Nordic Hydrology, 22, 1991, 211-226

Hydrology of Rivers of the Cryolithic Zone in the U.S.S.R.

The Present State and Prospects for Investigations

B. L. Sokolov

State Hydrological Institute, St. Petersburg, U.S.S.R.

The investigations provided the possibility to obtain a considerably better knowledge of the water balance of river basins and the water exchange between rivers and aquifers. The hydrological role of seasonal glaciation under the conditions of cold climate and permafrost has been studied and a methodological base for field studies of the specific phenomena and processes developed.

Introduction

Permafrost rocks, soils and strata occupy about 25 % of the land surface of the globe. The Antarctica, Greenland and islands with ice caps being excluded, this area makes about 21 million km^2 (14 %). Permafrost is most widely spread over the Asian and North American continents. It occupies considerable portion of the area of some countries: the U.S.A. (Alaska – 80 %), Canada – 50 %, the U.S.S.R. – 47 %, Mongolia – about 35 %, China – 23 %. Relatively small permafrost areas are located in mountainous regions of Europe (the Scandinavian Peninsula, the Caucasus, the Alps), in South America (the Andes), and on the islands of Honshu and New Guinea.

In the permafrost regions the formation of surface and ground-water resources and the hydrological regime of rivers are governed by some poorly studied peculiarities inherent to the permafrost or closely interrelated with it. Up till the recent time permafrost regions were a sort of »a blank« from the hydrological point of view.

Hydrological validation of the large-scale state programmes of the construction of the Baikal-Amur Mainline (BAM) 3,150 km long and the development of the areas adjacent to it, and the reconnaisance and exploitation of gas and oil deposits in the north of the Western Siberia brought about the need for a wide programme of field investigations which has been accomplished during the recent 15 years. Along with increasing the number of stations in the network of standard hydrometeorological observations, there were established experimental polygons with the observational programme aiming at a detailed investigation of hydrological events and processes. For this purpose different types of observations were made, such as: route surveys, aerial visual and aircraft landing-parties, airborne surveys and satellite observations. The already available methods and technical devices were adapted for studying the specific events and processes, and besides this, new methods, instruments and technical devices were developed.

The investigation results improved considerably the former knowledge on the formation of water resources and regimes in the cryolithic zone and provided information on some new laws of fundamental importance. These seem to be of scientific and practical value not only for the U.S.S.R. but may also be helpful for specialists in other countries which have permafrost regions.

The present paper gives a review of the three most valuable research results. Hence, it does not include methods developed for computing hydrological characteristics, mathematical expressions used in the methods or reflecting natural laws, and statistical estimates, the reader can find them in pertinent references cited in the text. The author intends to give a more detailed description of the above issues and other results in future papers.

Water Exchange between Rivers and Aquifers

The research results showed that the cryosphere as a water exchange system (Melnikov *et al.* 1984) »works« with a considerably greater »stress« than it was believed earlier. The role of the lithogenic link in the general water cycle appeared to be much more important. In fact, there is a review of the opinions concerning the correlation of the surface and subsurface components of the water resources. This fundamental conclusion is based on the use of a new technique for the assessment of the subsurface flow into the rivers of the cryolithic zone since it provides more accurate estimates of the portion of ground-water resources that are drained by the rivers (Sokolov and Sarkisyan 1981). Better estimates are obtained through an independent determination of each genetic component of the subsurface river feeding taking their intra-annual and long-term dynamics into account. For instance, the computed values of the annual ground water inflow to the rivers of the north-eastern part of the U.S.S.R. appeared to be 1.4 times greater than the estimates which were obtained earlier through hydrograph separation into surface and ground-water components (Sokolov 1986). In some river basins, predominantly with ground-water icings, the above estimates appeared to be 2-4 times greater (maximum 10 times greater). In the basins free of icings the increase was from 5 to 30 % due to the assessment of water accumulated in the ice cover of rivers.

Field investigations mainly in the BAM zone revealed the existence of a highly intensive exchange between the rivers and the aquifers drained by them. The former ideas about the insignificant role of the water exchange in the formation of the surface and ground-water resources became obsolete. More intensive water exchange can be explained by the fact that surface and ground-water bodies are connected locally and discretely in space and in time by means of taliks of different origin at narrow near-river areas. That means that the greater part of the drainage basin does not participate in the formation of the ground-water resources that contribute to the streamflow. It just follows from the above that river and ground water (over-, intra- and under-permafrost) as a rule makes a unified hydrodynamic system (Noveishaya tektonika etc. 1975; Romanovsky 1983; Tolstikhin 1974; Beven 1987, and others).

