RUNOFF GENERATION AND STORAGE IN WATERSHED

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Contents

Summary

Runoff generation process includes a lot of partial processes connected with the common phenomenon of water transfer from the land surface back into the ocean. The analysis of this phenomenon is characterized by two distinct aspects: water balance (with focus on runoff “losses”) and temporal behavior (connected with redistribution of runoff in time).

The concept of the dynamic state of a river basin is exceptionally important. The

integral state characteristic is solid and liquid water amount in the basin at every given time moment. The sequence of points of the calendar in the system of coordinates: discharge in the point of concentration - water accumulation in the watershed - is a phase trajectory characterizing the behavior of the river basin as a system transforming precipitation into runoff.

The concept of runoff elements is important too. The system of the latter determines the relation between the volume of moving water in the basin and the intensity of its inflow into the channel system; in other words it determines the form of water movement in the basin. Runoff elements - surface, soil and underground are characterized by various extensions in the time of their response to the water inflow. If for the surface runoff these are minutes, for the underground one of the low depths - centuries and thousand of years.

Runoff formation conditions are very different in various geographical zones and landscapes.

1. Introduction

Runoff generation is a complex multi-factor process. It consists of a large number of interconnected partial processes localized within the boundaries of a river basin. The latter absorbs, redistributes, accumulates, disperses and directs flows of substance (precipitation, runoff, evaporation) and energy (radiation and convective heat exchange), coming from outside and leaving from there. Therefore, by the process of runoff formation, one should understand not only a direct appearance of water able to flow down in the future, but the whole complex of a definite group of partial processes which together form the land part of the hydrologic cycle (water circulation in nature).

Let us imagine a real river basin with its relief and landscapes, being watered by rain and covered with snow, absorbing the flows of solar radiation and contacting with the air ocean with its winds, clouds, warmth and cold. Interaction takes place between meteorological fields and the underlying surface, which is presented as a sort of mosaic, assembled by the discrete landscape formations.

A river basin with its orography, rocks, underground waters, soil and vegetation cover, hydrographic system, water bodies and objects created by humans concerning the water getting into its boundaries carries out a double function: on the one hand it together with weather determines the relationship between precipitation, runoff and evaporation (water balance), on the other hand - it realizes redistribution of runoff in time (transformation).

Runoff in natural way is usually subdivided into melted and pluvial. Formation of the latter is relatively more rapid and a roughly proceeding process. Of particular importance is the fact that the both kinds of runoff interact and complement each other. But it is only in nature. In the traditional hydrology they are alas separated from the beginning to the end.

One should distinguish the other two kinds of runoff - surface and underground runoff. The latter, in its turn, can be subdivided into several categories depending on the depth of melted and pluvial waters penetrating into the soil and rock mass (layering of underground runoff), and therefore, by the degree of their regulation.

The problem of the relationship of surface and groundwater types of runoff formation is important. The first known runoff theories based on direct observations are connected with the postulate about surface flow. The departures from the habitual rule were usually regarded as the exceptional. Nearly at the same time the rejection of the very possibility of flood formation by underground runoff became popular. The attempt to prove the insignificance of maximal modulus of underground runoff was based on the comparison of the filtration coefficients with the velocities of surface runoff. Actually, at the places of rapid underground runoff formation a thick underground drain system, where velocities of flow of pluvial and melted waters can be only in some times lower than surface ones, is developed.
Then the pendulum swung back and now one can meet the statements not only in hydrological but even in the literature on overlapping disciplines about sufficiently trivial role of the classical surface runoff.

Two kinds of flood runoff correspond to the surface and underground types of runoff generation. Floods formed by surface runoff are characterized by significantly higher maximal modulii of runoff, short duration of passing, quick response to rain intensity change, which becomes particularly noticeable with the decrease of a watershed area.

