STUDYING OF FORMATION OF SURFACE AND UNDERGROUND WATERS USING THE REMOTE SENSING METHODS

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In this paper a possibility of using satellite data in modeling formation of surface and underground waters is demonstrated with an example of mountain water catch.

Use of remote sensing techiques for studying, maintenance, and protection of natural resources makes the solution of hydrological and hydrogeological problems much easier since they provide simultaneous survey of vast areas, high speed of information extraction, and the possibility of multiple survey of objects of a specific interest. In studying the surface water catch the remote sounding data are most frequently used for obtaining information about areal characteristics of the underlying surface (in their dynamics, as a rule) – dimensions of different water objects and territories covered with snow as well as zoning of water catches according to the conditions which determine their water regime. The descriptions of hydrological processes in a water catchment basin, in particular, the processes of drain formation, which are usually obtained based on mathematical models can be successfully supplemented and corrected using the remote sounding data. Thus, according to estimation from Ref. 1, the drain prediction accuracy has been improved by 8–10% owing to the use of satellite information in the traditional prognostic dependences. When simulating the surface water catch the remote sensing data can be efficiently used for calibrating the model parameters. Although the behaviors of hydrological processes in plain and mountain water catches are different, the differences are of minor importance from the point of view of applicability of satellite data in the models.

By way of example we consider the possibility of using satellite data in simulating the drain formation processes for a mountain water catch. The model constructed with the account for a vertical zonality of meteorological elements is intended for calculating a drainage hydrograph in a locking range as well as for determining snow reserve, altitude position of seasonal snow boundary, the degree of water–catch snowcover and water inflow to its surface.[2]

Satellite data on snowcover of water catches were used for calibrating the parameters and varifying the models. The thawing rate h_T was calculated by formula (1) without the account of the radiative effect and by formula (2) when taking this effect into account:

$$h_T = \kappa_1 T , \quad (1)$$

$$h_T = \kappa_1' T + m R (1 - A) . \quad (2)$$

For summer and spring calculations also take into account nonlinear dependence of h_T on T occuring in these seasons due to the effect of solar radiation on snow thawing:

$$h_T = a_1 (T - T_0)^{a_2} . \quad (3)$$

Here T and R are the average, over observational period, air temperature and total radiation incident on 1 cm^2 area; k_1 and κ_1' are the thawing coefficients; A is the albedo of snowcover; m is the empirical coefficient; T_0 is the temperature at which snow starts thawing; a_1 and a_2 are the coefficients determined from data of many years observations of snow thawing in the region under study. The formulas for calculating the rate of thawing and the values of the coefficients κ_1, κ_1', and m were selected based on the results of a comparison made between the degree of snowcover of the water catches and seasonal vertical boundary of snow on different dates determined from the satellite photographs and calculated based on the model with different combinations of coefficients in the aforementioned formulas. When making the comparison we also checked the correctness of the choice of coefficients in the distribution of precipitation over the water catch heights

$$X(H, t) = X(H_0, t) \left[1 + \kappa_2(H - H_0) + \kappa_3(H - H_0)^2\right] \quad (4)$$

and of the air temperature. In formula (4) $X(H_0, t)$ is the amount of precipitation at the weighted mean height of a water catch H_0, κ_2 and κ_3 are the coefficients being chosen during numerical simulations based on the results of the field observation.

Model calculations were made for basins of the rivers Gavasai and Kassansai (the northern slope of Fergana valley, Chatkal'skii ridge, Western Tien–Shan) with 657 and 1130 km^2 areas of water catches, respectively. Above the closing section lines (Gava and Kyzyltokoi) these are typical Middle Asian rivers with snow supply, a portion of drainage being formed with rains. The volume of the whole outflow during the spring floods (80–85 % of the annual drainage) is determined by winter stock of snow and precipitations fallen out during the spring floods. The spring floods normally start in the first half of April and terminate in August. The maximum drainage occurs in May and early June, in July it sharply falls off. The annual average drainage rate of water in Gava section line is about 6 m^3/s, in the Kyzyltokoi section line it is about 8 m^3/s, the maximum drainage rates occurring during the floods reach about 40 for the Gavasai river and 60 m^3/s for the Kassansai river.[3]