According to the data of field investigations in the central part of the BAM zone (the river basins of the Guilui, Niukzha, Olekma and other rivers) an intensive channel-water exchange takes place during the summer-autumn low flow period at 90-98 % of the total river length (Kolotaiev 1988). As to the direction of the water exchange we can differentiate three types of river reaches:

1) reaches only with inflow of ground water located mainly in places where rivers cross the faults of the earth's crust (water exchange coefficients, K, vary from 0.1 during the low flow to 0.5-0.6 during rainfall floods);
2) river reaches only with filtration (loss) of river water into the sub-channel loose sediments, located mainly in places where river crosses the zones of higher rock jointing (K reaches 0.6);
3) river reaches with alternating direction of water exchange: during the low flow river water infiltrates into the sub-channel deposits, while during the rainfall floods ground water discharges into the rivers.

River reaches of the above types usually alternate with each other along the river length. However, there may be a series of reaches only with ground-water inflow or river water outflow into the sub-channel deposits. The total value of water exchange of different direction (the absolute value) often exceeds the value of water discharge at the outlet, which is caused by a repeated transformation of river water into ground water, and *vice versa*.

Water exchange between the rivers and the aquifers is highly dynamic during the warm season of the year. On the whole it follows synchronously the variations in precipitation: the maximum values of the coefficient of the dynamics vary from 10 to 30, which testifies the very important role of ground water in the streamflow formation during the periods of high water content in rivers. One should mention also the synchronous variations of water exchange at the river reaches of the above types. In winter water exchange is localized on the reaches with water discharging taliks where ground-water icings are formed.

Some investigations attribute the lessening of the coefficient of flood runoff during the warm period from 0.8-0.9 to 0.1-0.2 only to the increase by the beginning of the winter of the depth of seasonal thawing of ground and accumulation (loss) of a certain portion of precipitation in it (Vasilenko and Khersonsky 1978) and thus they deny the role of the above-mentioned exchange. Detailed investigations at the experimental polygon »Mogot« in the central part of the BAM zone showed that water exchange plays a rather important role in the water balance even of small river basins with area of 3 to 30.8 km^2 and causes the change in the runoff coefficient of 30-40 % during the warm periods of some years.

The above conclusion seems to be important not only from the theoretical but from the practical point of view as well. The existing methods for computing streamflow characteristics, mainly of low flow, do not take into account the intensive and spatially variable water exchange between rivers and ground-water basins. For instance, minimum discharges at neighbouring reaches of one and the same small or medium-size river may differ by 50-70 %. On large rivers these differences are less distinct.

The Role of Seasonal Glaciation in Water Resources Formation

Recent investigations provided a very important conclusion about the great role of phase transformations of water in the water exchange of the cryolithic zone which in former days was not taken into account in the water balance of river basins. We have the best knowledge (though insufficient as yet) on the water exchange role of phase water transformations of the first type – water freezing and ice melting accompanied by seasonal glaciation: the formation of icings of different types of ice – river ice, condensation ice, injection-segregational subsurface ice. These are cryogenic water objects the formation of which is governed in time and space by specific laws. Their formation leads to the redistribution of ground-water resources making a part of surface (river) water resources, shifting them from the cold season to the warm period of the year. Therefore winter runoff here is only a part (often rather small) of the lithogenic link of the total water cycle which is under the draining effect of surface streams. For example, in the BAM zone winter streamflow makes about 10 km^3 per year, or only 52 % of the underground inflow into rivers (18.9 km^3 per year). The rest of the volume of the ground water drained by

Table 1 – Approximate estimates of the volume of natural water participating annually in phase transformations (water freezing and ice melting) within the area of the cryolithic zone of the U.S.S.R.

Cryogenic water body	Volume, km^3/year
Icings	
– of ground water	50.0
– of river water	41.2
– of snow water (including condensation ice, according to V. R. Alexeev)	200.0
River ice	22.2
Seasonal underground ice of injection-segregational origin:	
– mainly within icings fields (river valley bottoms)	10.5
– in the layer of seasonal freezing of soil (on the slopes of river basins)	158.0
Total:	481.9

rivers participates in seasonal phase transformations. In the north-east of the U.S.S.R. in the basins of the Yana, Indigirka and Kolyma Rivers the formation of the ice cover of rivers consumes water volumes that exceed the winter river discharges at the outlet 10.4, 2.6 and 2.5 times respectively (Sokolov 1986).

