Water-Balance Metrology

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Abstract

The State Hydrological Institute (SHI) of the Russian Federation is in possession of four kinds of metrological standards, namely: water-evaporation measuring, precipitation-measuring, water-level measuring and water-flow speed measuring. Two of them are situated at the Valdai branch of the SHI, and the other two are located at the experimental base of the Ilyichevo settlement near St.Petersburg. The use of all four standard measuring devices enables us to evaluate the level of error when measuring input and output of water in a closed hydrological system. Now we have the resulting values of errors in these standard measuring devices. To evaluate the values, we used the method of comparison, which, also, made it possible to reveal the role of meteorological factors influencing the systemic and the casual errors in these measuring devices. The check-up scheme of functioning of the devices was also examined. The data, received as the results, make it possible to measure, with more precision, the water output errors when calculated after the water-balance equation.

It is hardly possible, in one article, to dwell upon all kinds of hydrological measuring. So, we'll only treat the problems connected with measuring of the water level, the water-flow speed, precipitations and evaporation.

Theoretically, the water-level measuring is the simplest procedure. In the State Hydrological Institute (SHI), we have a Standard Facility Unit for checking-up water-level measurers (SULM) certificated as a standard measuring device of the first rate with the error level of ±0,5 mm at the measuring range of 0 to 10 meters. A special method of indirect check-up of the level measurers has been worked out after an original scheme to be used at the working sites directly in the float-wells. The problems here are mainly of a technical character.

Now, let us dwell upon the problems connected with measuring the water-flow speed and expenditures of water. From the mathematical point of view, an expenditure is a calculation from an integral of the following type:

$$\iint_S V dx dy , \qquad (1)$$

where S is a cross-section, x and y are co-ordinates of the cross-section, V is the water-flow speed at the point fixed with co-ordinate values of x and y.

The co-ordinates and the cross-section itself are fixed with a relative error of about 1-2%, while the relative error of speed, measured with hydrometric rotators, can reach 20% and more at lower speeds of the current.

The cause is simple and quite understandable. On the one hand, it is conditioned by the rotator-producing technology, and, also, by a specific way the individual function of a hydrometric rotator is transformed, on the other.

Usually, as it is fixed in the State Standard Specifications (GOST), it is presented as a kind of piece-linear approximation.

$$\begin{aligned} V&=a_1*n+b_1 \text{ at } V<V_0 \\ V&=a_2*n+b_2 \text{ at } V>V_0, \end{aligned} \qquad (1)$$

where a and b are coefficients, n is a number of turns of the rotator, V_0 is a critical zero point.

The situation is not much better when we use the following formula as a kind of individual transformation function:

$$V=a*n+\sqrt{b*n^2+c}, \tag{2}$$

where *a, b, c* are coefficients.

The point is that formula (2) gives a systemic component of error. At the critical zero point, curve (2) positions higher than the values of the individual transformation function of the rotator, i.e. at the critical zero point, the value of the second derivative of the individual transformation function must be higher than that calculated after formula (2).

In connection with this, we'll dwell upon the following two tasks.

First, when calculating coefficients for piece-linear approximation, one should make efforts to achieve minimal values of relative error, i.e. the additive component of error should be minimal, even if it would cause the higher values of the error multiplicative component. At present, it is not possible to completely give up using the piece-linear approximation, because it is referred to almost in all the GOST specifications mentioning hydrometrical rotators. To make changes in those specifications is a long, laborious and expensive procedure.

Second, we put forward a new individual transformation function of rotators. The proposed formula makes it possible to considerably reduce the systemic component of error, and, in some cases, to eliminate it completely.

The coefficients for piece-linear approximation are determined by minimizing the functional:

$$F(a,b)=\sum\rho(V_i-a*n_i-b)^2\rightarrow min,$$

where ρ is the weight function, V_i-is the speed of the current, n_i-is the turn frequency of the rotator, *a* and *b* are the coefficients sought for. As a result of minimization of functional *F(a,b)*, we come to coefficients *a* and *b* as:

$$\mathrm{a}=\frac{\sum_{i=1}^{N}\rho V_i n_i\sum_{i=1}^{N}\rho+\sum_{i=1}^{N}\rho V_i\sum_{i=1}^{N}\rho n_i}{\sum_{i=1}^{N}\rho n_i^2\sum_{i=1}^{N}\rho+(\sum_{i=1}^{N}\rho n_i)^2}$$

$$\mathrm{b}=\frac{\sum_{i=1}^{N}\rho V_i-\mathrm{a}\sum_{i=1}^{N}\rho n_i}{\sum_{i=1}^{N}\rho}$$