Pluvial and melted waters infiltrating through the soil-debris mass and sooner or later reaching the channel belong to various categories of underground runoff. The ways and the time of migration of such waters depend on soil and rock structure and can be widely different. If the time from the beginning of rainfall on the watershed surface till the moment of flow into the channel system is not so great for a separate flood wave to lose its individuality; one can speak about a rapid underground runoff. It is always significantly more regulated than the surface runoff and the definition "rapid" is made to emphasize its difference from the veritable underground runoff. A precise boundary between all three kinds of runoff is obviously absent.

Both kinds of flood flow (surface and rapid groundwater) are widely observed in mountains and plains and they generally participate together in feeding the channel system in every river basin.

Below, partial processes forming a complex of the phenomena called "runoff generation" are listed:

1) Processes and phenomena on a basin surface

- Precipitation (rain or snow). Their phase state determines the difference in water fate during the initial period of the history of its stay within the river basin
- Heat energy exchange of the basin surface with the atmosphere and space
- Interception of rainfall drops by vegetation cover. Snow retained on the crowns of trees especially of coniferous ones is a splendid sight but hydrologically it is a temporary phenomenon: very soon it is thrown down by the sun and wind
- Snow cover formation. This complex process is reflected by changing of its four

basic characteristics - depth, density, relationship of “liquid” and “solid” water amounts and temperature
- Snowmelt and snow cover destruction
- Water yield from snow
- Infiltration and formation of surface runoff of water and chemical substances which are jointly among the most important partial processes. Concerning the fate of water getting to the watershed’s surface it appears as a process - divisor
- Storage of a part of a surface runoff formation in drainless depressions of slope micro-relief
- Soil erosion

2) Processes and phenomena in soil or near-surface layer of rock

- Heat energy dynamics
- Dynamics of soil waters is one of the most complicated processes leading to retention of water in a soil and regolith layer, its loss by evaporation and underground runoff formation
- Evaporation
- Formation of soil and underground flow of water and chemical substances

3) Runoff transformation in runoff elements
4) Channel runoff transformation - redistribution of water getting into the hydrographic system of the river basin
5) Runoff in the point of concentration is a result of interaction of the considered complex of processes.

2. Processes and Phenomena on the Watershed Surface

2.1. Precipitation

The moment of contact of snowflakes or rain drops with the earth surface signifies the beginning of a whole system of the processes of the land part of the hydrologic cycle (see *Precipitation*). It is thus important to know - whether snow or rain falls. It is preferable to formalize and to simplify this estimation as far as possible. In this case the division of precipitation into liquid and solid forms is usually carried out by suitable critical air temperature (temperature threshold) which can be defined as corresponding to the situation when the appearance of water drops and snowflakes is equally likely. Often $+2\,^{o}C$ is accepted as such critical temperature.

The information on water equivalent of snow obtained with the help of precipitation gauges at the meteorological stations is not authentic. Therefore making corrections to the measured solid precipitation is compulsory. “A failure to measure” the falling snow is still a reality which all those hydrologists who in total precipitation see not the indices of humidification, suitable only in regressional models but water balance elements, should take into consideration. One of the most eloquent examples of such underconsideration is given by the observations at the high-mountain meteorological station the Anzob pass (3349 m) in Tadjikistan where not more than 1/3 of the real norm is measured.

The intensity of precipitation is of great hydrological importance. Its role is particularly exceptional in the processes of surface runoff formation (rain storm intensity) and appearance of snow avalanches (snowfall intensity). The observation data on precipitation intensity are always deficient and rarely complete. This defect is only slightly compensated by the information on precipitation duration which, together with the depth can characterize the average intensity for the separate rains and snowfalls. Such situation introduces some vagueness into the information on precipitation. It should be constantly taken into consideration when solving practical problems of hydrology.

2.2. Thermal Energy Exchange of the Basin Surface with the Atmosphere and Outer Space

The earth surface receives thermal energy basically directly from the sun and as a result of turbulent heat exchange with the atmosphere. Thermal energy influencing physical and particularly phase state of water thus determines many peculiarities of the land part of the hydrologic cycle.