The author of the present paper approximately estimated that within the area of the cryolithic zone of the U.S.S.R. an enormous volume of natural water, namely 482 km^3 per year (see Table 1) participates in the phase transformations of the first type. For comparison: the volume of runoff from mountain glaciers of the country makes 25 km^3 per year (Krenke 1982). Over the globe (without the Antarctica, Greenland and islands with ice caps) the icings of ground and river water accumulate annually no less than 160 km^3, whereas the icings of all types accumulate 1,500 km^3 of natural water.

The hydrological role of the icing phenomena is most important. The formation of icing fields reaching in area 70-80 km^2 with an average ice depth of 3-5 m (maximum to 10 m) occurs mainly as a result of the cryogenic discharge from groundwater basins evidently due to the action of the internal cryogenic stress fields in the course of freezing of the ground water – frozen rock system (Tiutiunova and Tiutiunov 1988). The water cycle involves ground water of the zone of free exchange and of the zone of slow water exchange. Thus, there works a certain »cryogenic pump« that extracts water from deep interior part of the earth and conducts it through icings into the rivers. Hence the lower boundary of drainage becomes still lower and rivers get additional ground water feeding. A certain portion of water resources is redistributed in space (in the vertical and longitudinal profiles of river basins) which is superimposed on the intra-annual and long-term regulation of river and ground flow by icings.

In some river basins in the north-east of the U.S.S.R. with icings area of 10 % and more, icings accumulate annually and discharge into a river network as runoff from icings up to 250-300 mm of water. In fact, we speak about a new source of river feeding by icings in the cryolithic zone. The coefficient of icing feeding of rivers for a year reaches 0.3-0.4, and when the icing area is particularly large the coefficient rises up to 0.5-0.6, which means that 50-60 % of the annual river flow is controlled by icings. During the spring flood period the coefficient varies from 0.2 to 0.3 reaching 0.7-0.8 in some river basins. The streamflow formation role of icings is comparatively small in summer-autumn period (0.1-0.2) due to high water content in rivers and smaller size of icing fields.

The seasonal glaciation controls a considerable, often the main portion of ground-water discharge into rivers and natural ground-water resources. For example, the coefficient of icing control of ground water feeding of rivers in the north-east of the U.S.S.R. varies from 0.1-0.3 in plain regions to 0.5-0.7 in mountain and tableland regions. Over 70 % of this area the coefficient exceeds 0.3. In the basins with abnormally high percentage of icing area it reaches 0.8-0.9, *i.e.* 80-90 % of ground water drained by the rivers accumulate annually in icings.

It was also stated that the seasonal glaciation is one of the important »climatic« factors that increases the long-term variability and areal irregularity of surface and ground-water resources of the cryolithic zone, especially during the winter period. For example, in the BAM zone the long-term variability of streamflow is 1.5-2.0 times greater than the variability of the total subsurface inflow into rivers including also the water volume in the cryogenic (ice) formations (Sokolov and Liubimov 1986). In the north-east of the U.S.S.R. the ground-water component of streamflow for a year in river basins with icings varies from 0.08 to 12.9, whereas in river basins without icings it varies from 0.16 to 3.06 $l/(s \times km^2)$, which means that areal discreteness of this characteristic for river basins with icings is 8 times greater. The local cryogenic discharge of water of deep circulation mentioned above also contributes to this phenomenon. It is most probable that the formation of middle-size, large and gigantic icings happen mainly due to the overflow of deep ground underpermafrost water from neighbouring river basins in which this disturbs the correlation of the water-balance components due to the increase in loss components accompanied by the increase of the income components in the basins with icings. Therefore practical computation of stream-flow components in the permafrost regions should be made carefully due to higher discreteness of their spatial distribution.

Specific Features of the Regimes of Rivers with Icings

Icing areas in river valleys create a specific type of landscape of the cryolithic zone with a special hydrological river regime that depends on the geomorphological peculiarities, on a system of intensive hydrothermal processes of glacial-cryogenic origin, and on icings proper, that are highly dynamic in time. This specific nature is most evident in the areas of formation of ground-water icings.

