# HYDROLOGY OF SLOPING TERRAIN

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## Contents





## Summary

The hydrology of a sloping terrain is mainly mountain hydrology, i.e., it is a sphere of land hydrology being distinguished because of the determining influence of land inclination and altitude.

An inclination and a slope aspect connected with it render many-sided influence on runoff formation. First of all, the increase of land inclination causes an increase in the contact area of basin surface with the atmosphere which, in its turn, with the other conditions being equal, increases evaporation and intensifies heat exchange processes.

The difference in slope also determines a dispersion of solar radiation input to slopes with all the consequences following that. The increase in flow velocities, the reduction of the response time of runoff elements and the growth of erosion intensity are connected with the increase in inclination.

When inclinations are large there is a possibility of display of a number of specific hydrological phenomena, such as ice- or rock-falls and the following catastrophic outbursts of the natural dams which form, the outburst of mountain lakes and intraglacial water reservoirs, formation of debris flows of small and high density, rush of snow avalanches and display of landslide processes.

## 1. Introduction

Slopes are the main element of a hilly or mountain relief inevitably connected with such territory properties as absolute altitude and ruggedness. And hydrology of sloping terrain is mountain hydrology. The latter can be distinguished into a special sphere of land hydrology just because of the determining influence of inclination and altitude of the district. Mountain hydrology can be divided into two parts. The first of them concerns the peculiarities of runoff formation in mountain conditions, the second one deals with the hydrological processes developing almost extremely in the areas of great inclinations. District inclination finally determines the flow existence as such. And if inclinations are small, all the processes proceed slowly. With the increase in inclination, the situation changes. Thus, a display of the whole series of the specific natural phenomena is possible.

Speaking about inclination it is always necessary to know precisely which one among the trigonometric functions - sine or tangent - is meant. With small inclinations of the earth surface it hasn’t practical importance but with great inclinations it can lead to serious mistakes.

## 2. The Peculiarities of Runoff Formation in Mountain Conditions

Physics of processes of runoff formation both in mountains and on plains is the same. However, in mountain conditions all these processes are intensified to a greater extent and more prominently expressed. Relief without considering the direct influence on runoff through the district altitude, inclination and aspect of slopes renders an impact on the climatic conditions and landscapes which in their turn determine the size of runoff and its regime.

### 2.1. Spatial Interpolation of Meteorological Elements

The first thing a hydrology-analyst has to face in conditions of mountain country is a mottling of precipitation distribution which immediately entails a mosaic structure of soil-vegetation cover and heterogeneity of evaporation and runoff. Therefore, the problem of precipitation on the first sight being formally a meteorological one to a large extent acquires exceptional significance in hydrology (*see Precipitation*). Among so many important items concerning this problem, three basic questions are worth considering:

- about the necessity and conditional sufficiency of a number of meteorological stations and rain gauges and their selectivity (not always justified) in the way of an arrangement concerning macro- and meso-relief elements;
- about the errors of observations with the help of gauges and the necessity introduction of the essential corrections especially for solid precipitation blowing off;
- about spatial interpolation of precipitation.

The first question is connected with the sociological and economic aspects and should be taken into account as an inevitable fact which different countries have to consider by way of either understanding or reflecting. There are more closed high-mountainous meteorological stations in the world now than those again opened.

The second question is defined by the methodology of the introduction of corrections. But the really principled solution here is connected with the creation of gauges of new generation, though the ‘new life’ in hydro-meteorology in this case will begin not at once but only after many years of parallel work on the old and new equipment.

The third question is a subject of professional skill and enterprise of hydrologists and meteorologists. It is natural that the task of the successful interpolation in mountain conditions concerns not only precipitation but also the other meteorological elements.

During any hydrological analysis, computations and modeling reliable information on meteorological elements is always required. And the more detailed this information is, the better. Therefore, for hydrology the problem of spatial interpolation of meteorological elements has an essentially important meaning.

Two independent problems though having a certain generality differ as follows:

- Interpolation of the statistical parameters of meteorological elements (average long-time annual or monthly values, quantiles of distribution curves, etc.) over the territory (classical task of climatology). It applies to the construction of graphic or digital maps or their isolines of various scales;
- Interpolation of the meteorological elements themselves for the separate dates or other time intervals.