Comprehensively the situation is reflected by the thermal balance equation. However, not every meteorological station can give all the necessary information for this purpose. In many practical cases the effective temperature is a very good index of energy influence of the sun and the atmosphere: $\eta_{ef} = \eta + \varepsilon S$, where η is usual temperature, S - income of direct solar radiation with corrections on albedo, orographical shading, cloudiness and other local conditions, ε is empirical coefficient being selected from the condition of minimization of divergences of calculated and observed variables at the output of the models, at the input of which η_{ef} appears. The value S may always be calculated for every day and hour depending on latitude and altitude, aspect and inclination angle of a plot and by inserting all the necessary corrections.

2.3. Precipitation Interception by Vegetation Cover

When following rain the sun breaks through, nobody can be indifferent to the play of light in myriads of water drops in the tangle of brunches, on the leaves, pine-needles, and grass. However, it is not only beauty but it is a powerful mechanism of moisture dispersion back into the atmosphere, a sort of evaporation outburst...

Precipitation interception by vegetation cover is an important hydro-meteorological process that is usually underestimated.

Slight rain is almost entirely retained by vegetation. When precipitation depth increases, relative area of moistened phytomass surface and the amount of pluvial water reaching the soil surface increase too. When precipitation is heavy almost all the surface which, as a matter of principle, can be moistened, turns out to be moistened and precipitation interception approaches the maximal water holding capacity of the given vegetation association. When supposing that the increment of moistened part of the specific phytomass surface corresponding to the precipitation depth increment diminishes proportionally to this surface, the following equation is obtained:

$$P = (P_M - H_V)\left[1 - exp\left(-\frac{H}{P_M}\right)\right] \qquad (1)$$

where P_M is interception capacity (maximal water holding capacity of vegetation cover), H_V is water depth in interception capacity, H is precipitation depth. Parameter P_M is subject to the systematization on the basis of distinguishing the landscapes within every natural zone.

2.4. Snow Cover Formation

Snow cover brings many troubles to a hydrologist as it is able to appear, disappear, and change its thickness and density. And one more hydro-meteorological misfortune is the fact that measurement of solid precipitation is imperfect; it is accompanied by uncertainty and errors and is conducted at inadmissibly sparse system of points, especially in mountains.

Snow cover is formed as a result of solid precipitation accumulation on their consecutive summation for the separate snowfalls. Therefore, snow accumulation regime entirely corresponds to the regime of its falling at least during the period of constant negative air temperature. Thaws disturb this regularity leading sometimes to the negative derivative of curve of snow cover thickness in time.

Snow-drift leading to a different degree of unevenness of snow cover depending on the character of meso- and micro-relief and landscape type is of a special importance in spatial snow redistribution (see *Snow and its Distribution*).

Apart from snow cover water storage solid phase density is its most important property. Density of fresh snow is determined by the air temperature and wind conditions first of all. Snowdrift exerts strong compressing influencing on the forming snow cover.

Snow compression with the passing time under its own weight over short time intervals is not significant but during winter months especially in the regions with abundant snowfalls this effect is noticeable. Faster snow subsidence of wet snow in comparison with dry is well known. The process of freezing of water contained in snow introduces corrections to the increase of snow cover solid phase density.

Such thermophysical properties as thermal capacity and heat conductivity are directly connected with snow density. Specific volumetric thermal capacity of dry snow is determined very easily:

$$c_s^* = \gamma_s^* p^* \qquad (2)$$

where γ_s^* is snow cover density (kg m^{-3}), p^* = 2090 J (kg ^{o}C)$^{-1}$ - specific mass thermal capacity of ice.

Sufficiently large set of empirical formulas for calculation of dry snow heat conductivity coefficient is known but almost all of them do not satisfy the natural boundary conditions. The following interpolation equation is suitable:

$$\lambda_{\mathrm{s}}^{*}=\left[1+\left(1-\frac{\gamma_{\mathrm{s}}^{*}}{\rho^{*}}\right)\exp(0.1\theta_{\mathrm{s}})\right]\left[2.2\left(\frac{\gamma_{\mathrm{s}}^{*}}{\rho^{*}}\right)^{2.5}+0.02\right],\quad \theta_{\mathrm{s}}\le 0^{0}\mathrm{C} \qquad (3)$$

where θ_s is snow cover temperature (^{o}C) and ρ^{*}=920 kg m^{-3} is ice density.