This type of icings is formed in the same places from year to year and generates wide places in the near-channel and flood plain parts of the valleys. Hence there appear icing fields that strongly differ from the adjacent areas. These fields are usually forest free, relatively even, flat and wide, with stunted vegetation cover or without it at all. Their surface is composed of coarse rock fragments. The slope of an icing field is usually 3-5 times less than the slope of the river valley upstream and downstream of the icing. The width of an icing field is dozens and hundreds times greater than that of the rivers. The river stream here is divided into numerous shallow arms that migrate and dry up and there is no river in its usual form. In the course of the formation of large and gigantic icings the icing fields are completely covered by ice during 7-9 months annually, whereas during the rest of the year the ice cover is only partial. In the places of river icings the above landscape features are less pronounced.

The icing landscape rather strongly affects the hydrological, thermal, ice, and hydrochemical river regime, the sediment yield and the channel process. The quantitative estimates of the above parameters of the hydrological regime here differ dozens and sometimes hundred per cent in comparison with the pertinent characteristics of the adjacent icing-free parts of rivers. For instance, during the warm period icings appear to be a sort of specific landscape oasis, that is, a source of increased water content on the river basin surface: their specific water yield makes on the average during a season about 500 $l/(s \times km^2)$ of ice and sometimes reach 2,500-4,000 $l/(s \times km^2)$ due to seasonal and diurnal variations of the rate of ice melting, which on the average is 1.5-2.0 order greater than the specific annual discharge of rivers.

Icings and Water Regimes of Rivers

In the areas of river icings the river stage regime does not reflect the process of runoff depletion but characterize the hydrodynamics of the pressure flow under the ice. Icing formation causes pulsating water content in winter which differs in time and amplitude in different parts of the basin. On the rivers that freeze to the bottom icing formation is the only form of their winter regime. Icings act also as dams which leads to the fact that in river reaches with icings the maximum river stages are often observed not during the peaks of rainfall floods, but during the period of comparatively low spring floods. Spring-flood stages are dozens of centimetres (sometimes 1 m and more) higher than summer stages, though maximum spring discharges are several times (even 10 times and more) less than summer discharges. This fact is not taken into account by the existing techniques for computing maximum flow for project design. Therefore, the design-water stages often appear to be less than the actual stages, which leads to hazardous conditions in spring in the places of bridges and orifices, and sometimes even to their destruction. The intra-annual streamflow control by icings is accompanied by water-regime transformation which is caused by temporary accumulation of river water within icing fields with its later discharge protracted in time and by intensive interrelation of river and subchannel water. This leads to a considerable reduction of maximum discharges of rainfall floods, their lagging in time and to a considerably increased duration of floods. In summer water regime of rivers downstream of icings has distinct diurnal variations caused by pertinent changes in the water yield from icing areas.

Icings and Thermal Regimes of Rivers

In the course of icing formation in winter and their melting in the warm season enormous energy resources are involved in the processes of phase-water transformations, which tells upon the thermal regime of rivers. Icing fields act as a sort of natural heaters. During the first half of the summer there occurs a reduction in the heat runoff of rivers by 50-80 % due to the heat emission from river water and its dilution by cold icing water. In the second half of the warm period when a considerable part of icing fields is free of ice, river water is intensively heated. Hence the heat runoff increases by 50-70 % in comparison to the river reaches located upstream from icings.

Icings and River Ice Cover

River icings are formed practically on all the rivers of the cryolithic zone with length of about 700 km. The annual probability of their formation on a randomly chosen river reach is on the average 0.7. The depth of icings on the whole increases with the increase of the altitude of the locality, the rate of the increase being directly proportional to the contrasts in the topography. In the BAM zone it ranges from 0.2 to 0.6 of the total ice thickness on rivers. Higher values of this ratio mostly belong to mountain regions and lower values to tablelands. In the south of the areas of the West Sibiria, Trans-Baikal region, the basins of the Middle and Lower Amur River and of the north-east of the U.S.S.R. the above ratio reduces to 0.70-0.90 on rivers less than 10 km in length, and to 0.6-0.75 on rivers 500-1,000 km long. On the whole the ice cover of rivers in the cryolithic zone is formed by icings on 40-50 % in depth and on 50-80 % in volume. The total ice depth on rivers with icings reaches 3.0-3.5 m and more, and its width increases due to icing formation by 5-10 times. The ice cover has a complex structure due to the formation of icings of different types, which at present is not taken into account in the development of methods for computing and forecasting ice cover characteristics.