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The snowcovers of water catches and the altitude of a seasonal snow boundary were estimated based on the results of "Meteor" and "Kosmos" satellite–based photograph photometry using the MSU–S and MSU–M instruments which were operated in the visible and near IR ranges. Thus obtained images were interpreted either visually or using a computer. The October–June photographs taken in 1975–1986 with the resolutions 1 km and 250 m were used. The criteria used for selecting images were the absence of clouds, small perspective distortions, and a high angle of the Sun. All thus selected pictures were then converted by an opto–mechanical method and magnified to provide the scale of 1 : 2500000 (low–resolution pictures) and 1 : 1000000 (mean–resolution pictures). The boundaries of the basins under study were drawn in the pictures based on the specific features of the relief, i.e., river–beds and mountain ridges. The accuracy of determining the water–catch areas from low–resolution pictures depends on its dimensions and is about 12% for the Gavasai river and 8% for the Kassansai river. The computer–aided image contrasting and filtration enabled us to separate out small variations of brightness based on which it becames possible to make more accurate mapping than that carried out during visual treatment of the pictures.

The snowcover of water catches was determined from the tone contrasts on a picture. In the low–resolution pictures, within the limits of water catches under study the snow and snowless regions could be separated out. The mean–resolution pictures provided for identification of three gradations of tone: black, grey, and white, which were related to zero, 50, and 100% snowcover. In order to make automatic interpretation of pictures with a computer in an interactive environment we have isolated test spots corresponding to images of areas fully covered with snow and areas completely snowless. This procedure was carried out using the algorithm of element–by–element classification.[4] The snow boundary was determined by selecting a proper brightness threshold using segmentation of satellite images by the level–line method.[5] The values of brightness related to a snow boundary were calibrated based on the data of monthly airborne observations of snowcover of the basins under study. Variation of the brightness within 10 levels of the brightness scale (the entire scale of brightness variation from black to white was divided into 128 levels) was related to vertical variation of snow boundary of 100 m. The difference between the values of the snow boundary altitudes determined by the methods of element classification and level lines could reach 250 m. It should be noted, however, that the results obtained by the first method are close to those obtained by visual determination of the snow boundary position. The accuracy of determining the snow–covered areas was 6–10% for visual and 3–4% for computer–aided interpretation, depending, of course, on the resolution of the instrumentation of different satellites. Disagreement between the estimates of the snowcover caused by the differences in mapping its boundaries with a computer and visually was most pronounced for February pictures taken in different years (see Fig. 1*a*, *b*, c).

The computer–aided processing of images in two spectral ranges 0.5–0.6 and 0.8–1.1 μm revealed a 3% lower value of the snowcover when using near IR photographing. This value did not exceed the error in determining the degree of snowcover and did not allow the estimation of the area of simultaneous thawing from comparison of pictures taken in different spectral ranges. To make a choice among the formulas for calculating the thawing rate and for estimating values of coefficients of thawing we used satellite data on the degree of snowcover to estimate the intensity of water inflow into the water catch area.