At ρ=1, we come to the usual method of the least squares. In this case, approximation of the individual transformation function in the linear mode develops evenly within the whole range of approximation. For the piece-linear approximation, first we take several initial measuring points, and then – several closing points at the end of the measuring range. And after that, the following system of equations is to be solved:

$$V=a_1*n+b_1 \quad \text{at } V<V_{critical}$$
$$V=a_2*n+b_2 \quad \text{at } V>V_{critical}$$

As a result, we receive a value of the critical point $V_{critical}$. If the value of the calculated range does not coincide with the value of the critical point, we are to calculate coefficients *a* and *b* anew, and then to calculate the value of the critical point again. Such iterations are to be done until the bounds of the approximation range coincide with those of $V_{critical}$ .It is important to note here that $V_{critical}$ is calculated after formula:

$$V_{critical}=\frac{\mathrm{a}_1\mathrm{b}_2-\mathrm{a}_2\mathrm{b}_1}{\mathrm{a}_1-\mathrm{a}_2}$$

which actually is a ratio of two small quantities the exact value of which can never be determined, i.e. the critical point can occur at any place within the measuring range, including negative values of speed, which means that the individual transformation function should better be presented as a single straight line.

At ρ=1, approximation takes place within the whole measuring range. In this condition, the multiplicative component of error is close to zero, and the additive component of error, on the contrary, is rather big, which causes big values of relative errors of measuring (15-30%) at low speeds of the current depending on the type of rotator. At the same time, at the given value of the weight function, the relative error at fast speeds can be small and even smaller than 1%.

On the contrary, at $\rho=1/V^2$, the additive component of error is small, while its multiplicative component is big. In this case, the relative error in the initial part of the measurement range is getting smaller by 1.5-2 times, but at faster speeds, it is getting bigger by almost two times.

During the procedure of investigation of various weight functions, the following weight function was chosen:

$$\rho=1/(1-exp(-V_i^2))$$

At slow speeds, the chosen weight function behaves as $\rho\to 1/V^2$, at faster speeds it does as $\rho\to 1$. Thus, the chosen weight function yields minimal values of relative error at slow and at fast speeds alike.

Since the piece-linear approximation does not give a good reflection of behavior of a "real" individual transformation function of a rotator, it is important to find out a true transformation function of it and to give it an adequate physical ground. Formula (2) meets these requirements, but, as it was mentioned before, it gives a systemic component of error at the critical point. So, the value of speed, calculated after this formula, is overstated when measured close to the critical point. In the process of deduction of formula (2), a number of assumptions were taken. The formula deduction proper was based on the fact that the hydrological and the geometrical pitches of a rotator differ from one another. The difference between hydrological pressure on the outer and the inner surfaces of the rotator blade was determined after the pressure measured at the center of the rotator blade, which was incorrect. Besides, proceeding from the given physical model, it was not clear why the rotator did not rotate at slow speeds of the current, though, in fact, the speed and the pressure were actually there. But, at the same time, the given formula proved to be a good one, and it could not be neglected.

When deducing the formula for the individual transformation function, the following physical assumptions were considered.

First, at slow speeds of the water current, the rotator does not rotate because of the presence of static friction between its parts.

Second, when the water-current speed grows stronger, the static friction turns to sliding friction. At slower speeds, the value of sliding friction is smaller than that of static one. With further increase of the speed, sliding friction also increases and exceeds static friction. As a result, the individual transformation function of the rotator gets almost completely paralyzed, i.e. when the water-current speed increases still further, it does not cause any noticeable increase in the rotation speed.

