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ANALYTICAL REVIEW OF METHODS FOR CALCULATING EVAPORATION FROM A WATER SURFACE

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ABSTRACT

Evaporation loss is an important issue in hydrology. Any water project especially in arid and semi-arid regions must consider evaporation in planning, design, and operation. Because of the importance of the evaporation in hydrological cycle and water budget in addition to the different methods used to calculate it, the significance of studying these methods. The paper dealt with research and analysis on the different methods of measuring evaporation, in which an overview of the method, the scientist who created it, in addition to the scientific analysis of the method, the modifications made to it by other scientists, the conditions of use, the problem in each method and the methods of calculating the coefficients involved in it. The paper also dealt with the accuracy of each method in calculating evaporation. The methods of measuring evaporation that the paper touched upon are Water balance, Evaporators and evaporating basins, Heat balance, Turbulent diffusion, and Empirical formulas. The paper gives a good analytical review of the mentioned methods. An analytical review was done of these methods by discussing uses, applications, and problems faced by these methods.

KEYWORDS: Evaporation, Water Surface, Dalton, Zaikof, Water balance, Heat balance, Water bodies.

1.0 INTRODUCTION

Environmental, industrial, and climatic changes are affecting the hydrological cycle of different regions, worldwide. Due to such changes, the shortage of water resources has become a serious threat to arid environmental areas, such as the Kingdom of Saudi Arabia (KSA) and Sudan. Evaporation loss is an important component of the hydrological cycle and precise estimation of the rate of evaporation from various sources of water plays an important role in the planning, design, and operation of natural water resources, particularly in arid regions. Therefore, the evaporation loss should be given appropriate attention while dealing with water/energy budgets and climate change impacts.

2.0 BACKGROUND

Evaporation of water is the most important process of the hydrological cycle, providing water vapor to the atmosphere. At the beginning of the 19th century, Dalton[3] was the first to establish a quantitative law describing the rate of evaporation as a function of the saturated vapor pressure and the partial vapor pressure in the air surrounding the evaporating liquid. Modifications of Dalton's law in various empirical forms still take place.

In the 19th and first half of the 20th century, the main theoretical concepts were formulated and methods for assessing evaporation were developed for various underlying surfaces.

A great contribution to the development of the theory of evaporation was made by scientists: Ya.I. Frenkel, V.V. Shuleikin, E.M. Oldekop, M.I. Budyko, G.I. Taylor, W. Schmidt, H.W. Sverdrup, H.L. Penman and others.[11,21,24]

The following methods are used to assess evaporation from the water surface in the practice of hydrological research

1. Water balance
2. Evaporators and evaporating basins
3. Heat balance
4. Turbulent diffusion
5. Empirical formulas

3.0 Methods For Calculating Evaporation from A Water Surface

Let us start briefly on the main provisions of these methods.

Water balance method

About a reservoir, the water balance equation is as follows:

$$\frac{ds}{d\tau} = P - E + Y + Y' \text{...............(1)}$$

Where: $\frac{ds}{d\tau}$ change in the amount of water in the reservoir over time τ ; P - precipitation, dropped on the surface area of the reservoir; Y - is the difference between the surface inflow into the reservoir and the outflow of water from the reservoir; Y' - the difference between underground inflow and outflow of water from the reservoir; E - evaporation from the surface area of the reservoir.

In the absence of runoff and inflow of water, the equation of the water balance of the reservoir takes the following form:

$$\frac{ds}{d\tau} = P - E \text{...............(2)}$$

The most widespread use of the water balance method for assessing evaporation from water bodies has occurred since the mid-40s of the 20th century.[9,12] However, the use of the water balance method to assess evaporation from the surface of water bodies can be associated with significant errors, especially for short time intervals. In some years, random errors in determining the balance elements, in particular, the difference in groundwater inflow and outflow, as well as changes in water reserves in the reservoir can be large.

Therefore, the total error in calculating evaporation as a residual member of the balance equation can be significant.