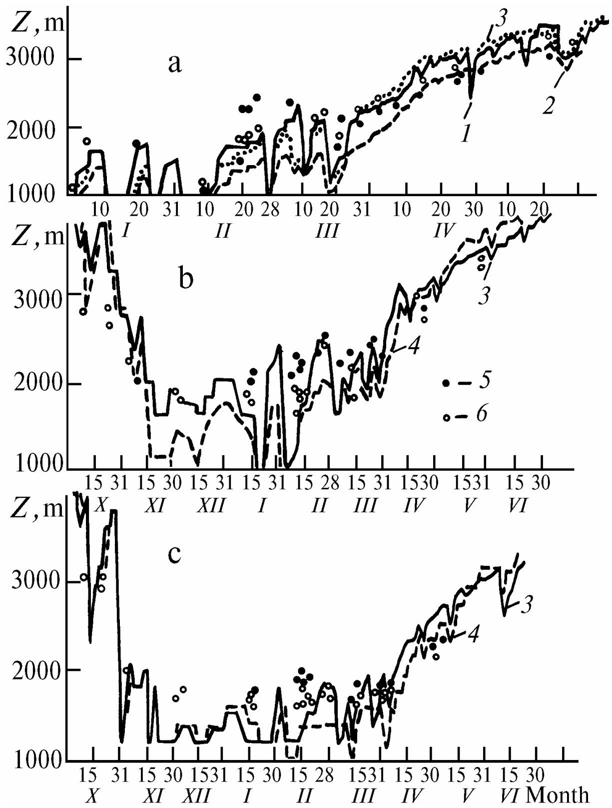

FIG. 1. Altitude position of a snow line for the basins of the Gavasai river, in 1978 (a) and in 1983 (b); the Kassansai river, in 1983 (c). The calculational results obtained using a model for six–hour (1) and day (2–4) intervals and the results of the analysis of satellite data: 1) and 3) using formula (1), $K_1 = 5$ mm/(deg·day); *2) using formula (2),* $K_1' = 1.8$ mm/(deg·day), $m = 0.011$; *4) using formula (3); 5) visual interpretation; and, 6) computer processing.*

In order to calibrate the model used we have compared calculational data on snow resorces for the basins of Gavasai and Kassansai rivers with those obtained by different techniques. Thus, in the case of Gavasai river the comparison was done using data of ground–based measurements with snow stakes carried out in January, February, and March of different years, as well as using data of snowcover observations with snow stakes observed from an airplane and data of gammagraphing obtained during the same periods. In the case of Kassansai river only data obtained with snow stakes observable from an airplane were available for comparison. Data on the snow density were taken from observations at weather stations in the valley. The aforementioned comparison of the snow–boundary altitudes obtained from the model and satellite data is given in Fig. 1*a*, and *b* for 1978 and 1983 for Gavasai river and for 1983 for Kassansai river. Similar comparison was made for both these water catches for all years considered in this study. The best agreement was obtained using the thawing coefficients value of 5 mm/(deg·day) although in some cases certain disagreement occurred between the snow boundary position and the degree of snowcover. This can mainly be accounted for by the neglect of diurnal behaviors of temperature especially in the vicinity of 0°C point. The calculations with a 6–hour step confirmed this assumption. Disagreement between the model estimates and satellite data in this case reduced to 150–200 m (Fig. 1*a*, *b*, *c*) what is within the error limits of the snow boundary determination from satellite data. The difference between the model calculations and satellite data can also occur because of: (1) an excessive reaction of the model to insignificant amount of precipitation under conditions of simultaneously decreasing temperature down to negative values, what is described as a sharp increase of snowcover and does not relate to actual behavior of the processes of snow thawing; (2) neglect of the snowcover nonuniformity including slopes of different exposures and the floors of valleys; (3) inaccuracy in topographic mapping of satellite pictures relative to particular water catches and the errors in the picture transformations as well as (4) insufficient resolution of a scanning instrumentation, and some other causes.

A comparison between the calculational data on the snow boundary altitude and the degree of snowcover obtained using linear and square–law extrapolation of the precipitation amount distribution with height showed that a linear approximation can be used for the basins under study.

Using a model the obtained values of melt water inflow were transformed into the hydrographs of the water outflow through the final section lines. The agreement between the calculated and actual hydrographs for all years of measurements (1975–1986) was estimated visually based on the plots and using a criterion of quality. Depicted in Fig. 2*a*, *b*, *c*, and *d* are the calculated and actual hydrographs of outflows of both rivers during different years. The best agreement was obtained for the years with low and moderate power of water outflows.

Similar approach to the use of remote–sensing data has been used in calculations of the drainage of the valley–river floods. To estimate moisture content of the soil and losses caused by total evaporation and filtration which determine the water inflow to the river–bed and water bodies, a model of moisture transport in the system "soil–vegetation–atmosphere" is used for averaging all of the components of water balance with respect to soil types and types of vegetation. Then this model is matched with the model of the flow formation. The hydrological characteristics are averaged based on the remote sensing data. At present, this approach is successfully developed at the Institute of Water Problems of the Russian Academy of Sciences.

To study regional peculiarities in the formation of underground waters and the character and degree of underground and surface water relations, as well as to provide their protection and determination of the degree of ecological changes of the environment and its underground component caused by long–term intensive anthropogenic influence the Institute of Water Problems has developed methodological principles of processing the data obtained from space. The methodology has been tested at different polygons of the European part of Russia as well as during space experiments carried out by international crews over the territories of Mongolia, Syria, and Afghanistan.