The first problem comes to an assignment of the statistical parameters in the territory points, the second one - of the concrete values of precipitation, temperature, air humidity and other meteorological elements (hourly, daily, monthly, etc.).

The second problem is often solved directly by the usual linear interpolation. But under mountain conditions this way is practically unacceptable, unless only for the utopian territory completely covered with meteorological stations. In a general case, the standardization of the variable by the suitable climatic characteristic is presented as an expedient procedure. For essentially positive values, the multiplication by the corresponding standardized factor (for instance by inverse magnitude of long-time average annual precipitation, air humidity, etc.) is enough. For such an element such as air temperature its reduction to the sea level with the help of long-time average gradient is expedient. And it is necessary to be careful about temperature inversions but this question is connected with the procedure of standardization.

The operation of standardization leads the second problem to the solution of the first one as there is a necessity of transition from interpolated standardized values by way of inverse operation to the usual ones. The interpolation itself is implemented rather strictly within the framework of triangulation - of division of the earth surface into a system of triangles adjoined to each other in the corners of which there are meteorological stations. Then the value of meteorological element for any interesting point inside of any triangle is calculated as average—weighted between the three known values.

Finally, the definition of the climatic values of air temperature and humidity in any point of the territory almost doesn't cause special difficulties. The problem of spatial precipitation distribution research is really complicated. For mountain territories this problem is still actual and basically unsolved. Some successful realizations for the separate areas can hardly be considered to be final, besides, they are usually based on drawing local indices of various sort that deprives all the constructions of a necessary generality. Altitude above the sea level and distance to the most important orographic points or lines in the given area (for instance seashore or range axis) may be mentioned as such indices. Meteorological station height is the most frequently used index. Relation of precipitation characteristics, for instance, the average long time annual total and altitude even within relatively small mountain basins (100 - 1000 km$^2$) are sometimes close and expressive and sometimes fall apart. Some uncertainty is inherent in them. The statement: the more is altitude the more is precipitation - can hardly serve as a consequence of the analysis of such relation. Often it simply doesn't correspond to the reality. But such relations can be very useful if one considers two-dimensional space "altitude - precipitation" to be an interpolation-extrapolation plane where the whole climatic picture of curves including hypothetical ones but not contradicting to the observation data can be constructed. Such constructions sometimes may be on the frontier sphere between science and art.

As an expedient and less subjective approach to decide about the task, it is possible to direct moisture carrying flows through the mountain system to the meteorological station or the calculation point of interest to us. As a result, a sufficiently universal orographic measure unequivocally and closely connected, for instance, with the annual norm of precipitation can be chosen. As the prototypes of such measure the following can be deduced:

$$\mathrm{D}_1 = \sum_{\mathrm{BP}}^{\mathrm{CP}} \Delta\mathrm{z}(+) - \varepsilon \sum_{\mathrm{BP}}^{\mathrm{CP}} \Delta\mathrm{z}(-) \qquad (1)$$

$$\mathrm{D}_2 = \sum_{\mathrm{BP}}^{\mathrm{CP}} \Delta\mathrm{z} \cos\varphi \qquad (2)$$

where $\sum_{BP}^{CP} \Delta z(+)$ is total of positive and $\sum_{BP}^{CP} \Delta z(-)$ - of negative relative altitudes along the straight line drawn on the way of moisture carrying air masses movement from the basic point (BP) up to the calculation point (CP) of interest to us; $\varepsilon > 1$ is chosen as empirical coefficient, $\Delta z$ is difference of altitudes at the rectilinear stretch of thalweg with the angle $\varphi$ concerning the direction of the air masses moving ($\varphi = 0^{o}$, $\cos\varphi = 1$; $\varphi = 90^{o}$, $\cos\varphi = 0$; $\varphi = 180^{o}$, $\cos\varphi = -1$). It is possible that orographic measure should be calculated along the line prolonged further than CP for considering the pre-ascension effect.

Both for getting the values of orographic measure and for mapping itself, the most suitable is the topographical map of 1:500 000 scale.

