LONGTERM FORECASTING OF SNOWMELT RUNOFF

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Summary

The striking special feature of the hydrological condition of rivers in a moderate and cold climate is a spring flood – the yearly repeating long rise in river water levels, caused by snow melting and by precipitation in the period of snow melting. Calculations and forecasts of the characteristics of spring floods are necessary for planning mitigation works to decrease the losses from these floods. It is also a basis for the design and operation of water management systems. In this article the principles of long-term forecasting of the characteristics of runoff and maximum water levels of spring floods are presented. The common form of the physical-statistical relations of spring runoff and quantities of snow melt and rain water which enter the drainage basin, the autumnal moistenings and also the indices of soil freezing of the river basin is

discussed. The influence of the special characteristics of landscape on the form of these relations is shown. The questions of the calculation of capacitive detention, evaporation, water absorption into the soil and the melting of frozen soil in the hydrological simulation model and the forecasting of the characteristics of spring floods are discussed.

1. Background Information

Snowmelt flooding is an annual rise of water levels on the rivers, caused by snow melting and precipitation during the period of spring thaws. It is typically found both in moderate and the cold climate. In Canada, in Alaska, in the mountain regions of the West USA, in the mountains the Sierra Nevada in California, in the northern regions of USA, snow forms a the significant and some times the predominant source of river supply. Snow flood is a characteristic feature of the hydrological condition of Russian rivers. It’s a factor of utmost importance to be taking into account when planning the economic use of the available water resources and this has lead to the increased interest in its study and, especially of its forecasting.

In the northern hemisphere the date of the beginning of spring flood, as it moves from the south to the north, varies from March to April. The duration of the spring flood, may be less than one month for the small rivers, but increases to three to four months for the big rivers. The longest duration of flooding recorded, from April to November is found in the river plains of river Konda (West Siberia, Russia). This river is characterized by a low swampy drainage basin and the exceptionally extensive submerged floodlands, which accumulates vast quantities of water. Along the mountain rivers, whose basins stretch from the low-altitude to the high-altitude mountain zones, the duration of flooding up to seven months is connected with the non simultaneous snow and ice melting occurring in the different high-altitude zones.

It is necessary to have long-term forecasts of the elements of snow flood in order to give early warning of possible flooding to the population, to administrative bodies and industrial and agricultural enterprises These forecasts are equally necessary for plants producing hydroelectric energy, for the planning of the business of water transport on temporarily navigable rivers and for those employed in the water industry itself: for the optimum regulation of runoff by reservoirs, for operational provisions of water-intake and other water-engineering constructions.

The extremely high spring water and floods connected with this are caused by the combination of the following conditions: rainy autumn, severe winter, large snow accumulation, late cold spring (or early spring but very simultaneous) with the heavy precipitation, the sudden rapid onset of warm weather.

On the rivers, which run in the sub-meridian direction (Lena, Yenisey, Ob, etc.), as a result of an earlier onset of spring weather in the south, the wave of seasonal flooding is moved to the north and breaks up the stable ice cover. As a result, the probability of flooding, caused by the formation of the ice jams, is increased. Frequently the ice jams are formed in one and the same stretch of rivers, as a result of the geomorphologic special features of the structure of the river bed, such as the presence of sharp river bends, islands, narrows, and rapids.

The degree of the influence exerted by each factor listed above varies across the territory and at different points of time. For example, in some cases floods are mainly connected with the accumulation of extremely high water equivalent of snow cover during the long winter (with the relatively small influence of other factors). In other cases the determining influence is exerted by precipitation of heavy rain during the period of snow-melt, or extraordinarily high autumn moistening of the river basins, which can be aggravated by conditions of deep soil freezing, that increase the soil's permeability. Finally, if factors favorable to high water content and to the formation of ice jams are combined, floods on catastrophic scale occur. According to the frequency (probability of exceeding) of maximum water level the following subdivisions are made: with frequency smaller than 0.1% - historical flooding, with a frequency from 0.1 to 1% - extreme flooding, severe flooding — with a frequency from 1% to 10%; heavy flooding — with a frequency from 10 to 25%, the appreciable high flooding – with a frequency from 25 to 40%, average flooding – with a frequency from 40 to 60% and the low level flooding – with the frequency higher than 60%.