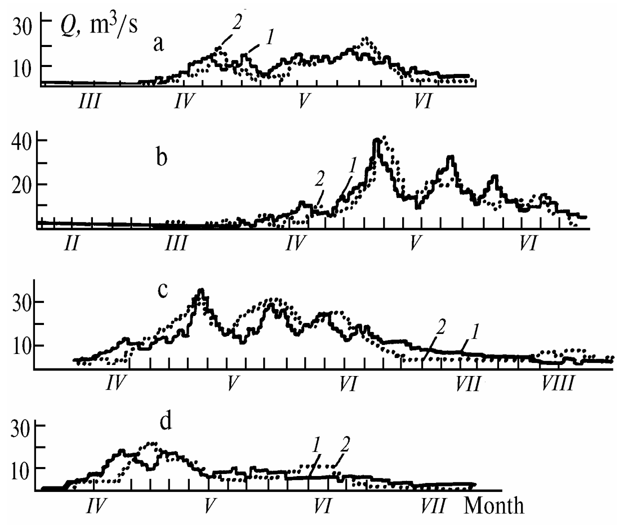

FIG. 2. Actual (1) and calculated using K_1 = 5 mm/(deg·day), *(2), hydrographs of the Gavasai river outflow – mountain settlement Gava: a) 1975, b) 1980, and of the Kassansai river – mountain settlement Kyzyltokoi: c) 1980, d) 1982.*

From the entire information contained in satellite pictures we have extracted the information about physiographic components of the landscape (relief, hydrography, vegetation, tectonics, etc., i.e., the drawing of a photoimage is analyzed) which is related to hydrogeological conditions of the territory under study. The main idea of the technique of hydrogeological interpretation is to study information content of satellite pictures in different spectral ranges, to determine and separate out direct, indirect, and combined features which occur not occasionally but form regular combinations in different natural territory systems, and then to consecutively reveal and store the information about hydrogeological phenomena and processes. The process of interpreting information obtained from space is divided into three steps. The first one is analytical identification of the landscape components, then follows the development of synthetic indication schemes, and compilation of specialized and general hydrological maps.

For a series of analytical maps and schemes reflecting some aspects of general geological and hydrological peculiarities of the territory is compiled, based on the revealed features after establishing their indicative roles. These are the maps of water points and water displays, density of a river network and erosive division of the landscape, vegetation cover, litholo–facial, tectonic (lineaments and ring structures) geomorphological elements of the landscape, etc.

The analysis of a plan of hydrographic net gives an idea of composition of rocks, fracturing, and enables one to find zones of depth fractures, elements of folded structures, relation of valleys with neotectonic uplifts. The study of types of landscape forms makes it possible to find regions of supply, sink, and discharge of underground waters, to estimate the relation between the surface and underground waters, to determine geogenetic complexes of rocks, their power, peculiarities of lithologic composition, and fracturing of the rocks.

The study of mountain rock strata based on the data of photographing from space is of interest not only for determining the composition of mountain rocks but mostly for estimating spatial distribution of their filtering properties. This makes it possible, for different regional hydrogeological constructions, both to simplify a stratigraphic foundation in geologically complicated regions and, taking into account the genesis of water–bearing rocks, to separate out geofiltering media of some or other types based on their morphostructural features and to determine the nature of their occurence and boundaries of spreading. This, in turn, enables one to quantitatively estimate the penetration factor and capacitance of rocks for making preliminary estimates of underground water drains and resources.

The identification of tectonic elements including lineaments and ring structures plays an important role in establishing regularities and conditions of formation, movement and discharge of underground waters of the territories under study. Determination of a hydrogeological function of breaking disarrangements allows also a hydrodynamic situation in the region to be estimated and the interconnection between hydrogeological taxons and their boundaries to be found.

Vegetation cover is also of hydrogeological importance since it enables one to establish a composition of surface deposits, depth of occurrence of the subsoil water, a character of their mineralization, processes of moisture transport in the region of aeration, and the rate of developing exogeneous processes (bogging, salting, etc.).

