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METHODS OF DETERMINATION OF THE WATER CONTENT IN SNOWPACK IN MOUNTAIN WATERSHEDS ON THE TERRITORY OF SLOVAKIA

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The authors submit in this paper a brief analysis of some problems involved in the determination of the water amount in the snowpack, either by direct measurements or by indirect evaluation, and also describe the obtained results. In the focus of the research were problems connected with the determination of the snow amount, the evaluation of the measured data, the computation of the water amount in the snowpack as well as the change of water equivalent with the altitude, including also the regionalization of those relations on the territory of Slovakia. In addition, results of research on the extrapolation of results from direct measurements from unforested to forested areas are prezented, as well as the results of research on the indirect evaluation of the water amount in the snowpack from the basic meteorological elements.

INTRODUCTION

Even if taking into account the various aspects of the research on the snow cover in our country [14], yet one of the dominant problems from the point of view of water economy is the problem of how large and how distributed in time and in space is the water amount in this huge natural reservoir. The solution to this problem is not simple, nevertheless serious efforts must be made in obtaining the utmost accuracy in the solution to this problem. It is the decisive factor in the more economical utilization of the water accumulated in the snowpack; in addition, it also affects the protective measures against the unfavourable consequences arising from the concentrated runoff from the melting snow. Any forecasting technique of runoff from snowmelt, no matter for what purpose developed (short—term or seasonal runoff from melting snow, the most economical utilization of the water storage, or protection against floods, etc.), requires highly accurate data, these being the key-factor mostly affecting the accuracy and the effectiveness of the applied of forecasting method. In the submitted paper authors review the present situation in the determination of the water amount in the snowpack of mountain catchments on the territory of Slovakia within the framework of the re-

rearch programme of the Institute of Hydrology and Hydraulics of the Slovak Academy of Sciences. The problems are briefly elucidated from the methodological point of view, there are described the applied procedures and also are referred to previous results described in the already published papers.

With the aim to obtain a better accuracy in the calculation of the water amount in the snowpack at a fixed datum we have focused our attention to a group of problems linked with the measurements of snow accumulation (networks, devices and methods of measuring), with the processing of the measured data, with the calculation of water content in the snowpack. Besides that, attemps were made to find out the relations between the water equivalent of the snowpack and the altitude above sea level including the regionalization of these relations on the territory of Slovakia (Turčan J.).

At the same time subject to investigation was also the problem of obtaining more accurate data on the water amount directly measured in the snowpack over the watershed taking as a basis the complex relationship between the main hydrological parameters of the snowpack on the forested and unforested areas of the watershed (Babiaková, G). A further problem was the indirect evaluation of the water amount in the snowpack by means of the basic meteorological elements (Šimo, E.).

EVALUATION OF THE WATER AMOUNT IN THE SNOWPACK OVER THE CATCHMENT AREA BY MEANS OF DIRECT MEASUREMENTS

The complexity of this evaluation is directly proportional to the complexity of the regime of the snow cover formation, characterized by a large variability both in space and time.

The hydrological research, involving the determination of the snow storage or of the water content in the snowpack, necessarily has to take into account the complexity of distribution of the snow accumulation.

The entire problem of the direct determination of the water content in the snow cover involves two closely linked groups of questions: the first group includes the measurement of the snowpack accumulation, and the second group the evaluation of the measured data and the calculation of the water content in the snowpack. The both groups of questions have not been answered satisfactorily so far, respectively there problems are still in the stage of solution, not only in our region, but all over the world.

As far as regards the direct measurement of the snow accumulation, much attention has been paid to the following problems: devices for the measurement of the depth, density, and water equivalent of the snowpack, their application at the measurement point, the selection of sites for measuring the hydrological characteristics of the snowpack, the organization of the snow measurement network, etc. All these questions formed the first stage of the research programme in snow hydrology at our Institute. The works published by V. Kozlík (4, 5, 6) analyse in detail the snow-measurement network established in Czechoslovakia from the standpoint of accuracy and representativeness of the snowpack measurements. The research work on the representativeness of the snow measuring methods resulted in the design of the so called genetic-geographical network (7, 16), the principle of which is the selection and suitable distribution of the snow measuring elements (point, course, zone, model) over the area so, as to make the measured data representative for the adjacent area with the required accuracy.