The main source of the supply of rivers during the spring flood is the water which is formed in the process of melting of the water equivalent of the snow cover (*S*), accumulated during the cold season of the year. The precipitation (*x*), which falls in the period of snow melting, is usually several times less than the water equivalent of the snow cover. The conditions of the runoff of this precipitation are almost identical to the conditions of the runoff of melt water. To distinguish the runoff of this precipitation from the snow melt runoff is difficult; therefore we summarize these forms of runoff jointly and propose to designate as the runoff of melt water (Y, mm).

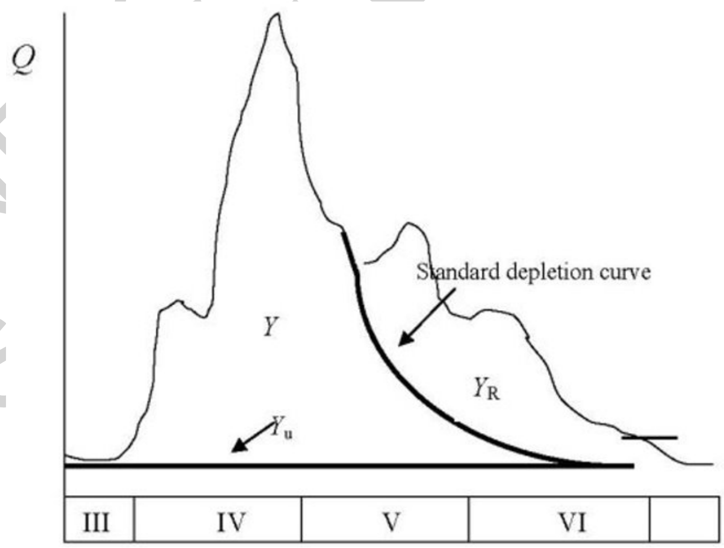

Figure 1. The partitioning of the hydrograph of spring flooding according to the type of water supply (Q – water discharges, other symbols are mentioned in the text)

The precipitation, which falls on a rapidly drying surface of a river catchment after the thawing of the snow, infiltrates the soil and is normally consumed by evaporation.

However, in years of substantial rain, it causes an additional rise of water discharge during the period when flooding is decreasing in the forest zones. Rain runoff in the period of receding floods is determined by the partitioning of the hydrograph with the use of standard depletion curve (Figure 1).

Runoff resulting from the underground water supply of river is determined by the value of the water discharge corresponding to the underground water supply of river at the end of winter. It takes into consideration the duration of spring flooding.

As a result of partitioning of the hydrograph of spring runoff according to the type of water supply of rivers (Figure 1), the three components of summary runoff in the period of spring flooding are determined: 1) runoff of snowmelt water Y (it is formed as a result of snow melt and the income of precipitation in this period), 2) rain runoff Y_R (it is formed by the precipitation which falls after the thawing of the snow) and 3) underground runoff Y_u.

It is possible to pick out the three groups of basic methods of long-term forecast of the runoff of snow flood: 1) statistical methods, 2) physical – statistical water balance methods and 3) methods of mathematical modeling of the process of build up of runoff.

2. Statistical Methods Used in Forecast

The statistical methods of forecasting use pairing or multiply correlation of snow melt runoff Y with the factors (predictors) which determine this runoff, for example, the water equivalent of snow cover, the indices of autumn moistening, the depth of soil freezing and others (Quick, 1965; Popov, 1963). The different methods of selection ("sifting") of predictors are used and also the more complex methods of computing of runoff field are applied according to the prescribed field of predictors are used.

Predictors are determined according to the data provided by point hydrometeorological observations. They reflect variables from year to year governing the condition of forming of runoff (water equivalent of snow cover, the autumnal moistening of the catchments, the depth of the soil freezing, and so on). The appropriateness of any predictor depends not on its particular correspondence to measurements at a particular point, but on how well it reflects general conditions on the river basin. Predictors, in fact, emerge as indices, which, changing in a way similar to the full value of the examined value, are capable of reflecting its influence on the process being investigated.