At the next stage of the analysis and generalization of analytical maps the synthetic landscape–typological and landscape–indication schemes are constructed. They are developed based on the geological and geomorphological principle, i.e., one separates out morphostructural blocks occuring due to geotectonic conditions of the territory and studies their relationship and genetic relations. The established logical relations between the determined taxonomic subdivisions and the conditions of spreading the underground waters make it possible to judge on a hydrogeological situation on the territory investigated.

These maps are being drawn up based on synthesis of data from three sources: identification of the landscapes in satellite photographs, analysis of interrelations or the results of analytical interpretation (hydrographic net, geomorphological, geobotanic), and analysis of data of field studies. These maps include the interpretation features which characterize mean and minor elements of the landscape, typical vegetation cover and its density, lithologic characteristics of covering deposits, outcrops of bed–rocks, water manifestations and their timeliness, direction of tectonic disarrangements and extent of rock fracturing, manifestation of different natural processes and phenomena on the surface (caves, landslides, talus, saline lands, freeze covers, swamping, etc.).

In addition to landscape indicating schemes, the structure tectonic ones are also drawn at this stage. The content of the latter defines the information about geological structure of the territory which can be used for specifying hydrogeological conditions (correction of boundaries of hydrogeological taxonomic units, determination of the direction of underground water flows which are often localized in the regions of increased fracturing and in the wings and arches of geological structures, establishment of a hydrogeological role of breaking violations, strongly affecting the formation, movement, and discharge of underground waters, relation between pressurized and ground waters, etc.) (see Fig. 3).

The aforementioned synthetic landscape and structural schemes reflecting the relation between shaping components and geological and hydrological conditions allow one to compile general and specific hydrogeological maps at the final stage. The loading of hydrogeological maps depends on details of studying natural territory systems using remote sensing methods and can include hydrogeological zoning, areas of spread, and characteristics of water–bearing horizons and systems, some quantitative indices of collecting and water–conducting properties of water–bearing rocks, and relative characteristics of the value of the underground drainage[6] (Fig. 4). Special hydrogeological maps show some aspects of hydrogeological peculiarities of the territory under study and include maps of water points and water manifestations, depths of underground water occurrence and mineralisation during different periods of time, drainage of the territory, effect of tectonic and neotectonic situations on hydrogeological conditions, and others.

Detailed analysis of pictures taken from satellite enables one to refine mutual position and boundaries of spread of artesian basins and different–orders hydrogeological massives, some ideas about natural resources and geological reserves of underground waters, in particular, in almost inaccessible and poorly studied regions.

The discussed methods of using the remote sensing information when studying the surface and underground waters can be considered as an initial step in constructing a system for monitoring natural waters of the land. However, the development of the system of monitoring, in its classical sense, is very expensive and time consuming and cannot be realized because of current cuttings of funding for hydrological and hydrogeological sciences. Therefore the use of information obtained from satellites at different time is the only method for studying peculiarities and conditions of natural–water formation.