In the mentioned design it is suggested to use portable equipments like portable snow stakes for measuring the snowpack depth, or portable snow-weighing gauges for measuring the snowpack water equivalent. However the use of the existing modern devices allowing the continuous measurement of the water equivalent of snow (utilization of the radioactive emitters, snow pillows, etc.) in our country in the years ahead is very unlikely. In spite of the advantages of these modern devices allowing the automation of the snow measuring process, they are characterized also by various disadvantages if compared with the traditionally used snow weighing gauges (possible failure, non-representativeness of the measured values with regard to the snow conditions in the adjacent area, supply of informations from only one measuring point, high cost, etc.).

More suitable appear to be those measurement methods that supply relatively fast informations on the snow storage upon large areas, e. g. the photogrammetric surveying (ground, airborne, satellite) or methods using the natural radiation emitted by the Earth.

The results obtained in our experiments in which we used the ground stereophotogrammetry for measuring the snowpack depth [17] proved that, in our conditions, it is suitable to measure the snowpack depth by photogrammetry on the so called „indicating plots"; a correct selection of the number and of the position of these plots in larger catchment areas provides data which, after supplementing them by the values of the snowpack density, may be used in the calculation of the water amount in the snowpack.

The results obtained in the research of the snowpack variability confirmed that the distribution of the snow accumulation in mountains is non-homogenous [8, 15, 20]. The non-homogeneity of the snowpack distribution was considered also in the desing of the genetic-geographic snow-measurement network and is characterized by the fact that in the case of a variable distribution of the snow accumulation, there exist certain regularities. Detailed measurements and research in experimental and representative basins helped to unveil these regularities.

In our country the problems of the snow hydrology are being studied in the experimental catchment area of the creek Bystrá (Low-Tatra mountains), from where a very detailed snow measurement data has already been obtained, and used in the solution of a number of research problems.

The most significant regularity in the distribution of snow storage is the dependence of the water equivalent upon the altitude. This dependence is evident already at the start of the snow cover formation, and shows a very expressive character particularly during the culmination of the snow accumulation prior to the snow-melt season.

Knowing the relation of the snow water equivalent to the altitude, it is then possible to transfrom tre non-homogeneous results obtained from the measurements of the snow water equivalent to a homogeneous statistical sample [18]. Such sample is characterized by a much smaller variability (expressed by the coefficient of variation) and can be processed by using the methods of mathematical statistics.

Other dependence have been found between the snowpack water equivalent and the exposition of the slopes, the vegetation cover, and other less significant characteristics. In general however, the proportion of these factors with respects to the accuracy in determination of the distribution of snow accumulation proved to be less substantial. More significant relations have been found so far only in smaller watersheds. In larger areas it proved to be sufficient to take into account only the relation of the snowpack water equivalent to the altitude.

Identification of such a relationship enables, provided a suitable located and dense measurement network, to determine the water content in snowpack with accuracy corresponding to the demands of water management and hydrological practice. A method has been developed [19] for calculation and assessment of the accuracy in determination of the water content in snowpack. The use of this method and its accuracy theoretically depend on how the water equivalent of snowpack is being measured.

If the requirements on the accuracy of the determination of water content in the snowpack are not too high—in cases of the rough estimations of the water amount stored in the snowpack — the approximate methods of calculation can be used. Then the detailed snow-measurement network can be simplified by the optimal selection of the snow-measurement station from which the measured data can be used in the calculation with the required accuracy. Similarly can be used the data from the existing snow measurement network if less accurate results are sufficient. Even in some such simplified cases the obtained accuracy of results was satisfactory for practical use. Both mentioned methods were used in the determination of the water content snowpack in the basin of the river Orava and the obtained results were used as a base for the estimation of the spring inflow into the Orava-reservoir [9].

On large areas characterized by a variable relief, the variability of the snow accumulation will be larger.