Third, at certain speeds, there comes a phenomenon of resonance. The point is that a rotator is a simple electromechanical system. The system theory yields the fact that, if a dynamic system undergoes influence of a permanent force (in our case, it is the water-current speed), at a certain level of influence, there comes a phenomenon of resonance at the frequencies equal to the system's proper oscillations. In a rotator device, there must be three proper frequencies. The first one is determined by the speed divided by the screw pitch. The second is the speed divided by the screw diameter, and the third one is the speed divided by the difference between the geometrical axis and the rotation axis. We will not take here the third frequency for a subject of investigation, since it is observed only at very fast speeds, and the existence of this very resonance frequency leads to physical destruction of the rotator. The first resonance frequency is well known, as it conditions the appearance of the Epper loop on the individual transformation function. The second resonance frequency has practically been rarely studied which can be explained by the fact that it is found on the very edge of the measurement range and, sometimes, beyond it. On the other hand, probably, there is a big decrement of fading on this frequency. And still, it is important, because the existence of this resonance frequency makes the obstruction of the individual transformation function take place later than is supposed by the physico-mathematical model of the rotator chosen by us.

In this paper, we do not dwell upon phenomena connected with resonance, nor do we with the Epper loop. We do study phenomena connected with problems of friction. As a result of our efforts, we put forward the following formula for determining the individual transformation function:

$$V=k_1*n+k_2/n+k_3, \qquad (3)$$

where k_1, k_2 and k_3 – are coefficients concerning friction features.

Now, let us see what relations are between earlier formula (2) and this new one (3). At faster speeds, both formulas turn into ordinary linear dependences. At slow speeds (when the number of rotations is small too), formula (2) takes the form of:

$$V=a*n+\sqrt{c}+\frac{b\sqrt{c}}{2*c}n^2,$$

i.e. that of a parabolic dependence. At that, the minimum of the parabola falls on the negative values of the rotation frequency. Formula (3) presents a rational function whose numerator is a parabola, and whose denominator is a linear function. The parabola is in its minimum at the negative values of rotation frequencies. Within the limits of the measuring error, both formulas coincide. Differences are noticeable only when close to the critical point. As aforesaid, formula (2) for approximation of the individual transformation function gives a systemic error near the critical point. Formula (3) is free from this defect. The point is that the second derivative with respect to n (rotation frequency) in formula (2) is smaller than that in formula (3) near the critical point, i.e. at the critical point, formula (3) shows a more steep curve.

Thus, we propose a weight function which makes it possible to receive a minimal value of relative error at the piece-linear approximation of the individual transformation function within the whole range of measuring.

For us, it is important to determine the water output, for which we shall calculate integral (1) when we have values of the water-current speed distributed at the cross-section of the river.

Along with determining measuring errors at each observation point at a certain moment of time for solving tasks of hydrology and meteorology, it is necessary to evaluate errors of averaged (indirect) measuring too. For this purpose, a model of a hydrological field is built. Depending on the model of the field, evaluations of errors differ from one another. There can be a great number of such field-models, and, as a rule, their authors evaluate errors of the models by themselves. Building of the models is based on various assumptions. It is more often that they propose a model of a homogeneous and isotropic hydrological field. Homogeneity means that average quantities and their dispersions of a hydrological characteristic do not depend on the observation point and are equal at various points of observation, i.e.:

$$\overline{f}(\rho_1)=\overline{f}(\rho_2)=\ldots=\overline{f}\,,$$
$$\sigma_f^2(\rho_1)=\sigma_f^2(\rho_2)=\ldots=\sigma_f^2 \qquad (4),$$

where ρ is co-ordinates of a hydrological field.

Isotropy means that correlative characteristics of different observation points do not depend on their respective positions, but they only depend on the distances between them.

Let us assume that we determined the water-current speed at several points of the river cross-section. The randomly placed observation points must be pinned to a certain co-ordinate system where condition (4) is to be met. Then the standardized averaged error at point k, measured in relative units, will be equal to:

$$\mu(k,l)=2\int_0^1\int_{k-l}^{k+l}(1-x)(1-|r-l|)r_f(l,\sqrt{x^2+y^2})dxdy\ ,$$

where r_f is a standardized correlative function of the results of measuring.
Though it is not always possible to keep to the conditions of homogeneity and isotropy, this approach gives good evaluation of meteorological characteristics and their errors.

