field of study of the role of condensation waters in the aeration zone and of the vapour from the mantle in the ground water balance on land.

Certain attention should be given to the study of the salt and heat balance of different crustal zones in natural conditions and under the influence of man’s industrial activity. Special importance is acquired by the study of the role of tectonic fractures and diagenesis in the water, salt and heat balance.

These problems in future should be solved with the application of data about deep crustal structure, natural and artificial isotopes, determination of the age of free ground waters and porous solutions and methods of modelling. The modelling of natural hydrogeological processes should be carried out on the basis of an extensive application of computers and the analysis of materials about deep structural drilling.

Attention should be given to the elaboration of theoretical and practical problems concerning artificial replenishment of ground waters resources.

A successful elaboration of the methods of evaluation of ground waters balance with consideration of modern achievements in adjacent fields of knowledge calls for close international cooperation within the International Association of Scientific Hydrology, IUGG, and other similar organisations.