Areas exist where it is suitable to use a particular and relatively close dependence of the water content in the snowpack on the altitude. Such dependence will differ from that one valid for the adjacent areas. Research on this problem resulted in the development of a method by which it was possible to select such similar areas (watersheds, resp. groups of watersheds) over the territory of Slovakia [21]. The method resulted in a relatively very detailed distribution of the territory into areas characterized by an almost homogenous distribution of the snow accumulation. In this way, a basis has been established for the formation of subsets of the data measured for the determination of the water accumulation of the snow cover, and also a basis for the rational arrangement of the snow measurement networks in larger catchment areas, significant for water economy.

The application of methods suggested for the direct calculation of the water content in the snowpack proved that, even with a small number of the snow measurement stations, a satisfactory results can be achieved, provided the application of the representative method of measurement of the snowpack water equivalent. With data measured in the experimental basin of the creek Bystrá (area 35 sq. km, altitude above sea level: 575 to 2043 m) an accuracy has been obtained that by far exceeded the requirements of the practice (deviations less than ± 5 %). This high accuracy results from the very dense snow measurement network installed on a small area of the basin. In the basin of the Orava-reservoir (area 1182 km^2) the simplification of the very detailed snow measurement network down to two snow courses resulted in an ± 10 % accuracy of the calculation.

Such results can be achieved only if establishing in the investigated catchment area first a temporary (4—6 years) detailed snow measurement network in order to obtain accurate calculations of the water content in the snowpack, and then by symplifying it to an economically suitable extent (for continuous measurements), related to the desired accuracy level.

EXTRAPOLATION OF THE DIRECT MEASUREMENTS FROM UNFORESTED TO FORESTED AREAS

The forest, as a part of the catchment area, creates special conditions with respect to the formation and accumulation of the snowpack. The determination of its effect on the formation and distribution of the snowpack during the winter season requires the instalation of a sufficient number of the snow measurement stations in the forest. As far as regards the present situation in Slovakia, the number of snow measuring stations is unsatisfactory and, in addition, there is only little hope (from the reasons of organisation) that the number of such stations in the forested areas will be significantly increased in the future years. It is therefore urgently necessary to develop a method of the indirect evaluation of the amount of water in snow stored in the forest based on the data of snow measurements on open areas. This method should encompass a relation of the water equivalents of the snowpack on open and forested areas, depending upon the weather conditions of the winter period and morphology of the examined territory. The results obtained from the measurements of a genetic-geographical network in the basin of the Orava — reservoir yielded valuable informations on the snow depth, density, and of the snow water equivalent, respectively, in the forest and in the unforested areas and proved to be useful in the determination of the relations between them. A description of this genetic-geographical network, and of the measurements carried out, can be found in [1, 20]. The forest formations are represented by the spruce-tree, this being a monoculture in the catchment area.

As far as regards the determination of the differences in the snow cover formation in the forested and unforested areas, and the expression of relations between them, in general two approaches can be used: either a genetical one in a broad sense, or a statistical approach, using the comparison of the differences of the snow depth and density in both considered environments. In the first approach the differences in the snow cover formation are determined in dependence on the climatic conditions of the winter period, and in dependence on the orography. The experiments carried out with the aim to achieve results by using the genetical approach were not very succesful [1]. Due to the relatively small and therefore incomplete set of the measured data it is impossible, at the present time, to determine the relations between the accumulation of snow and the meteorological elements. A more complex study of the dynamics of the entire process has not yet been made, so far. For this reason we have concentrated our efforts to find out relations that would enable us to calculate, by means of a simple method, the depth of snowpack, as well as its density and water equivalent in the forest form the data measured on unforested areas. From the entire winter we used data evailable characterizing the period of the continuous increase of the snowpack up to its maximum value [1]. The closeness of the relationships with respect to the snow depth calculation was expressed by the coefficients of correlation, these reaching the value of $r = 0{,}70-0{,}86$ for higher altitudes, and $r = 0{,}50-0{,}65$ [3] for the lower situated areas of the basin. An important effect showed large temperature fluctuations in the lower parts, this having been also the cause of a discontinuous increase of the snow cover, interrupted by frequent occurences of snow melts.