If the distance between two observation points is short, the correlative function has a broad range. If the distance is long, the correlative function assumes a form of an isolated one. When the distance gets longer, the correlative function tends to gain in width which is conditioned by the influence of the seasonal observation factor. Thus, for the correct evaluation of error of averaged results of measuring, along with homogeneity and isotropy, the important condition is the density of observation points. Mathematically, it is presented as a degree of the filling expansion on the observation basis.

Summarizing of the given models lies in the fact that a hydrological field should be regarded as a combination of homogeneous and isotropic fields, which, practically, means that all the observation points are divided into *N* groups within which the condition of homogeneity and isotropy is realized. Despite the fact that, in the majority of cases, it is impossible to do, the observations cannot last very long. But when it is possible, the summarized evaluation of error at each observation point will be equal to the statistical sum of errors in each group of observation points with their respective weights.

$$\mu = \sum_{i=1}^{N} p_i \cdot \mu_i$$

Weight p_i of each group depends on the density of observation points and their metrological characteristics.

In some cases, using some specific method, we can correct the values of the speed at the observation points to keep the requirements of homogeneity and isotropy.

For practical purposes, it is important not only to evaluate hydrological characteristics at various points, but also to know the degree of precision of the values received, because this makes it possible to judge upon the effectiveness of the used model of hydrological field itself. For this purpose, we'll consider a field of hydrological characteristics. This field must be homogeneous and isotropic and, besides, it must be differentiable, which would simplify its mathematical analysis considerably. Dispersions and averaged values of the metrological field depend only on errors of the rotator readings at the observation point and on the measuring methods, which is quite justifiable in the majority of cases. Correlative functions will be determined by the systemic component of error.

This approach helps to evaluate errors of metrological characteristics received with the use of the hydrological-field models, thus allowing us to evaluate effectiveness of the model in use.

Metrological facilities for measuring precipitations are quite well known. There is a widely recognized standard complex for precipitation measuring at the experimental base of the SHI at the Valdai (the Valdai control system for atmospheric-precipitation measuring – VCS) which is part of the equipment of a special precipitation-measuring testing ground organized in 1964 and intended for investigation of the devices and methods for atmospheric-precipitation measuring. It consists of three Tretiakov precipitation measurers placed among the bushes to protect them from the wind. The distances between them are not bigger than 20 meters. Besides, at the same testing ground, just near the VCS, they placed, behind a double fence, a few more Tretiakov precipitation measurers which served as standard devices for mutual interrelated comparison, as well as still more precipitation measurers to be used as ordinary working measuring devices for observation in the field.

To evaluate adequately an error of any type of measuring, it is necessary to have an initial standard dominating the whole verification scheme. But here it was impossible to evaluate the VCS measuring errors by traditional methods of comparing them with those of the dominating standard, because they did not have any at their disposal. So, they used an earlier method of comparing the devices' readings with one another which allowed to evaluate errors in the absence of a standard measuring device. However, application of this method allowed to evaluate only a casual component of error. But the fact of absence of systemic component of error, when measuring precipitations with the help of VCS, was revealed only after the many-year investigations.

To evaluate the casual component of error when measuring precipitations with VCS (taken either as a whole complex or as some of its separate devices), they used the foresaid method of comparison of readings of the precipitation measurers with one another. It was based on the assumption that the value of the input signal, received by each measuring device under investigation, was the same. In this case, this assumption was well justified, because the VCS components were placed quite close to one another. Thus, to determine the casual component of error, it was enough to evaluate an averaged quadratic deviation of readings of each precipitation measurer. The casual components of error are considered to be independent. So, the averaged squared difference between readings of devices *k* and *j*, at the same value of the input signal, will be:

$$M\left[\left(X_{nj}-X_{nk}\right)^2\right]=\sigma_j^2+\sigma_k^2 \tag{5}$$

where X_{nj} is the reading of value *n* (1≤*n*≤N) by measurer *j* (1≤*j*≤*L*), *L* is the total number of measuring devices, *M* is a mathematical expectation of the casual value. If we evaluate all the averaged squares, basing on experimental data (X_{nj}), it will give us a system of *L(L-1)/2* equations, which will make it possible to determine *L* independent values of σ_j^2. Then solving system of equations (5), we receive the following formula for evaluation of dispersion of readings of device *l* :

$$\overline{D}_l=\left[N(L-1)(L-2)\right]^{-1}2\sum_{k=1}^{L}\sum_{j=k+1}^{L}\sum_{n=1}^{N}\left(X_{nk}-X_{nl}\right)\left(X_{nj}-X_{nl}\right) \tag{6}$$

Value $\overline{D}_l$ is an irremovable value of the dispersion we sought for. To receive a more adequate value of dispersion, it is necessary to estimate some characteristics of selective statistics.