Icings, Sediment Yield and Channel Processes

The areas liable to annual icing formation, *i.e.* icing fields, are the areas of abnormal erosion-accumulation processes. The interaction of the components of the above process reveals direct and reverse relationships which testify to their self-regulation. The intensity of these processes here is at least one order higher than that on the adjacent icing free river reaches for the two following reasons. Firstly, the eroding action of streams is observed every year in a certain elevation range equal to the sum of ice thickness and water layer on its surface that is variable in time. Constant changes of the network of ephemeral streams lead to complicated changes of the erosion and accumulation of the solid matter. Secondly, the landscape formation processes of glacial-cryogenic origin are much more active here: physical weathering of rocks, ground swelling, thermokarst, frost clefting, mechanical suffusion and ice »action«. The reconstruction of the landscape, the change of the streamflow kinematics lead to a special type of channel process, namely, multiarmed channel due to icings (Snischenko 1984). The rate of the bank shifting here is 5-10 times greater in comparison to icing free river reaches. The reduction of the conveying capacity of the stream due to the widening of the river valley bottom and the reduction of the slope on the whole leads to solid matter accumulation, its differentiation by particle size from the upper to the lower parts of the icing field, to the reduction of suspended and tractional load by 85-95 %

Icings and Chemical Discharge of Rivers

Icing processes are accompanied by the cryogenic metamorphism of the chemical composition of the natural water with the formation of precipitates consisting of hardly soluble salts, mainly calcium carbonate with the admixture of magnesium carbonate and calcium sulphate (Ivanov 1983). This brings about two main consequences, namely, slowing down of the chemical cycle and the reduction of ionic discharge of rivers. According to the author's estimate the formation of icings of ground, river and snow water causes precipitation of 4.6 ± 0.5 tons of chemical substances in the U.S.S.R., whereas on the global scale it makes 30 million tons. On the regional scale the index of cryogenic precipitation of salts varies from 0.01 to 1.4, and in a basin with abnormally high percentage of icing area the above index may reach 5.0 tons/km^2 year. In the mountain regions of the north-east of the U.S.S.R. specific discharge of suspended sediments makes about 7 ton/km^2 year. Hence, in some river basins 50-60 % of the suspended load may consist of fine particles of non-soluble salts, which appear to be the result of the cryogenic metamorphism of the chemical composition of the natural water due to icings. For this reason the ion discharge in such basins is 30-50 % less than in the adjacent rivers without icings.

Prospects for Future Investigations

The above results show that the hydrology of the cryolithic zone is only at the initial stage of its development. This is for two reasons.

The first reason is the insufficient understanding of the role of the lithogenic link in the general land water cycle, *i.e.,* the role of the ground (more precisely, subsurface) water in the formation of streamflow. The use of the natural isotopes, the analysis of the chemical composition and water temperature in different countries outside the permafrost zone during the recent 10-15 years have brought scientists to an understanding of the extremely important role of the underground water exchange in the hydrological cycle. It appears that the ground-water component of streamflow during the period of spring snowmelt floods and rainfall floods varies within the range of 60-90 %. Only 10-20 % of this ground water component consists of the precipitation of the given year while the rest of it is formed by the precipitation of the antecedent 2-10 year period (Herrman *et al.* 1979, 1986; Herrman and Stichler 1981; Hooper and Shofmaker 1986; Kimura 1986; Kobayashi 1985, 1986; Martinec *et al.* 1982; Rodhe 1981, 1983). In fact, streamflow is a sort of »cocktail« of water of different ages. Proceeding from this Kuusisto (1982) suggested that all hydrologists should review their theoretical knowledge about the formation of the hydrological cycle. Our results discussed above support this fundamental conclusion. Our findings, however, are based mainly on the analysis of the hydrological role of seasonal glaciation only, the components of which, unlike the groundwater streamflow component, may be assessed by means of direct measurements. Therefore, the main target of future investigations in the permafrost zone is to study the role and the genesis of ground water in the formation of streamflow. The author believes that the solution of the above problem is the key to the understanding of the dominant processes of the hydrological cycle in general and in the permafrost zone in particular.