The aim of the further research was to develope a method by means of which it would be possible to determine indirectly the snowpack density in the forest by using of those meteorological data that indicate the change of the snowpack density. In the first stage we used as characteristic value the time of the bedding of the snow cover, expressed by the number of days, the number of days with a wind speed $\geq$ 4 m/sec., the sum of the maximum positive air temperature, and the total precipitation, all data measured from December 1-st. The obtained results are described in [2, 3]. A better accuracy was obtained by determining of the relation of the snowpack density in the forest to the snowpack density in an unforested area [3]. The quantitative expression of the difference in the snow storage in the considered both media (forested and unforested) would mean the determination of the mutual relations „forested and unforested area" with respect to the snowpack water equivalent.

In the calculation for the determination of the snowpack water equivalent in the forest we used the data of the snowpack water equivalent measured in the unforested area, as well as the characteristics of the meteorological elements that have been used in the indirect determination of the snowpack density. The values of the resulting correlation coefficients were in the range from 0,86 to 0,97. These relations are naturaly of a local significance and hold true only for the basin in consideration. In another catchment area with a different areal representation of the forest, even with the same type of the forest cover, these relations would be also different and therefore the application of the achieved results in another catchment area is practically impossible without having been first satisfactorily verified.

INDIRECT EVALUATION OF THE WATER AMOUNT IN THE SNOWPACK OF THE CATCHMENT AREA

Taking into consideration the methods used in the forecasting of the runoff volume from the stored snowpack [9, 10], we made attempts to answer the question as to how and to what extent it is possible to substitute the directly measured data of the water equivalent of the snowpack (usually available only from a short period) by an indirect index which would relatively reflect the change in the amount of the snow accumulation at the beginning of the spring snow-melt in the particular years of a suitably long period. In the analysis of the possibilities to determine such an indirect index we used on one hand the available data on the snow cover, on the other hand following data:

total precipitation, air temperature and degree-day factor [11]. Due to incomplete or missing data on the hydrological parametres of the snow cover an analysis of the indirect index was carried out in which the afore-mentioned basic meteorological elements were used. This indirect index represents a simple model of the formation of the water storage in snowpack of the basin. This formation consists of two contradictory processes, i. e. the accumulation and the snow melt process.

As criterion for the evaluation of the state of the fallen precipitation the daily measured data of the air temperature (average, maximum and minimum values of the air temperature) were used. In case of need to obtain a more accurate differentiation of the total precipitation (rain and snow) the calculation would be far more complex, The snow-melt was made proportional to the positive mean daily air temperature, i. e. to the positive degree-days and to the degree-day factor (φ), expressed in mm of water from the snow-melt corresponding to one positive degree-day. The trend of the (φ) — values changing with the air — temperature and with the time, has been explained by more physical reasonings. In spite of this, the used φ — values as they are represented in the used scheme, are to be considered as being only an extreme simplification of the reality (both the quantitative data as such, and the trend of their increase with the increasing air temperature during a given time interval and towards to the spring months). Such an established indirect index of the water accumulation in the snowpack, analyzed in [12, 13], represents an example of the utmost extreme simplification of the complex processes of the snow accumulation and its decrease during the winter season. This indirect index also reveals what extreme and yet still acceptable simplifications can be applied, and how large is the domain for research in oder to achieve a higher accuracy in this calculations.

A comparison of the results of calculations with direct measurements of the water accumulation in the snowpack in the basin of the Orava-reservoir revealed that, even in the case of using the extremely simplified assumptions on the water storage formation in the snowpack, and a minimum of the used informations, yet acceptable results were achieved. In [12, 13] are presented the results of the calculation of relations between the directly measured values and the calculated indirect indexes of the water amount in the snowpack for the particular years of the period 1967/1968—1973/1974 and in the entire period. The resulting correlation coefficients (r) were within the range 0,84—0,96, and its value for the entire used period was $r = 0{,}94$. The errors of the estimation expressed by means of the standard deviation of the directly measured and computed values was within the range of $\sigma = 19{,}0$—6,0 mm in the particular years, and $\sigma = 15{,}8$ mm for the entire used period. Assuming the average maximum water accumulation in the snowpack of the basin to be 150 mil. m^3 [9] then we derive this accumulation by using the indirect index in the considered years with an accuracy of about $\pm 12\,\%$. The submitted scheme of calculation is able to depict not only relatively the changes in the snow accumulation in the particular years of the considered period, but yields also quantitative values which are enough close to those obtained by direct measurements. In view of the fact that the applied meteorological data represent the basic input data for the calculation, it is possible to apply this scheme even in larger catchment areas.