Let *N* casual values of error of readings X_{nl} *(n=1,…,N)* of measurer *l*, have density of probability P_l. Then the characteristical function for casual value $\overline{D}_l$ assumes the form:

$$H_{\overline{D}_l}=M\left[\exp\left(i\omega\overline{D}_l\right)\right]=\int_{-\infty}^{+\infty}\prod_{m=}^{L}d\overline{X}_m P_m^N\exp(i\omega\overline{D}_l) \tag{7}$$

Index *m* determines the total number of measuring devices under investigation. Equation (7) can be simplified and presented as:

$$H_{\overline{D}_l}(\omega)=\left[h_{\overline{D}_l}(\omega)\right]^N \tag{8}$$

where $$h_{\overline{D}_l}(\omega)=\int_{-\infty}^{\infty}\prod_{m=1}^{L}dX_m P_m\exp\left[\frac{2i\omega\sum_{k=1}^{L}\sum_{j=k+1}^{L}\left(X_{nk}-X_{nl}\right)\left(X_{nj}-X_{nl}\right)}{N(L-1)(L-2)}\right]$$

For evaluation of $\overline{D}_l$, we'll reiterate the procedure of determining *N* values of *L* measurers, and after each reiteration we'll evaluate $\overline{D}_l$ after formula (6). As a result, we'll receive a selection to be used for evaluation of empirical density of probability $\overline{P}(\overline{D}_l)$ in the form of:

$$\overline{P}(\overline{D}_l)=\sum_s A_s T_s(\overline{D}_l) \tag{9}$$

where T_s- is a randomly selected set of orthogonal functions within range of (a_l,b_l), A_s is a coefficient of expansion.

Now, using expression (9), we'll build the empirical characteristical function:

$$\overline{H}_{\overline{D}_l}(\omega) = \sum_s A_s \int_{a_l}^{b_l} T_s(\overline{D}_l)\exp(i\omega\overline{D}_l)d\overline{D}_l \tag{10}$$

As an orthogonal basis, we'll use a set of trigonometric functions. In fact, it is possible to use any set of orthogonal functions in which we know the meanings of integrals in expression (10).

Let

$$T_s(\overline{D}_l) = \cos\left[\frac{\overline{D}_l - a_l}{b_l - a_l}\pi s\right], \tag{11}$$

then we have

$$\int_{a_l}^{b_l} T_s(\overline{D}_l)\exp(i\omega\overline{D}_l)d\overline{D}_l = \frac{i\omega\exp(i\omega a_l)\{1-\exp[i\omega(b_l - a_l) - \pi s i]\}}{\omega^2(b_l - a_l)^2 - \pi^2 s^2}(b_l - a_l)^2 \tag{12}$$

If we use trigonometric functions as an orthonormalized basis, b_l=2π, a_l=0.

Substituting (12) into (9), we'll receive an expression for a characteristical function of empirical density of probabilistic evaluation of dispersion:

$$\overline{H}_{\overline{D}_l}(\omega) = \sum_s A_s \frac{i\omega\{1-\exp[i2\omega\pi - \pi s i]\}}{4\omega^2\pi^2 - \pi^2 s^2}4\pi^2 \tag{13}$$

Because of lack of information concerning the law of distribution of probability density $P_l(X_l)$ of reading errors, we compare the characteristical function of empirical probability density (13) with that of theoretical probability density in the vicinity of zero $(\omega \to 0)$. For this, we'll expand the under-integral expression in formula (8) into the Taylor set, and determine an approximate value of characteristical function of probability density of dispersion evaluation at any value of probability density of reading errors of the measurers:

$$h_{\overline{D}_l}(\omega) \approx 1 + \frac{i\omega\overline{D}_l}{N}$$

Similarly, at $(\omega \to 0)$, we'll expand, into the Taylor set, the right part of expression (13) for characteristical function of empirical probability density of dispersion evaluation:

$$\overline{H}_{\overline{D}_l} \approx A_0(b_l - a_l) + \frac{i(b_l^2 - a_l^2)}{2}A_0\omega - \omega\sum_{s=1} 2\frac{(b_l - a_l)^2}{\pi^2(2s-1)^2}A_{2s-1} \tag{14}$$