The second reason, which is closely interrelated with the first one, is the insufficient knowledge on the specific hydrological processes under the conditions of the permafrost zone mentioned above. We have the best degree of knowledge on the streamflow formation role of icings of ground and river water. There have been developed methods for field investigations (Izuchenie naledei etc. 1984) and for the assessment of river feeding by icings (Practicheskie rekomendatsii etc. 1986; Sokolov and Sarkisyan 1981). However, up till now there is still no full understanding of the mechanism of icing formation which is closely interrelated with the processes of circulation of ground and river water in the water systems of the cryolithic zone in case of their freezing. In this respect we consider as highly important the results of investigations carried out by Cane (1981) in Alaska in the Fairbanks region. He showed that ground and river waters are in close interrelation throughout the winter. Similar conclusions were obtained by Veiletti and Thomas (1979) in the Keewatin region (the north-western area of Canada). There is practically no understanding of the mechanism of the discharge of sub-permafrost water, that annually forms middle-size, large and gigantic icings and also seasonal underground ice of the injection-segregational origin. According to the investigation results in the BAM zone the latter prevail over 40-80 % of the area of icing fields, its mean depth being 0.3-0.5 m (maximum to 2.0-2.5 m) and its volume making 15-45 % of the volume of ground-water icings. That means that it plays an important role in the formation of the water balance and water resources of the cryolithic zone. The same also applies to the so-called »condensation« ice that forms in spring in the layer of coarse detritus (stone streams) on the slopes and peaks of not very high bald mountains. Thus, the second main problem of further investigations in the field of river hydrology of the cryolithic zone is the study of the mechanism of the formation during winter and destruction during the warm period of the cryogenic water bodies, *i.e.* the study of the elements of seasonal glaciation, analysis of the processes of localization of pressure and non-pressure streams in the river valleys and on the slopes, the study of ice formation proper, and also of the accompanying events and processes related to the hydrological regime of rivers.

The third main task is to study regional and global laws governing the distribution of certain components of seasonal glaciation of the cryolithic zone on the basis of catalogues, inventories, etc. that are prepared with the help of ground observational techniques and remote sensing. The U.S.S.R. has accumulated such experience in the North-East and in the BAM zone (Katalog naledei etc. 1980, 1981, 1982). Under the ideal conditions there should be special data banks that would help to improve and realize the programme of monitoring of the cryogenic formations as the indicators of the natural and anthropogenic climate changes, of hydrogeological conditions of the permafrost zone, of surface and ground water resources, of the conditions for the construction and use of various projects. For the solution of the above problems it is necessary to improve the old methods and to develop new techniques for mapping the parameters of ice formations at different levels of generalization.

The fourth main task is related to the study of the hydrological role of the depth of seasonal freezing and thawing of ground. This is one of poorly investigated problems. The results available of field investigations (Vasilenko and Khersonsky 1978; Cane 1981; Gieck and Kane 1986; Price and Gibbon 1987; Roulet and Woo 1988; Slaughter *et al.* 1983; Veiletti and Thomas 1979 and others) are still inadequate for the elaboration of consistent scientific concepts and for the development of methods for the estimation of streamflow parameters of the cryolithic zone.

Such phase transformations as evaporation, condensation and sublimation and their role in the water balance of river basins, their influence on stream and ground flows should also be studied very soon. It is quite probable that under the conditions of the severe climate and permafrost they play quite an important role.

The above findings should be discussed against the background of the general insufficient knowledge of many traditional problems of hydrology (Burges 1986). Moreover, some hydrologists point out the coming crisis in the theoretical hydrology since the laws and principles that are used give good results in laboratory experiments but prove to be useless in solving the basic hydrologic problems at the macrolevel (Beven 1987). In view of the above they suggest various ways: a better agreement between the theory and observation results, development of a physically based explanation of the results of the statistical analysis of time and space random processes, combination of deterministic and statistical methods of analysis and description of hydrologic events and processes (Yevjevich 1987); the use of the maximum enthropy principle (Singh and Rajagopal 1987), spatial integration and the prediction of the uncertainty (Beven 1987), theory of systems (Kundzewicz 1987), etc. For the cryolithic zone it would be necessary to combine these conceptional ways of hydrology development and the above discussed peculiarities of water resources and river regime formation.

Conclusion

Specific natural conditions governing the formation of water resources and hydrological regime of rivers in the cryolithic zone require special methods for their investigation and scientific generalization of the observational data. Some basic results outlined here represent the initial stage of such special investigations. Many aspects of the specific conditions, however, are very poorly studied and there is a relatively broad knowledge only of some of them. Inadequate amount of available information due to the sparse network of hydrological observational stations impede the development of reliable design hydrological techniques for practical purposes. The above considerations and high cost of observations in poorly inhabited and hard-to-access regions with severe climate require co-operative scientific and practical efforts of specialists on the international level. The need for such co-operation is justified not only by the economic factors, it is also validated by the existence of certain common temporal and spatial laws governing the formation of water balance components of river basins, cryogenic water bodies and characteristics of surface and ground-water resources in the cryolithic zone. The latter proposition the author of the present review intends to highlight in future specialized papers.