On the one hand we recognize that the calculated indirect indices of the water accumulated in the snowpack may only temporarily substitute the data of direct measurements which are irreplaceable for certain types of hydrological calculations and forecasts. However, on the other hand, these indirect indices in some cases may be quite sufficient, and in consequence, no need then will arise to organize and finance a large-scale direct measurements. For example, if a continuous day by day calculation of the water amount in the snowpack during the winter-spring season will be needed, then their calculations and expressions by indirect indices will be unavoidable. Periodical direct measurements will then represent checking points of the day by day calculations. It is evident, that also such calculations represent an economical effect.

Doubtless exist other real possibilities of obtaining a more accurate value of the indirect index. A larger or smaller simplification, or reversely, a further improvement of this model will result from the mentioned range and quality of the hydrometeorological data in the particular catchament areas. Further analysis of the data and of the factors involved in the contemporary theoretical conception of the process of the water storage formation in the snowpack will then establish a suitable base for the modification of the model for the particular catchment areas.

CONCLUSIONS

The submitted paper shows the fact, that attention is paid to the problems connected with the direct measurements of the main hydrological parameters of the snowpack as well as to the determination of the indirect indices within the framework of the hydrological research on the carpathian rivers on the czechoslovak territory. The obtained results are applicable in practice. Direct measurements of the snowpack provide us with the most reliable informations on the snow regime in the watershed, if the arrangement of the installed snow measurement network corresponds to the variability of the snow storage distribution. The data on the snow accumulation in the forest, which in the Carpathians covers a large parts of the catchments, can be indirectly derived. The water amount in the snowpack evaluated from the measured data provides a basis for development of a more accurate indirect procedures used in the determination of the snow storage. Taking into consideration real time intervals between the direct measurements, and the practical needs to know the daily values of the snow accumulation for short — or longterm forecasts of the runoff from the melting snow (mathematical modelling of this process), it becomes apparent that an ideal method will be the combination of the direct measurement of the snow accumulation with its indirect evaluation in the interval between two measurements. Such a method gradually increases the accuracy of the indirect methods, and allows the transition from the indices of the snow accumulation to quantitatively real values.

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ЙОЗЕФ ТУРЧАН, ГАБРИЕЛА БАБИАКОВА, ЭДУАРД ШИМО

МЕТОДЫ ОПРЕДЕЛЕНИЯ ЗАПАСА ВОДЫ В СНЕЖНОМ ПОКРОВЕ ГОРНЫХ БАССЕЙНОВ НА ТЕРРИТОРИИ СЛОВАКИИ

Если мы представим модель процесса накопления снежных запасов, оттепели и стока из них во всем зимне — весеннем периоде в виде комплекса, состоящего из некоторого числа субмоделей, мы обнаружим, что в самом начале мы встречаемся с основной проблемой определения самого важного параметра-величины и пространственного распределения запаса воды в снежном покрове. В докладе приводится короткий разбор некоторых проблем, связанных с определением этих запасов при прямом или косвенном их определении.

Используя прямо измеренные данные, мы вывели способ расчета объема воды в снежном покрове для отдельных бассейнов. Исследование зависимости водного эквивалента снежного покрова от высоты над уровнем моря и связанная с этим районизация этих зависимостей на

территории Словакии позволяет использовать этот способ расчета в любом бассейне. Данные о запасах снега в лесу, который в большинстве случаев покрывает значительную часть площади наших бассейнов, мы вывели косвенным путем из измеренных величин на открытом пространстве и из метеорологических факторов, которые вызывают разницу в образовании запаса снега на обоих вышеупомянутых пространствах. Было показано, что при отсутствующих прямых измерениях снежного покрова можно косвенным путем вывести показатель запаса воды в этом покрове, исходя из самой простой схемы расчета, включащей основные метеорологические элементы — суммарные осадки и температуру воздуха. Ввиду данного объема доклада очень коротко характеризуем проблематику с методической точки зрения, информируем об используемых методах и предупреждаем на статьи, опубликованные нами, в которых приведены достигнутые результаты.