Evaporation from the snow cover surface is relatively little, on the average from 0.1 to 0.3 [mm (day)$^{-1}$], but it should be always taken into account as a factor influencing snow cover formation.

2.5. Snowmelt and Snow Cover Destruction

Spring heat flow from the atmosphere is almost entirely spent in the snow mass for heating and snowmelt. The latter does not come until snow temperature is 0^{o}C. As a matter of fact, melting can begin earlier but thawed water having appeared in the upper layers of snow cover percolates downwards and freezes again with heat given off as a result of which snow recrystallization and temperature profile alignment up to the entire isothermality when θ_s = 0^{o}C takes place. After that snowmelt begins.

The amount of snow melted during a day is determined by the thermal balance relationship but the easiest way is to suppose it to be proportional to the average daily positive air temperature. It is the only meteorological value being observed, information on which is always the most complete. Such a way of definition of day melting is very simple and reliable enough. But the attitude to it is very ambiguous and very often it is connected with the opportunities of hydrologists to overcome a temptation of accepting proportionality coefficient called snowmelt coefficient to be constant. It is usually done but its instability in time causes anxiety at once. Usually the influence of various kinds of factors explaining this instability is basically connected with the ignored impact of solar radiation having a precisely pronounced annual course. If one uses the effective temperature instead of the air temperature and introduces the relation of snowmelt coefficient and snow density, the depth of melting may be calculated more confidently:

$$\mathrm{h_m}=\zeta^{*}\frac{\gamma_{\mathrm{s}}^{*}}{\rho^{*}}(\eta+\mathrm{jR}) \qquad (4)$$

where ζ^{*} is coefficient of icemelt**,** mm (^{o}C day)$^{-1}$; η is average daily air temperature; *R* is calculated daily income of solar radiation, J (day)$^{-1}$; *j* is conditional constant (empirical coefficient), ^{o}C day J^{-1}.

Heat brought by rains and heat flow from the soil-ground layer also influence snowmelt process. Heat flow is not so great but its effect is long and therefore hydrologically significant. The situation changes when snow cover is on the permafrost.

As a result of snowmelt snow cover depth rapidly decreases. After all, only spots of snow are left ("particoloured" landscape) and then they disappear too.

2.6. Water Yield from Snow

During melting liquid water percolates into the snow cover stratum. The ratio of "liquid" and "solid" water depths β is a good index of snow water saturation. Some maximal water holding capacity $\beta_м$ is inherent to snow cover as well as to soil cover. Maximal water holding capacity takes place as a result of saturation of snow stratum with water and following flowing down of all its surpluses. The value $\beta_м$ decreases as snow recrystalization occurs and ice cores grow. On the average

$$\beta_{\mathrm{M}} = 0.15\frac{\rho_0}{\rho^*}\left(\frac{\rho^*}{\gamma_{\mathrm{s}}^*}-1\right) = 0.163\left(\frac{920}{\gamma_{\mathrm{s}}^*}-1\right) \qquad (5)$$

where ρ_0=1000 kg m^{-3} is water density.

Comparing the current value β with its critical value $\beta_м$ one can judge about snow readiness to water yield, i. e. to the process of running out of water from snow cover to the earth surface.

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Bibliography

Apollov B. A., Kalinin G. P., Komarov V. D. (1974). Course of Hydrological Forecasting [in Russian], 420 pp. Leningrad, USSR: Hydrometeoizdat. [There is a description of runoff formation processes used in hydrological forecasting in the book]

Budagovskiy A. I. (1981). Evaporation of Soil Waters. [in Russian] In: Nerpin S.V. (Ed.) Physics of Soil Waters, 13-95. Moscow, USSR: Nauka. [It presents a very deep description of one of the most important elements of hydrological cycle]

Gerrad A. J. (1981). Soils and Landforms. An Integration of Geomorphology and Pedology, pp. London - Boston - Sydney: George Allen and Unwin. [Interesting ideas of a non-hydrologist on runoff formation processes are presented in the book]