References

Beven, K. (1987) Towards a new paradigm in hydrology; IAHS Publ., No. 164, pp. 393-403.

Burges, S. I. (1986) Trends and directions in hydrology, *Water Resources Res., Vol. 22,* No. 9, Supl., pp. 1-5.

Cane, D. L. (1981) Physical mechanics of aufeis growth, *Canadian Journal of Civil Engineers, Vol. 8,* No 2, pp. 186-195.

Chacho, E. F., and Bredthauer, S. (1983) Runoff from small subarctic watershed, Alaska, Permafrost, 4th Int. Conf. Proc., July 17-22, pp. 115-120.

Gieck, R. E., and Kane, D. L. (1986) Hydrology of two subarctic watersheds, Proc. Symp.: Gold Red. Hydrol., Fairbanks, July, 1986, Bethesda, Md. pp. 283-291.

Herrmann, A., Koll, I., Leibundgut, Ch., and Maloszewski, P. (1986) Anwerdung von Tracertechniken zur Erfassung des Wasserumsatres in kleinen Einzugsgebienten, *Dtasch. gewasserk. Mitt., Vol. 30,* No. 4, pp. 85-93.

Herrman, A., Martinec, J., and Stickler W. (1979) Study of snowmelt – runoff components using measurements. Symposium on the Modelling of Snow Cover, Hannover, New Hampshire, pp. 288-296.

Herrman A., and Stichler, W. (1980) Groundwater-runoff relationships, *Catena, Vol. 7,* No. 2-3, pp. 251-263.

Hooper, R. P., and Shofmaker, Ch. A. (1986) A comparison of chemical and isotopic hydrograph separation, *Water Resour. Res., Vol. 22,* No. 10, pp. 1444-1454.

Ivanov, A. V. (1983) Gidrokhimicheskie protsessy pri naledoobrazovanii (Hydrochemical processes during aufeis formation). Vladivostok. Izd-vo DVO AN SSSR, 108 p.

Izuchenie naledei. Metodicheskoie posobie (Investigation of icings. Textbook of methodics) (1984) Pod red. B. L. Sokolova, L. Gidrometeoizdat, 156 p.

Katalog naledei zony BAM (Catalogue of icings in the BAM zone) (1980) L. Gidrometeoizdat, vyp. 1, Naledi verkhnei chasti basseina r. Chary (Icings of the upstream part of the Chara basin), 63 p.; (1981) vyp. 2, Naledi basseina r. Mui (Icings of the Mui basin), 84 p.; (1982) vyp. 3, Naledi basseina r. Verkhnei Angary (Icings of the Upper Angara basin), 96 p.

Kimura, Sh. (1986) Horedoboku siendse hokoku, Bull. Nat. Res. Inst. Agr. Eng., No. 25, pp. 1-91.

Kobayashi, D. (1985) Separation of the snowmelt hydrographs by stream temperatures, *J. Hydrol., Vol. 76,* No. 1-2, pp. 155-162.

Kobayashi D. (1986) Separation of snowmelt hydrograph by stream conductance, *J. Hydrol, Vol. 84,* No. 1-2, pp. 157-165.

Kolotaiev, V. N. (1988) Vodoobmen rek i basseinov podzemnykh vod v raionakh mnoglotetnei merzloty (Water exchange of rivers and ground water basins in the permafrost regions), Trudy V. Vsesoiuznogo gidrologicheskogo siezda, Tom 2, Vodnye resursy i vodny balans, L. Gidrometeoizdat, pp. 379-386.

Krenke, A. N. (1982) Massoobmen v lednikovykh sistemakh na territorii SSSR (Mass exchange in glacial systems within the USSR area), L. Gidrometeoizdat, 288 p.

Kundzewicz, Z. (1987) On the input of system science ot hydrology, IAHS Publ., No. 164, pp. 331-339.

Kuusisto, E. (1982) The true origin of runoff? *Geophysica, Vol. 19,* No. 1, pp. 47-53.

Martinec, J., Oeschger, H., Schotterer, U., and Siegenthaler, U. (1982) Snowmelt and ground water storage in an Alpine basin, IAHS Publ., No. 138, pp. 169-175.

Melnikov, P. I., Voropaiev, G. V., and Sharbatyan, A. A. (1984) Kriosfera kak vodoobmennaya sistema (Cryosphere as a water exchange system), Doklady AN SSSR, t. 279, No. 3, pp. 587-590.