Statistical methods are more frequently adapted for developing of the forecasts of spring runoff of mountain rivers. In the mountains a large territorial variability of the characteristics of the water balance is observed. The reliability of hydrometeorological information in these areas is insufficient, which is not helpful for the application of the water balance approach to the long-term forecasting of snow floods.

3. The Physical-statistical Water Balance Method

3.1. Equation for Snowmelt Runoff

The method of physical- statistical water balance relies basically on the water balance equation, written in the form of equations of runoff for capacitive or infiltration – capacitive types of the water absorption by catchment (Popov, 1963). In case of the capacitive type of water absorption, the percolation of water in the soil occurs practically with the same speed, with which it enters the surface of soil. The runoff becomes possible only from those areas of the basin, in which the water-holding capacity has been completely filled. The distribution of the depth of filling of water-holding capacity (h) over the area of the catchment is specified with the function $\varphi(h)$.

$$\varphi(h) = \frac{A_a(h)}{A - A_0}, \qquad (1)$$

where $A_a(h)$ – the active area of the catchment, within whose boundaries the water holding capacity is completely filled with the emergence of water depth h up to the surface of the basin; A – area of basin; A_0 – the value of the blind drainage area in the basin, within whose boundaries the water holding capacity is very large and is never completely filled up. A striking examples of this are endorheic lakes with their areas of basins, or the territories, whose surface is covered with thick layers of sandy sediments, completely transforming the surface runoff into underground runoff, which reaches the river beds and streams immediately after the end of the spring flood.

Let us presume that the quantity of snow melt water (S_t) and the depth of the watery precipitation ($x_{t\,t}$) for the period from the beginning of the snow melt till the moment t are known. The total water depth $H_t = S_t + x_t$ will arrives during the period under investigation for the filling of water holding capacity. Let the water depth H_t increase by the value dh. In that case the volume of runoff dW , caused by the coming of the water depth dh, is equal to

$$dW_{(h=H_t)} = A_a(H_t)dh = (A - A_0)\varphi(H_t)dh. \qquad (2)$$

Volume of runoff, cause by the coming of all water depth H_t , is

$$W(H_t) = \int_0^{H_t} dW(h) = (A - A_0)\int_0^{H_t} \varphi(h)dh, \qquad (3)$$

and depth of runoff

$$Y(H_t) = \frac{W(H_t)}{A} = \frac{A - A_0}{A}\int_0^{H_t} \varphi(h)dh, \qquad (4)$$

or

$$Y(H_t) = (1-w)\int_0^{H_t} \varphi(h)dh \,, \qquad (5)$$

where $w = A_0 / A$ – the part of constant blind drainage area of the river basin.

In practice the several suitable distribution of $\varphi(h)$ are used. Here is one of them:

$$\varphi(h) = 1 - \exp\left(-\frac{h}{p_{\max}}\right), \qquad (6)$$

where $P_{\max}$ – the total water holding capacity of river basin (maximum water losses), in mm of water depth.

The second type of water absorption is the infiltration type. In this case the intensity of percolation of water is less then the intensity of its coming to the soil surface. The runoff is formed due to the excess of the coming water depth above the depth of percolation.

In the nature, the prevailing type is the infiltration-capacity type of water absorption: overland runoff is possible after the filling of comparatively large interstices of soil and locked depressions of the relief, if the intensity of water feed exceeds the speed of the percolation of water into the unfilled fine-porous capacity of the ground (analogy with a perforated bucket). From the capacitive model of runoff (5) it is easy to switch over to the more common infiltration-capacitive model, if we take into account the water infiltration in the dense soil layer I_t in the formula of the depth of the filling of capacity H_t , that is $H_t = S_t + x_t - I_t$,

$$Y(H_t) = (1-w)\int_0^{H_t = S_t + x_t - I_t} \varphi(h)dh \qquad (7)$$

It should be noted, that in practice for the description of the forming of the snow melt runoff the capacity model is the most frequently used model (5). Obviously, in this case the parameter of runoff losses will already characterize the total maximum losses to infiltration and capacity absorption.