This circumstance limits the application of the water balance equation for the estimation of evaporation.

The water balance method was used to assess evaporation from the surface of large water bodies like the Caspian and Aral seas, and lakes Sevan and Balkhash.[6,7]

The water balance method is quite often used as a control method when substantiating various empirical dependences of evaporation on the determining factors.

Evaporators and evaporating basins method

The evaporator method evaluates evaporation using a water balance equation.

When using observational data obtained from evaporators, to assess evaporation from a reservoir, the ratio is usually used:

$$E = kE' \text{...............}(3)$$

Where: k is the reduction factor; E'- evaporation by the evaporator. M.P. Timofeev.[22] noted that no rigorous physical or other proofs were presented to confirm the validity of the relation (3). Subsequent research was empirical. By these studies, it was found that for floating evaporators of the same size, the values of the coefficient "k" vary greatly both in time and across the territory. The operation of floating evaporators is associated with great difficulties in their installation and observation. Therefore, floating evaporators are not widely used in practice. Evaporator designs and methods for measuring and calculating evaporation from a water surface have been reviewed several times.

Among the recent works, it should be noted research carried out by employees of the Valdai branch of the State Hydrological Institute V.I. Kuznetsov,[16] V.I. Kuznetsov, and T.G. Fedorov,[17] as well as A.R. Konstantinov.[15] Based on the studies of the above authors, it has been established that the GGI-3000 evaporators give more reliable evaporation results in comparison with the "A" class evaporators (USA). The authors considered methodological issues related to the choice of location, installation, and operation of various types of evaporators and basins, and the generalization of observation data on evaporation.

As a result of the generalization of observation data on floating evaporators GGI-3000, it was recommended to use the following formula to estimate evaporation from the surface of small and medium-sized water bodies, the surface area of which does not exceed 40 km^2:

$$E = E^* \frac{\beta}{\alpha} \text{...............}(4)$$

Where: E - evaporation from the surface area of the reservoir; E^* - evaporation from the reservoir at the point of installation of the floating evaporator, estimated by the formula:

$$E^* = 0{,}88E'' \frac{e_0 - e_{200}}{e_0' - e_{200}} \text{...............}(5)$$

Where: e_0, e'_0- average monthly maximum water vapor pressure, determined by the temperature of the water in the reservoir and the evaporator (bar); e_{200}- average monthly absolute air humidity at a height of 200 cm from the surface of the water on a floating evaporation plant (bar); *E''*- evaporation of the floating evaporator GGI-3000, mm. The values e_0 and e'_0 - are estimated for each observation period, and then determined for the calculated time interval (decade, month).[23]

The β parameter for the tundra, forest, and forest-steppe zones is taken depending on the area of the reservoir, and for other zones - equal to unity. The parameter α is determined graphically depending on the length of the airflow acceleration for the installation point of the floating evaporator.

It was shown in the study,[13] that evaporation measured on floating evaporators with an area of 20 m^2 is approximately equal to evaporation from small water bodies. To switch from readings of floating evaporators with an area of 3.0 m^2 to an estimate of evaporation from a reservoir, a transition coefficient should be used, which is 0.86, and when switching from readings of GTI-3000 to evaporation from a reservoir, the value of this coefficient is 0.8.

In a study,[13] a method was proposed for calculating evaporation from a reservoir using data from the GTI-3000 continental evaporator.

In recent years, evaporation tanks with an area of 20 m or more have been widely used to assess evaporation from a reservoir. At the same time, in early studies, it was assumed that evaporation basins with an area of 20 m^2 characterize evaporation from small reservoirs. However, these considerations, according to M.I. Budyko,[11] were in contradiction with the theoretical studies of several authors. Based on these provisions, it was concluded that the actual dependences of evaporation on the driving factors can be established with the help of evaporation tanks with an area of 20 m^2. According to a study,[23] continental evaporation basins with an area of 20 m^2 can be used to assess evaporation rates from the surface of small water bodies.