## 2.2. The Influence of Altitude, Inclination and Slope Aspect on Runoff Formation

The determining influence of the absolute altitude of the region on the climatic conditions of runoff formation is rather obvious and in many respects is similar to the influence of latitude. The increase of the altitude is usually accompanied by the atmospheric pressure fall, temperature and air humidity decrease, growth of direct solar radiation, probability of phase transformations, appearance of mountain and high-mountain landscapes up to all-the-year-round firn fields. Long winter and short summer, late spring and early fall are typical for regions of great absolute altitude.

In order to analyze the features of altitude influence over water balance of mountain catchments, various sorts of exponential relations are often deduced. But many of them turn out to be of book-keeping approach over the physical one. For instance, an increase in evaporation from snow cover with the increase of altitude is ascertained sometimes. But basically it is only the consequence of snow cover occurrence and not because of the direct impact of altitude on the process intensity. Generally, with the other conditions equal the atmospheric pressure reduction with altitude should promote more evaporation. In particular due to this reason the extent of evaporation from water surface increases with the absolute altitude.

The difference of altitudes in a river basin and to be exact an area distribution by altitude zones renders a direct impact on the runoff regime. The increase of an altitude range entails increase in duration of snowmelt and a large quantity of water connected with it. If on the plains of the temperate zone a large amount of water normally lasts for 15 - 50 days, in mountains with a height from 3000 to 5000 m, it takes from 100 to 180 days. The area of synchronous snowmelt limited on the one side by the front and on the other side - by the rear of snowmelt slowly creeps upwards in the course of time. The front of the snowmelt has approximately the position of the “zero” isotherm, the rear is a seasonal snow line. The separate glaciers and snowfields left below the latter bring the additional originality into the regime of river runoff prolonging high water up to the approach of autumn colds.

The ultimate cause of the influence of slope aspect on the direct and mediated runoff formation conditions is a difference in the amount of solar radiation received. The consequences of this fact are engraved in the formed landscape structure of each mountain territory.

The difference in the course of runoff formation processes at the slopes of various exposures is essential, even if these slopes are inverted to the same water course. The contrasts of the slopes of northern and southern exposures are especially striking. One can often observe pictures when one of these slopes is covered with wood and another with meadow or steppe vegetation. The phenomena of the determining influence of the slope orientation proves to be valid with any transition to macro-relief scales.

Frequently one forgets about the inclination influence when considering runoff formation processes. And this influence is crucial, especially in mountain conditions. It is important, for instance, to pay attention to it when making a combined mathematical description of heat and moisture transition.
Understanding of the main inclination influence on runoff processes should be based on three important though trivial facts:

- the real area of contact of underlying surface with the atmosphere is always greater than its horizontal projection
- the movement of water flow in soil and friable-detrital rock takes place vertically
- the flow of the thermal energy is directed perpendicularly to the slope surface

The co-ordinate systems convenient during describing of heat and moisture flows when $\alpha > 0^{o}$ formally don't coincide what should be taken into account. In the case of the environment discretization one should precisely remember that if $\Delta z$ is thickness of rated soil layers parallel to the slope surface and used in the calculation of thermal energy dynamics and $\Delta x$ is thickness of layers in the calculation of moisture dynamics then

$$\Delta x = \frac{\Delta z}{\cos\alpha} \qquad (3)$$

So, when $\alpha = 60^{o}$ $\Delta x/\Delta z = 2$. The practical hydrological consequences of the above-mentioned factors which need serious consideration while carrying heat and water exchange calculations are the following: under the other equal conditions the value of the earth surface inclination in $\cos^{-1}\alpha$ times increases the values of heat input into snow cover, soil or regolith; ice or snowmelt, evaporation from soil, precipitation interception by the vegetation cover, the initial runoff losses. But the superficial retention decreases or becomes neglectfully small. Probably, it is not necessary to remind that all this doesn't concern the precipitation layer, which entails changing of components of water and heat balances of sloping terrain in comparison to those close to horizontal.

Chezy-Manning formula is used more frequently than of others for calculation of average water flow rates when the motion is steady.

$$V = KH^{0.067}(\sin\alpha)^{\psi} \qquad (4)$$

where $K$ is coefficient accounting flow movement resistance, $H$ is average over effective cross section depth of flow, $\alpha$ is angle of channel bottom inclination, $\psi = 0.5$. Probably the range of inclination changing and inclinations themselves in the empirical formulas which Chezy himself had were so small that the question of flow rate dependence on inclination has never been properly set. For the real mountain streams when $\sin\alpha \geq 0.004$ $\psi = 0.17$. Just such influence of inclination on flow rate and time of flow or concentration which becomes stronger than it has been supposed in the scope of Chezy formula should be accounted.