Using expression (14), we'll receive the following formula for evaluation of a casual component of error of readings of device *l* :

$$\overline{\sigma}_l^2 = \frac{a_l - b_l}{2} - \sum_s 2\frac{(b_l - a_l)^2}{\pi^2(2s-1)^2}A_{2s-1}$$

The casual component of error of the VCS measuring was determined on the basis of many-year observations about quantities of precipitations during the period of time from January 1973 to December 1985. All the cases were sorted into three groups: hard precipitations (snow) – 1705 cases, liquid (rain) – 1727 cases, mixed (snow with rain) – 375 cases. We determined error values for each of the three types of precipitations. As a result of the investigation, it became clear that the absolute *(mm)* and relative *(%)* values of error of the VCS and its components depended on the quantities of the measured precipitations and could be approximated by the revealing functions which were common for all types of precipitations:

$$\sigma_{P_l} = cP^{d}\,[mm]$$
$$\sigma_{P_l} = 100\ cP^{d-1}[\%]$$

where *P* is the level of precipitations measured by the three components *(mm)* at VCS, *c* and *d* are empirical parameters of the revealing functions. It is important to note that parameter *d*>1, that is why the relative error gets smaller when the quantity of precipitations grows.

But it was impossible to use directly the comparison method for evaporator error-evaluation, because we did not have a sufficient quantity of devices of the same type functioning in similar conditions. Besides, the systemic component of error for evaporators was very big, and its values varied in readings from one evaporator to another, and from one measuring method to another.

We investigated data received at the SHI field ground at the Valdai in the period from 1967 to 1994. Each of the four experimental grounds was placed in different conditions: continental, on the lake-side, and on the water-surface of the lake. We also compared the data on evaporation at three 20 m^2 –pools situated at different experimental grounds: continental, methodical and lake-sided. We found out that the difference between systemic components of the three 20 m^2 –pools did not exceed 0,1 mm, while the casual component was below 0,6 mm. We used the method of comparison in this investigation, though such an approach was not quite correct in this situation, because each pool was influenced by different outer conditions.

For further analysis of evaporation-measuring errors, it was necessary to minimize the systemic component of measuring error. We could not do it directly, because we did not have a standard evaporator, and because we conducted measurements in the field conditions. So, we minimized the difference of systemic component of error taken from different evaporators: 20 m^2 -, 5 m^2 -, 3 m^2 –pools and the GGI-3000 installation. At that, we assume that the systemic component of error for the 20 m^2 –pool is small as compared with the other evaporators. For this, we build dependence of the evaporator-reading differences from various meteorological parameters. Building of the dependence model is based on the following assumptions.

First, we assume that the systemic error component depends on a number of meteorological parameters and takes the form of a complex multi-dimensional function. The first approximation gives a linear dependence on the parameters, i.e.

$$\Delta E = \Delta_0 + \sum_{i=1}^{n} \Delta_i t_i \qquad (15)$$

where t is the value of parameter i, n is the number of parameters. The values of parameter t are given in units relative to their averaged meaning.

$$t_i = \frac{t_{исстенное}}{t_{среднее}} - 1$$

Second, the bigger is the size of evaporator, the smaller is the systemic component of error. The bigger sizes cause the Δ to approximate exponentially to its utmost values.

Third, at the appropriate choice of the range scale, we can get the exponent dependence for Δ. The range scale is assumed to be the value of geometric size of d in the α power.

At the first approximation, we build dependence of the systemic component of error on parameter t in the form of an exponential dependence on the evaporator size.

$$\Delta_i = a\exp\left(kd^{\alpha}\right)$$

where d is the square size of evaporator, *k*, α and *a* are its parameters. For each meteorological parameter, *k*, α and *a* assume values of their own. We investigated dependences of differences of systemic components of error of different evaporators for over than ten meteorological parameters.