In this case, evaporation from the reservoir is estimated by the formula:

$$E = E'''K_H K_3 \beta \text{..............(6)}$$

Where - E''' - evaporation from a pool of 20 m^2, mm; $K_н$ - is a parameter characterizing the effect of the depth of the reservoir on evaporation; $K_З$ - is a parameter characterizing the protection of the reservoir from the wind by steep banks, woody vegetation, buildings, and other obstacles.

The numerical value of this parameter depends on the ratio of the average height of obstacles to the average length of the airflow acceleration.

Heat balance method

The method of heat balance, first applied by Schmidt.[8] to assess evaporation from a water surface, is based on a universal relationship - the law of conservation and transformation of energy. At an early stage of research, the heat balance method was applied using empirical relationships between some of its elements.[11]

The next stage in the development and application of the heat balance method for evaluating evaporation was the use of the so-called "Bowen ratio" for calculating turbulent heat transfer in water bodies.[1]

Bowen's ratio for calculating evaporation from water bodies was first applied by Cummings N. and Richardson B.[11]

The heat balance equation is as follows:

$$E=\frac{(R^*-B^*)\Delta q}{\rho\Delta q+\frac{BC_p}{0.622}\Delta q}\text{...............(7)}$$

Where: Δq and Δt - the difference in specific humidity and air temperature at two heights above the water surface; R^* - radiation balance; C_p - heat capacity of air at constant pressure;

$$B^*=\Delta J-\Delta J_П-\Delta J_Г-\Delta J_л\text{...............(8)}$$

Where: ΔJ - the increase in heat in the reservoir for the period under consideration; $\Delta J_П$ - the difference in the amount of heat caused by the inflow into the reservoir and the outflow of water from it by the surface; $\Delta J_Г$ - the same due to the inflow and outflow of water by underground means; $\Delta J_л$ - heat exchange of the reservoir with the underlying soils.

In most cases, formula (7) is difficult to apply to estimate evaporation from a water surface due to the complexity of determining the element *B**.

It is often necessary to determine the radiation balance *R** not from observational data but to calculate it using empirical formulas.

There are some modifications to the use of this method, in particular, the approximate CL scheme. Penman.[21]

The heat balance method, when used correctly, leads to quite reliable results.

The application of the heat balance method is associated with the conduct of detailed actinometrical and meteorological observations over the water surface. These observations are quite laborious. As a consequence, the heat balance method has limited application.

Turbulent diffusion method

One of the promising methods for assessing evaporation from the surface of water bodies is the method of turbulent diffusion. This method is based on the provisions of the theory of turbulence, in the development of which Russian scientists.[11,19,20] and other scientists,[10,2] made a great contribution. The foundations of the turbulent diffusion method for evaluating evaporation in a real atmosphere were laid by the studies of G.I. Taylor,[5] and H. Jeffries.[11] However, the presence of uncertain parameters in the structure of the formulas obtained by them made it impossible to use them for quantitative calculations of evaporation. Further development of the theory of evaporation based on the use of the theories of turbulent diffusion is associated with the name of H.W. Sverdrup.[4] He got the following expression for evaporation:

$$E = \frac{\rho_1 D \omega (q_0 - q)}{ud + \frac{D}{H^2} \ln^2 \frac{z_1 - z_0}{z_0}} \text{...............(9)}$$

Where: ρ_1 air density, Z_0- the roughness of the water surface; ω - turbulence coefficient at a unit height; u - wind speed at height Z1; H^2 - aerodynamic constant equal to 0.38; q_0 - the concentration of saturated water vapor at the surface temperature of the water; D - molecular diffusion coefficient.

Formula (9) was used by Sverdrup to estimate evaporation from individual regions of the Atlantic Ocean. Sverdrup's formula was used by V.K. Davydov for calculating evaporation from the surface of the Caspian Sea. Further development of the theory of evaporation using the method of turbulent diffusion was carried out at the State Geological Institute by M.I. Budyko,[11] M.P. Timofeev,[22] A.R. Konstantinov,[15] and other researchers.