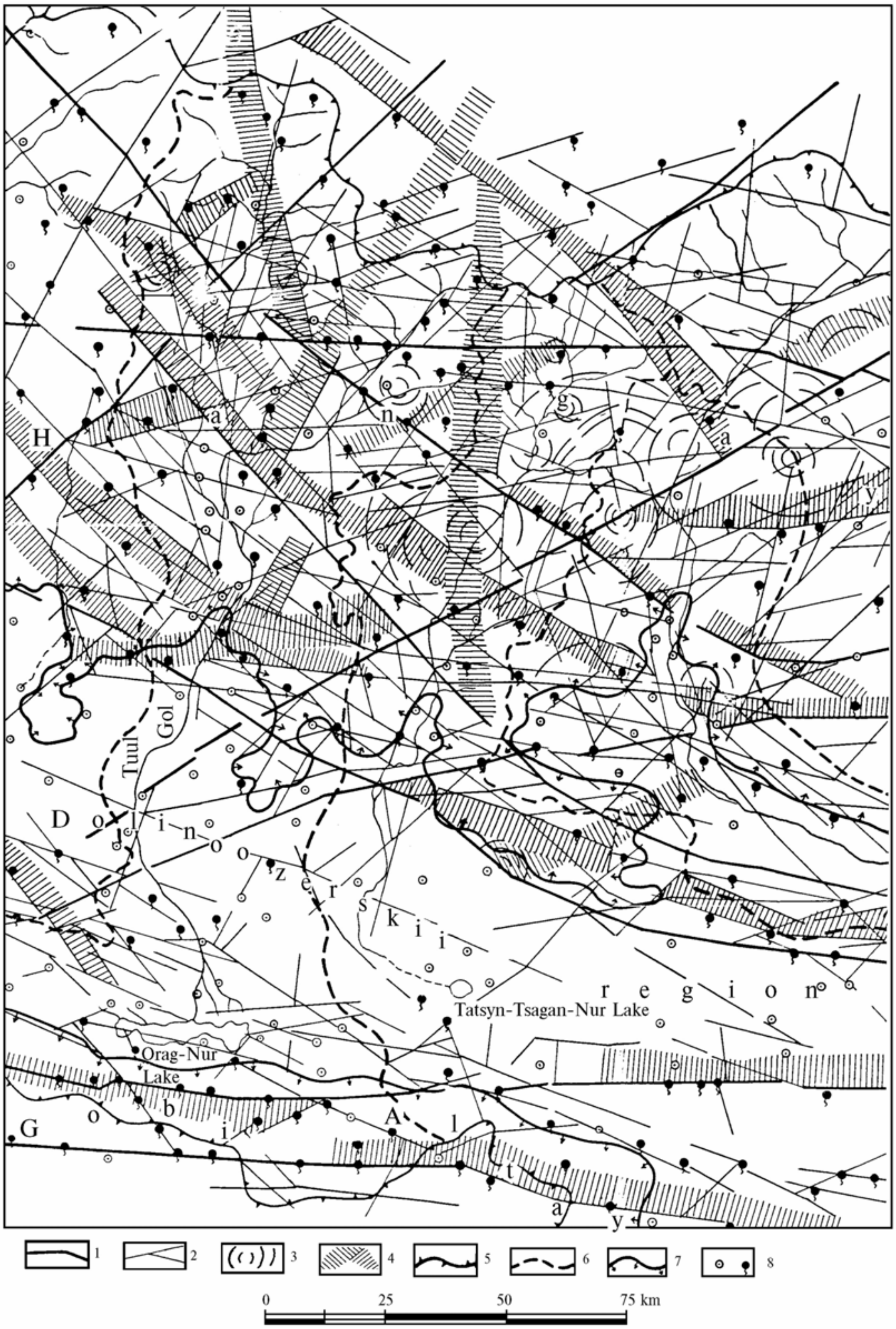

FIG. 3. A structure–hydrogeological scheme of the central part of the Dolinoozerski artesian basin of Mongolia (based on the results obtained from a synthesized satellite picture, spacecraft "Salyut–6", July 24, 1982). 1–4) breaking destructions: 1) regional depth breaks, 2) other breaks, 3) ring structures, and 4) zones of fracturing. 5–7) boundaries of: 5) the Dolinoozerskii artesian basin, 6) water–catch river basins, 7) regional areas of supply, and 8) water manifestation (holes, springs).