For determining parameters *k*, α and *a,* an iterative procedure was worked out. The initial value of parameter *a* corresponds to the mathematical expectation of reading differences between the GGI-3000 and the 20 m^2 –pool. Then we find the logarithm of mathematical expectation of reading differences between the 3 m^2 -, 5 m^2 -, and 20 m^2 pools. At the next step of iteration, we determine the value of parameter *a* anew. Using the new value of parameter *a* , we get new values of parameters *k* and α . So, this iterative procedure lets us get evaluations of the values of the necessary parameters. Using the values of parameters *k*, α and *a* , we can evaluate the systemic component of error of the evaporators in general form. After making corrections in the measurement, we can apply the new method of comparison which we worked out for evaluation of systemic component of measurement error.

Thus, we get an underestimated evaluation of the systemic component of error, while the casual component of error, received with the use of the method of comparison, is overestimated. After *k* of successive iterations, the systemic component of error gets bigger and more precise, while evaluation of the casual component gets smaller. The tendency of parameters *k*, α and *a* to move in the direction to coincidence proves the correctness of the chosen model.

The analysis of the situation shows that the value of error is mostly influenced by humidity and its parameters, and, also, by the heat spent on water heating. Such mesoparameters as the wind, do not make any significant influence on evaporation of the systemic component of measurement error. First, the wind increases evaporation which cools the water, and then evaporation decreases.

Here are the ranges of the values which parameters *k*, α and *a* can take:

a- from 0,1 to 0,5 mm
k- from 0,01 to 0,7
α- from 0,4 to 0,8.

For evaluation of the systemic component of error, we also use a modified model of the heat balance, as follows:

$$\Delta E=1{,}32\exp(0{,}19t)-1{,}20 \qquad (16)$$

where ΔE is the difference of one-day averaged values of evaluation measurements between GGI-3000 evaporator and GGI-3000TM thermal-insulated evaporator, *t* is the difference of one-day averaged values between the soil temperatures at the depth of 20 cm and the temperatures of the water surface in GGI-3000 evaporator.

Formula (16) was used for correction of values of evaporation in GGI-3000 evaporator, the one that was not thermally insulated.

But for thermally insulated evaporator GGI-3000TM, we applied a different formula:

$$\Delta E=0{,}016h+0{,}038\Delta h+0{,}019\tau-0{,}103\Delta\tau-0{,}652 \qquad (17)$$

where Δ*E* is the difference between one-day averaged values of evaporation for the thermally insulated evaporator and the 20 m^2 pool, *h* is a midday sun altitude (in degrees) in the middle of a month, Δ*h* is the difference in midday sun altitude between the first and the last day of a month, *τ* is the length of the day's bright time in the middle of a month, Δ*τ* is the difference of the length of the day's bright time between the first and the last day of a month.

It's clear that formula (17) is of empirical averaged character. To receive better results and preserve the general form of our new approach (15), we'll transform formula (16) into the following:

$$\Delta E = \Delta_0 + \Delta_1 h + \Delta_3 \tau$$

where *h* and *τ* are the same parameters in relative units as in (17). As a result, it was found out that the systemic component of error was influenced only by humidity, temperature and the heat balance parameters. The joint contribution of these parameters to the influence on the systemic error makes 82%. The wind speed and precipitations influence values of the systemic component of error just insignificantly. Thus, finally, for the systemic component of error, we got the dependence on the five parameters: humidity, the length of a day's bright time, maximal altitude of the sun over the horizon, temperature of the water and of the air. And so, we got the following formula for evaluation of the systemic component of error:

$$\Delta E = \Delta_0 + \sum_{i=1}^{n} \Delta_i t_i$$

The values of Δ depend on the type of evaporator and on the conditions of observation. Values of Δ for GGI-3000 are given in table 1.

Table 1

	Δ_0	Δ_1	Δ_2	Δ_3	Δ_4	Δ_5
Value	2,1	0,27	0,23	0,18	0,22	0,16

Influence of other meteorological parameters (about 18%) are ascribed to coefficient Δ_0 and can be treated as dispersion of values of the systemic component of error.

After correction of the results of measurement, we can also evaluate the values of the casual component of error using the comparison method as well as the traditional method assuming that the casual component of error for the 20 m^2 pool is insignificantly small. Close similarity of values of the systemic component of error, received with either of the two methods, proves correctness of our new approach.