Noveishaya tektonika i formirovanie mnogoletnemerzlykh porod i podzemnykh vod (Recent tectonics and the formation of permafrost rocks and ground water) (1975) Nauka, 124 p.

Prakticheskie recomendatsii po raschetu gidrologicheskikh kharakteristik v zone khozaistvennogo osvoievia BAMa (Practical recommendations for computing hydrological characteristics in the BAM economic development zone) (1986) L., gidrometeoizdat, 109 p.

Price, J. S., and Fitzgibbon, J. E. (1987) Groundwater storage – streamflow relations during winter in a subarctic wetland Saskatchevan, *Can. J. Earth Sci., Vol. 24,* No. 10., pp. 2074-2081.

Rodhe, A. (1981) Spring flood. Meltwater or Ground water? *Nordic Hydrology, Vol. 12,* No. 1, pp. 31-30.

Rodhe, A. (1983) Groundwater contribution to stream in Swedish forested till soil as estimated by 0^{18} – Isotope Hydrology. Proceedings of Symposium, Vienna, pp. 55-66.

Romanovsky, N. N. (1983) Podzemnyie vody kriolitozony (Ground water of the cryolithic zone). Izd-vo Moskovskogo universiteta, 232 p.

Roulet, W., and Woo, M. K. (1988) Runoff generation in a low Arctic drainage basin, *J. Hydrol, Vol. 101,* No. 1-4, pp. 213-226.

Singh, V. P., and Rajagopal, A. K. (1987) Some recent advances in the application of the principle of maximum entropy (POME) in hydrology, IAHS Publ., No. 164. pp. 353-364.

Slaughter, C. W., Hilgert, J. W., and Culp, E. H. (1983) Summer streamflow and sediment yield from discontinous permafrost head-waters catchments – Permafrost, 4th Int. Conf. Proc., July 17-22, pp. 1172-1177.

Snischenko, D. V. (1984) Nalednaya mnogorukavnost kak kharakternyi tip ruslovogo protsesse na rekakh zony Bama (Braided rivers in aufeis areas as a typical river bed process in the BAM zone), *Trudy GGI, vyp. 299,* pp. 59-63.

Sokolov, B. L. (1986) Stokoformiruyuschaya rol naledei (Runoff formation role of icings). Vodnye resursy, No. 1, pp. 3-14.

Sokolov, B. L., and Liubimov, G. A. (1986) Leyanoi pokrov i zimnii stok rek vostochnoi chasti zony BAMa (Ice cover and winter streamflow in the eastern part of the BAM zone), *Trudy GGI, vyp. 312,* pp. 11-33.

Sokolov, B. L., and Sarkisyan, V. O. (1981) Podzemnoie pitanie gornykh rek (metody kolichestvennoi otsenki) (Ground water feeding of mountain rivers (methods of quantitative assessment)), Gidrometeoizdat, 240 p.

Tiutiunova, F. I., and Tiutiunov, I. A. (1988) Kriogennyie polya napryazhenia v sisteme podzemnyie vody – merzlyie porody (Cryogenic stress fields in the groundwater – permafrost rock system). Tesisy dokladov Vesesoiuzn. sovesch. po podz. vodam Vostoka SSSR (XII soveschanie po podz. vodam Sibiri i Dalnego Vostoka). – Irkutsk – Yuzhno-Sakhalinsk, pp. 84-85.

Tolstikhin, O. N. (1974) Naledi i podzemnyie vody Severo-Vostoka SSSR (Icings and

groundwater of the North-East of the USSR). Novosibirsk, Nauka (Sibirskoie Otdelenie), 164 p.
Vasilenko, N. G., and Khersonsky, E. S. (1978) O koeffitsientakh pavodochnogo stoka rek tsentralnogo uchastka BAMa (On the coefficients of flood runoff of rivers in the BAM central area), *Trudy GGI, vyp. 254,* pp. 42-53.
Veiletti, J., and Thomas, R. (1979) Icings and seepage in frozen glaciofluvial deposits, District of Keewatin, N. W. T. – *Canadian Geotechnical Journal, Vol. 16,* No. 4, pp. 789-798.
Yevjevich, V. (1987) Some reflections on the the future of hydrology. – IAHS Publ., No. 164, pp. 405-414.

First received: 10 August, 1990
Revised version received: 23 May, 1991
Accepted: 12 June, 1991

Address:
State Hydrological Institute,
2 Linija 23,
St. Petersburg 199053,
U.S.S.R.