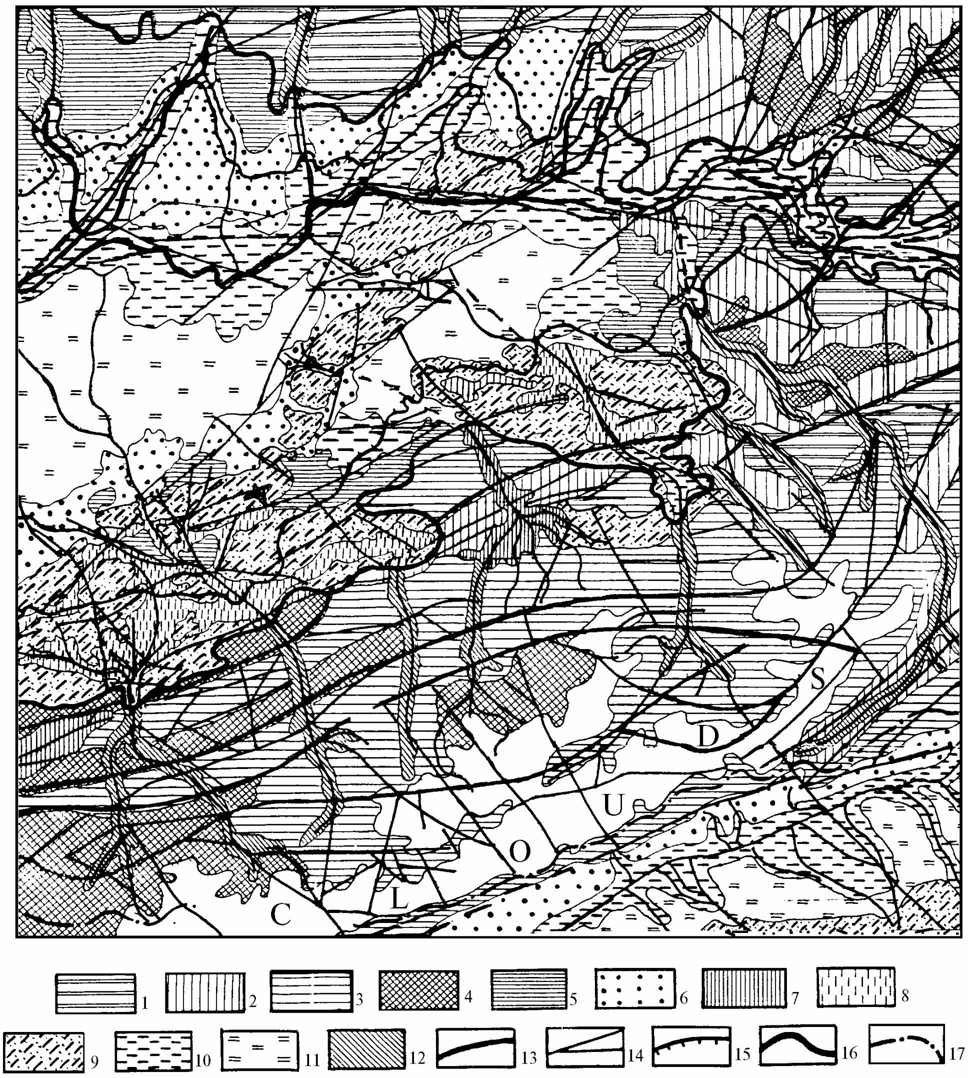

FIG. 4. Hydrogeodynamic scheme of conditions of forming underground waters in the Eastern part of the Fergana artesian basin (results of analysis of satellite pictures taken from an artificial satellite of the Earth "ERTS–1", June 4, 1973).

Regional areas of underground waters supply. 1–4) regions where the supply of underground waters occurs: into stratum–pore paleogene–Quaternary deposits due to infiltration of atmospheric precipitations (1), into Mesozoic fracture–pore rocks due to infiltration and inflow from adjacent water–bearing systems (2), into the upper and medium–Paleozoic fracturing cave rocks due to infiltration (3), and into metamorphic and erupted fracturing rocks of the lower and medium Paleozoic due to infiltration of atmospheric precipitations (4).

Local regions of supplying the underground waters: regions of local supply of blanket–pore waters of medium low–Quaternary deposits (5) and regions of local supply developing into zones of partial discharge of pore waters of carrying out cones (6).

The regions of drain and discharge of underground waters: regions of preferred spread of blanket–pore underground waters of Neogen–Quaternary deposits of intra–mountain (7) and other (8) depressions where there occurs partial discharge of fracture–vein and fracture–cave waters of Paleozoic formations; regions of preferred spread of pressurized waters in Mesozoic deposits covered with a low–power case of Quaternary formations (9); in the upper portions there exists a local supply and partial discharge over the valleys of rivers with fracture–pore waters of Neogen–Quaternary formations; the regions of drain and partial discharge by overflowing of pressurized underground waters in blanket–pore Mesozoic–Quaternary deposits (10); regions of preferred discharge of pressurized underground waters in blanket–pore Mesozoic–Quaternary deposits (11); regions of local discharge of blanket–fracture and fracture–vein waters of Mesozoic and Paleozoic deposits (12); breaking violations: regional and depth (13), others (14); boundaries: propagation of spread waters (15); regional areas of supply (16); and, of artesian basin (17).

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