

Methods for the computation of water balance of reservoirs

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SUMMARY: The paper presents methods for the study and computation of water balance of reservoir of the USSR for short design intervals (months, years).

MÉTHODES D'ÉVALUATION DE BILAN D'EAU DE RÉSERVOIRS

RÉSUMÉ : On présente les méthodes de l'étude et de l'estimation du bilan d'eau des réservoirs de l'URSS pour une période courte (mois, année).

MÉTODOS PARA EL CÁLCULO DEL BALANCE HIDROLÓGICO DE LOS EMBALSES

RESUMEN: En este documento se exponen los métodos para el estudio y el cálculo del balance hidrológico de los embalses de la URSS para cortos períodos (meses, años).

МЕТОДИКА РАСЧЕТА ВОДНОГО БАЛАНСА ВОДОХРАНИЛИЩ

А н н о т а ц и я : 1. Для крупнейших водохранилищ и зарегулированных озер СССР составляются оперативные водные балансы за короткие расчетные интервалы-годы, месяцы. Возможность постановки таких работ обеспечивается наличием широко разветвленной наблюдательной сети, принципы которой специально разрабатывались применительно к условиям озер и водохранилищ. 2. Расчет баланса предусматривает раздельное изучение и независимое определение главнейших составляющих баланса: поверхностного притока ($Q_{п}$), поступления воды за счет осадков ($Q_о$), стока через гидроузел ($Q_с$), испарения ($Q_и$), и аккумуляции в чаше водоема (A). Дополнительно на отдельных водохранилищах, на которых развиты эти процессы, учитываются временные потери воды на оседание льда на берегах ($Q_л$) и отток воды в грунт ($A_г$). 3. $Q_{п}$ — определяется по данным гидрометрических измерений, которыми, как правило, освещается не менее 70-75 % общего притока с водосбора. С остальной части бассейна сток вычисляется по его удельным величинам на основании данных измерений на реках частных водосборов. 4. $Q_о$ — определяется по наблюдениям островных и береговых станций, к показаниям которых вводятся поправки, учитывающие потери осадков на испарение, смачивание и выдувание, и исчисляемые раздельно для твердых и жидких осадков. 5. $Q_с$ — исчисляется по материалам учета стока на гидроузле с поправками, полученным путем контрольных гидрометрических измерений, выполняемых при заданном режиме ГЭС. 6. $Q_и$ — определяется расчетом с использованием данных наблюдений над гидрометеозементами, определяющими испарение с водной поверхности. Последнее время все более широкое распространение получают данные об испарении, получаемые по методу теплового баланса, основанного на материалах наблюдений над радиационным балансом и теплозапасами. 7. Аккумуляция определяется по разности объемов в чаше водоема на начальный и конечный моменты расчетного интервала. В качестве исходных при определении A используются сведения о среднем уровне, вычисленном для всего водоема в целом, а для периодов с четко выраженным уклоном — раздельно по участкам водохранилища. Средний уровень определяется по

водомерным данным с исключением искажающего влияния относительных колебаний уровня.

8. Точность расчета баланса крупных речных водохранилищ за месячные интервалы составляет 5-10, для годовых — 3-5 %, на отдельных наиболее изученных объектах соответственно 3-5 и 1-2 %

Water balance computation of inland lakes and reservoirs, constantly improved as the development of water resources of the USSR proceeds, is very important for the operation of reservoirs on rivers and of regulated lakes. Primarily, the water balance computation consisted only of the compilation of characteristics averaged for a long-term period, modern water balance computation is performed for a short-term design interval (a year or a month) and is intended to obtain information on the inflow and available water storage in the reservoirs. The possibility of such computation is provided by a wide observational network on lakes and reservoirs and by the completion of investigations of the methods for the determination of principal water balance components.

Besides a dense network of gauges on lakes where regular water level fluctuations are observed together with water temperature and ice phenomena in the littoral zone, special lake stations are operating in the USSR, and observatories are established on large lakes and reservoirs, where comprehensive investigations of hydrometeorological regime of lakes and reservoirs in the coastal zone and offshore are performed.

On the basis of generalization of long-term investigations on lakes the programme and the methods of observations have been unified and principles of the most rational distribution of observation stations have been developed, intended for the obtaining of data for the characteristic of different elements of the regime and first of all water balance of lakes and reservoirs.

Water balance computation for a short time interval (a month) is performed by the equation:

$$Q_{in} + Q_p - Q_{out} - Q_e \pm Q_s \pm Q_i = A$$

where:

Q_{in} surface inflow;

Q_p precipitation on the surface of the reservoir;

Q_{out} outflow through spillways or down the river, flowing out of the lake;

Q_e evaporation;

Q_s temporary water losses by saturation of shores of the reservoir;

Q_i temporary water losses by the ice left on shores after the fall of level of the reservoirs;

A accumulation of water in the reservoir.