## 3. Mountain Erosion

At any place where surface runoff is formed it is accompanied by erosion displays. Erosion activity is determined by three main factors - surface runoff formation intensity, erodibility of soil or friable rock to washout and inclination of the land. It changes in a wide range - from quite slow but undeviating process usually called “normal erosion” up to its extreme displays. The latter are observed in the regions of large inclinations, heaviest rains, poor vegetation, low infiltration capacity of soils and their high erodibility. In all the cases the presence of surface runoff forms the signs of its erosion work. Particularly one can judge about the activity of such kind of work by the expressiveness and density of slope rill system. The maximum density is displayed in ‘badlands’ where it can reach 5 $m/m^{-2}$ on steep clay slopes.

Inclination impact on erosion process can be estimated after consideration of the relationship of the forces influencing a soil particle. Shearing force is proportional to $\sin\alpha$, retaining force - to $\cos\alpha$. then ratio of the first to the second, reflecting influence of inclination angle $\alpha$ on erosion with the other equal conditions is proportional to $\tan\alpha$. Then one can judge about erosion intensity ratio on the slopes of various gradients by the following figures: $5^{o}$ - 1; $30^{o}$ - 6.6; $45^{o}$ - 11.4; $60^{o}$ - 19.8.

Special literature on erosion science is numerous but essentially it is empty. Methodologically the search of the relationships between erosion and surface runoff intensities is the closest to reality. The total intensity of soil erosion and surface inflow to the channel system taking into account soil waters released during erosion process is determined in this way:

$$j = g(1+\varsigma) + r. \qquad (5)$$

Here and further the following designations are used:

$r$ is intensity of surface flow to the channel system; $g$ is intensity of erosion (washout of solid substance of soil); $\zeta = u/(1-\varepsilon)$ is relative volumetric moisture of eroded soil (ratio of water depth to depth of solid substance of soil where $u$ is volumetric moisture and $\varepsilon$ is soil porosity). Erosion intensity is proportional to inclination angle tangent and some non-linear function of intensity of surface inflow to the channel system. Then finally we have:

$$j = \kappa \tan\alpha (1+\varsigma)(r + \lambda r^2) + r. \qquad (6)$$

Proportionality coefficient $\kappa$ can be called parameter of soil erodibility and the value $\lambda$ is non-linearity coefficient in the ratio of erosion and surface inflow intensities.

## 4. Outburst Floods

Great inclinations and altitude differences, especially when slopes are with weak stability, glacial phenomena and seismic impacts sometimes lead to dividing of rivers with natural dams, outbursts of which can be catastrophic. The events of such kind are always unusual and unique because “outlier” of values of discharges, levels, velocities occurs far beyond being ordinary. And conditions for outburst phenomenon formation are also extreme and have nothing in common with the usual state of river and its basin. The most burning aspect of the problem of natural dams suddenly appearing in river valleys, gorges and canyons is an estimation of life duration of a dammed lake. “To be or not to be”, what will overpower a river or a dam, that is the question. And in general, such lakes can be temporary, existing for a few hours, days, months or conditionally constant. It is intuitively clear that the longer is the time of the dam holding on, the greater is an outburst with the other equal conditions.

Detrital rock or ice is the material, which the nature uses for “building” of its dams.

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## Biographical Sketch

**Vinogradov Yury Borisovich** was born 7 December 1932 in Samarkand USSR. He is Head of Laboratory at the 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
- Professor of Hydraulics and Engineering Hydrology, 1990

**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
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- 1988. Mathematical Modeling of the Processes of Runoff Formation. Experience of the critical Analysis

**Range of Interests:**
Yury Vinogradov 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 at the head of a group of specialists carried out a number of experiments on artificial reproducing of natural Debris Flows of high density (Zailiyskiy Alatau Range, near Alma-Ata).

At present Yury Vinogradov works at a great 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.