The fact is that the intensity of snow melting rarely exceeds 0.2 – 0.3 mm/min; therefore the whole of the surfacing water is completely percolated into the soil, until the spare capacity of its upper horizons is almost completely filled up with the water. The alluvial soil horizons most frequently have substantially lower water permeability, and when frozen they become an aquiclude, on which the groundwater formed is perched. An aquifuge in the soil can also be formed in case, when the percolated melt water freezes at a certain depth due to the persistence of freezing conditions at this level (Komarov and Makarova, 1972; Popov, 1963).

The appearance of water perched on the ground surface (Figure 2) is the tell-tale sign of the filling of water-holding capacity. In this case surface runoff is formed on the slopes.

A similar mechanism in the forming of runoff is observed in regions where there are expanses of loamy and clayey soils. When these water-permeated layers are present on the surface rather than the fragmental material (talus, boulder-pebble sediments, rocky layers of soil), which is characteristic of mountain districts, a substantial part of the melt waters quite rapidly reaches the channels and rivers following the underground route. These waters, percolating through the relative aquicludes, join the waters lying at a sufficient depth underground, which provide the essential underground feed for the rivers.

The calculated dependence of the depth of the runoff of the spring flood from the water income to the surface of basin ($S+x$) during the period of snow melting can be obtained by integrating formula (5), after substituting into it the acceptable expression of the function of the territorial distribution of the depth of filling of the water-holding capacity $\varphi(h)$. If this function has an exponential form (see (6)), then

$$Y = (1-w)(S + x - P_{\max} \tanh\frac{S+x}{P_{\max}}) \qquad (8)$$

Figure 2. The results of perched groundwater, risen to the surface of the ground in a deciduous forest during the final period of snow melting. 2 May 1965, West Siberia, southern taiga (photo by Burakov D.A.)

if it has an hyperbolical distribution, then (Popov, 1963)

$$Y = (1-\omega)\left[S + x - \left(1 - e^{-\frac{S+x}{P_{\max}}}\right)\right], \qquad (9)$$

where P_{max} – as it was before, the total water holding capacity of the basin, w – the part of constant blind drainage area of the river basin, tanh – the function of the hyperbolic tangent.

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Biographical Sketch

Burakov Dmitry Anatolievich graduated with honors from the Geology-Geographical Faculty (Section of Hydrology) at Tomsk State University in 1962. He obtained his Candidate of Science Degree (equivalent to Ph.D.) from Geographical Science in 1967 at the Hydrometeorological Centre of Russia (Moscow) and his Doctor Degree in 1980 at Moscow State University.

From 1962 till 1987 Burakov Dmitry Anatolievich had been working as an assistant, senior lecturer and later on as professor and chief of the section of Hydrology at Tomsk State University. Since 1987 he has held the position of Director of the Krasnoyarsk Branch of the Siberian Hydrometeorological Research Institute. Currently he is Chief of Section of Melioration and Hydrometeorology of Krasnoyarsk State Agrarian University and Main Hydrologist of the Krasnoyarsk Centre of Hydrometeorology and Environment Monitoring.

His research interests are in the field of hydrology and hydrological forecasting. In 1965 -1972 Burakov Dmitry A. organized and conducted a series of studies of water balance research of the formation of spring runoff on the Vasyugans Swampy Massif (region) of West Siberia. Such research was unique for this territory. At Tomsk University, in 1983 – 1986, he had presided and conducted studies of hydrology of the Altai glaciers. Methods of forecasting maximum and daily water levels and water inflow into the reservoirs of Yenisey and Ob hydro power stations were developed under his management and are currently being used in practice of operational forecasting in the Siberian Departments of the Hydrometeorological Service of Russia. He has published more than 100 scientific publications. His basic works are devoted to the forecasts of the characteristics of spring floods of Siberia rivers. The results of the studies of Burakov Dmitry A. are included in several book and lecture notes. His scientific works are published in the central journals of the Russian Academy of Sciences, Hydrometeorological Service of Russia, Tomsk and other Universities.