All the components of the water balance are estimated independently, on the basis of data of appropriate observations.

Surface inflow (Q_{in}), which is the most important component of the income part of the balance, is computed on the basis of observations on hydrometrical stations, established to study this component of the water balance in the most comprehensive way. Hydrometric stations, established on main and small tributaries, provide regular measurements of discharge and subsequent determination of daily discharges. On the majority of large lakes and reservoirs of the USSR hydrometric measurements cover 70-90% of runoff from the drainage area, and in some reservoirs of arid regions during low flow, when runoff of small tributaries is practically zero, the total surface is measured by hydrometric installations. On lakes and reservoirs of the zone of excessive moistening the runoff from the ungauged part of the basin is computed for a given design interval according to runoff values, measured on rivers-analogues, located in similar physiographic conditions.

Precipitation (Q_p) is distributed unevenly over the water area and as a rule its value is less (in summer) in the offshore part of the reservoir than in the coastal zone due to the

attenuation of upward fluxes of the air over the water surface, stipulating the formation of local convective precipitation. In order to consider this effect and the total uneven distribution of precipitation over the water area, raingauges are established not only in the periphery of the reservoir, but also offshore, on islands and in lighthouses. Extrapolation of raingauge data to adjacent regions is performed by means of maps of isohyets for the water surface or by means of weighing, i.e. by relating raingauge records to the adjacent part of the lake (reservoir). Before the map of isohyets is plotted, the raingauge records are corrected for wind effect, wetting of the bucket and evaporation losses.

Outflow from lakes (Q_{out}) is estimated by hydrometric measurements in the outlet of the lake, and on reservoirs the outflow through turbines and spillways is estimated. The discharge at hydraulic structures is computed by the design characteristics of turbines and spillways with account of the capacity and head at the structure.

At the first stage of investigations it was supposed, that the accuracy of discharge measurements at hydraulic structures is greater than at hydrometric stations and the computation error does not exceed 1-2%. Later on it was found out, that the error of discharge computation was often 5-7%, caused, for example, by a certain discrepancy between the characteristics of the turbine capacity of a model and of a real turbine.

In order to make the estimation of discharge at hydraulic structures more precise, the calibration of turbines is performed under natural conditions as well as control hydrometric measurements, made in the lower pool of the hydro-electric plant according to a special programme at a specified regime of outflow through the hydraulic structure. These methods, in combination with reliable data on design characteristics as well as a regular control, made by means of water balance computation of reservoirs, provide the improvement of methods of streamflow estimation at hydraulic structures.

Evaporation from the surface of reservoirs (Q_e) is computed by the formula:

$$Q_e = 0.14 n(e_0 - e_{200}) (1 + 0.72 W_{200}) \text{ mm/month}$$

where:

- e_0 saturation vapour pressure, estimated by water temperature;
- e_{200} absolute air humidity (mb) at the altitude of 200 cm;
- W_{200} wind velocity (m/sec) at the altitude of 200 cm.

The numeric parameters of the design formula are computed by direct measurements on a reservoir. In order to obtain necessary data on the temperature of water in reservoirs an observational network is established at the littoral zone and offshore; the points of this network are distributed to cover all the parts of the reservoir with different thermal conditions. At the observational points the temperature is measured not only at the surface, but also at different depth, which makes it possible to compute heat storage in the reservoir for different dates. Meteorological data are obtained from meteorological stations located in the coastal zone and offshore, on islands and on barges laying at anchor.

Since evaporation from running-water reservoirs is small as compared with other water balance components and it is impossible to evaluate the accuracy of its determination by water balance, at present certain arrangements have been undertaken for the computation of evaporation by heat balance method. For this purpose special investigations of radiation balance of inland reservoirs are being made. These experiments result in initial recommendations for the computation of radiation regime over the surface of reservoirs using the data from continental actinometric stations. These methods in combination with the data on meteorological conditions over the reservoir and data on water temperature and heat storage provide to perform control computation of evaporation by heat balance method.

Temporary water losses by shore saturation (Q_s) are computed for particular reservoirs only, where hydrological observations of ground water level in the coastal zone are performed. On the basis of these observations Q_s is estimated by the equation

$$Q_s = \Omega \mu l_c$$

where:

Ω is the cross-section of rocks (m^2) restricted by the backwater curves; the lower curve corresponds to the lowest annual ground water table, the upper curve shows the location of ground water table in the given moment;

μ is the saturation deficit of rocks, determined as the difference between the actual humidity and the porosity of rocks;

l_c is the length of the coastal line of the reservoir at different water levels, in km.