Herrman A. (Ed.) (1999). Experimental Hydrology with Reference to Hydrological processes in Small Research Basins. Proceedings of the International Workshop St. Petersburg - Valdai, Russia, 2-6 June, 1997, 170 pp. St. Petersburg, Russia: Hydrometeoizdat. [The results of recent experimental researches and their influence on methodology and theory of hydrology are available in the proceedings]

Journal of Hydrology (1988), vol. 100, 508 pp. [Very good goal-directed collection of papers devoted to Physical Processes in Hydrology, particularly to hillslope runoff processes, groundwater hydrology and hydrological perspective]

Kirkby M. J. (Ed.) (1978). Hillslope Hydrology, 389 pp. Chichester - New York - Brisbane - Toronto: John Wiley and Sons. [In this collective monograph runoff formation processes are described in more detail than in usual books on hydrology]

Komarov V. D. (1959). Spring Runoff of Plain Rivers of the European Part of USSR, Its Formation Conditions and Forecasting Methods [in Russian], 296 pp. Moscow, USSR: Hydrometeoizdat. [One of the most serious descriptions of spring flood formation processes that appeared in the middle of 20-th century]

Nazarov G. V. (1981). Hydrological Role of Soil [in Russian], 215 pp. Leningrad, USSR: Nauka. [A good traditional presentation of the role of soil cover in hydrological cycle; runoff formation processes are considered]

Subbotin A. I. (1966). Runoff of Water from Melt Snow and Rain (by Experimental Data) [in Russian]. 376 pp. Moscow, USSR: Hydrometeoizdat. [Very good for its timely attempt to generalize the experimental data on runoff formation]

Subbotin A. I., Dygalo V. S. (1991). Experimental Hydrological Research in Moskva River Basin [in Russian], 265 pp. Moscow, USSR: Hydrometeoizdat. [One of the best descriptions of long-term researches of runoff formation processes with reference to the particular object]

Biographical Sketch

Vinogradov Yury Borisovich was born on 7 December 1932, Samarkand, USSR and is Head of Laboratory, State Hydrological Institute, St. Petersburg, Russia.

Education:

- Central Asiatic State University, Tashkent, Geographer-Hydrologist,1950-1955
- Postgraduate Study, Uzbek SSR Academy of Sciences, Tashkent, 1955-1958
- Candidate of Technical Sciences, 1960
- Doctor of Technical Sciences, 1972
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Professional Experience:

- Institute of Water Problems and Hydraulic Engineering, Tashkent, USSR, 1958-1964
- Kazakh Research Hydrometeorological Institute, Alma-Ata, USSR, 1964-1978
- State Hydrological Institute, St. Petersburg, Russia, from 1978

Community Activities:

Chairman of Debris Flows Committee, Scientific Boards of the USSR Committee on Science and Technology, and of the Academy of Sciences on Engineering Geology and Hydrogeology, 1979-1991

Publications:

Papers and Monographs on Hydrological Mathematical Modeling, including:

- 1967. The Problem of Hydrology for Rainfall Floods at Small Watersheds of Central Asia and South Kazakhstan.
- 1977. Glacier Outburst Floods and Debris Flows
- 1980. Sketches about Debris Flows
- 1988. Mathematical Modeling of the Processes of Runoff Formation. Experience of the critical Analysis

Range of Interests:

Organized and conducted the expeditions on studying of runoff formation and debris flows in various mountain regions of the former USSR (1957-1991). In 1970-1977 he as the head of a group of specialists carried out a number of experiments on artificial reproduction of natural Debris Flows of high density (Zailiyskiy Alatau Range, near Alma-Ata).

At present Vinogradov is working on an important generalizing monograph, devoted to the original methods of mathematical modeling of runoff formation, its contamination and catastrophic hydrological phenomena, development of methods of hydrological calculations and predictions of the new generation, ecological understanding of hydrology, questions of interaction of physical and stochastic hydrology and in the whole to the problems of the necessary changes in approaches, conceptions and methods of fundamental hydrological science.