On the basis of data on monthly water volume, temporarily left in the rocks, a graph $Q = f(H)$ is plotted; it provides the determination of the additional water inflow from the subsurface basin as water level of the reservoir falls. Temporary losses for rock saturation are usually not great; as a rule, they do not exceed 1 or 1.5% of the total outflow and total losses from the reservoir.

The amount of temporary water losses spent for the ice left on the shore and snow over the ice (Q_i) is estimated by the formula

$$Q_i = (F_{in} - F_{ter}) \frac{h_{in} + h_{ter}}{2} \cdot 10^4 \text{ m}^3$$

where:

Q_i amount of water in the ice and snow left on the shore;

F_{in} and F_{ter} initial and terminal area of the reservoir in km^2 estimated by the area-water stage relation curve;

h_{in} and h_{ter} initial and terminal water equivalent of ice and snow in cm, estimated by the records of coastal stations, located in different parts of the reservoir. On the basis of data on monthly amount of water accumulated in ice and snow a graph $Q_i = f(H)$ is plotted.

This graph makes it possible to consider an additional inflow of water, caused by ice, temporarily left on the shore during the recharge of reservoirs in spring.

Accumulation of water in the reservoir (A) is estimated as the difference between the water volume stored in the reservoir at the initial and terminal moments of the design interval. If the gradient of the water surface of the reservoir is small, then the water volume is estimated for the mean weighted level of the whole reservoir by the volume-water stage curve. If the gradient of the water surface is considerable, then the volume is estimated for individual parts of the reservoir using partial volume-water stage curves. The mean weighted level is estimated on the basis of data from stations, located in sites where wind set-up effect is eliminated. These sites are usually situated close to the geometric centre of the reservoir (axis of equilibrium) where the level is constant during water level denivelations caused by wind. The location of equilibrium axes for prevailing wind directions on a particular reservoir is estimated by the method of A. V. Karashev for the determination of wind water level denivellation.

The accuracy of water balance computation, as well as the duration of the design interval are stipulated by the accuracy of determination of balance components and first of all the most important ones, i.e. surface inflow and water accumulation in the reservoir. The probable error of hydrometric estimation of runoff is $\pm 5\%$, the error of the estimation of mean weighted level is ± 1 cm. Hence the absolute error of the estimation of water

accumulation in the reservoir is $\Delta = F \cdot 10^4 \text{ m}^3$, where F is the reservoir area in km^2 . The relative error of accumulation in comparison with the inflow $p = \Delta/V_{inf}$ is expressed by the equation:

$$p = \frac{F \cdot 10^4}{86\,400\,Qt} \%$$

where:

$V_{inf} = 86\,400 \cdot Q \cdot t$ is the volume of inflow in m^3 ;

Q discharge in m^3/sec ;

t duration of design interval in days.

The duration of the design interval is determined with the account of p value, which should not exceed the possible error of the hydrometric estimation of runoff, i.e. $\pm 5\%$. On the large reservoirs, when spring recharge is intensive, i.e. at a considerable inflow of water, p value tends to a great decrease; it shows a possible reduction of design intervals from a month up to ten days. On the contrary, during low water period when inflow is small, the design intervals should be extended up to a month in order to provide the required accuracy of water balance computation.

Since all the balance components are estimated in an independent way, the balance is co-ordinated by the equation $H = \Sigma I_n - \Sigma O_u - A$,

where:

H discrepancy of the balance;

ΣI_n total inflow;

ΣO_u total outflow from the reservoir.

In the USSR during the operation of reservoirs the current balances are computed for monthly and yearly intervals. On the average the discrepancy of monthly balances is $\pm 5\%$, yearly ones $\pm 1-3\%$. On newly created reservoirs where estimation of all the balance components is incomplete, the discrepancies are great, sometimes they are $\pm 15-20\%$ for particular months and $\pm 5-10\%$ for the whole year. The discrepancies of the balance comprise the errors of the estimation of all the balance components, and also the neglected elements of the balance, i.e. subsurface inflow and percolation from the reservoir. The approximate agreement of the balance testifies a small absolute value of the neglected elements proved by means of computation and special observations. According to these data the subsurface inflow into reservoirs equals 1-3% of the surface inflow, i.e. it is commensurable with the error of determination of the most important income component of the balance. Therefore, it is necessary to improve the estimation of other water balance components instead of performing difficult and expensive hydrological observations. This is the main objective of investigations of water balance of reservoirs in the USSR.