Empirical formulas

Despite the variety of existing empirical formulas for evaporation, all of them, with very rare exceptions, can be represented as:

$$E = \alpha(e_0 - e) f(u) \text{...............(10)}$$

Where: E - evaporation; e_0 - maximum water vapor pressure corresponding to the water surface temperature; e - actual vapor pressure in the air; u - wind speed; α - coefficient, taking into account the total influence of unaccounted factors on the evaporation process.

In Russia, the most famous are the formulas of V.K. Davydov.[8] B.D. Zaikof.[12,14]

To estimate evaporation from the surface of small water bodies and reservoirs, the formula of V.K. Davydov:

$$E = 15d'^{0.80}(1 + 0{,}125u) \text{...............(11)}$$

Where: E - evaporation, mm / month; d' - average monthly deficit of air humidity, mm; u - average monthly wind speed, m / s.

Average monthly values of air humidity deficit and wind speed are determined according to the data of the nearest meteorological station. To assess evaporation from the surface of small water bodies and reservoirs, V.K. Davydov, in the absence of wind speed observation data, recommended using a simplified formula:

$$E = 24{,}50d'^{0.80} \text{...............(12)}$$

Differences in the results of calculating the evaporation rate according to these formulas, according to V.K. Davydov, do not exceed 4 - 11%.

For the determination of evaporation from the surface of large bodies of water for daily intervals of time V.K. Davydov is recommended to use the following formula:

$$E = 0{,}48 d_1 (1 + 0{,}125u) \ldots\ldots\ldots\ldots\ldots (13)$$

d_1 - is the difference between the maximum water vapor pressure at water temperature and its actual elasticity in air at a height of 2.0 m; u - wind speed along the weather vane.

Formula B.D. Zaikof to assess evaporation from the surface of ponds and reservoirs for monthly time intervals are as follows:

$$E = 0{,}2i(e_0 - e_{200})(1 + 0{,}85u_{100}) \ldots\ldots\ldots\ldots\ldots (14)$$

Where: i - is the number of days in a month; e_o - is the elasticity of saturated water vapor, calculated from the water temperature, mm; e_{200} - elasticity of water vapor in air at a height of 200 cm above the water surface, mm; u_{100} - monthly average wind speed, m / s, at a height of 1.0 m above the earth's surface.

In the absence of observation data on the water surface temperature B.D. Zaikof recommended using the following formula:

$$E = 0{,}2i \times C^* d'^{0.78} \ldots\ldots\ldots\ldots\ldots (15)$$

Where: d'- deficiency of air humidity at a height of 2.0 m above the earth's surface;

C^* - is a parameter depending on the average ratio between the temperature of water in ponds and air, ranging from 1.4 to 2.2.

According to observations in the evaporator pools, S.N. Kritsky, M.F. Menkel and K.I. Russian.[8] obtained the dependence of evaporation on the difference between vapor pressures and wind speed in the form:

$$E = 0{,}13i(e_0 - e_{200})\sqrt{1 + 0{,}15u_{900}} \ldots\ldots\ldots\ldots\ldots (16)$$

Where: u_{900} - is the wind speed at a height of 9.0 m, determined from the data of the nearest meteorological station, formula A.P. Braslavsky and Z.A. Vikulina.[13] has the following form:

$$E = 0{,}13i(e_0 - e_{200})(1 + 0{,}78u_{200}) \ldots\ldots\ldots\ldots\ldots (17)$$

After analyzing all the available empirical formulas and making the appropriate adjustments, to estimate the monthly amounts of evaporation from the surface of all reservoirs, regardless of their size, VI Kuznetsov, VS Golubev, and TG Fedorova,[17] recommended the following formula:

$$E = 0{,}14i(e_0 - e_{200})(1 + 0{,}78u_{200})..............(18)$$

Formula (18) is applicable under conditions of equilibrium stratification when the temperature difference between water and air does not exceed 2 - 4 ° C.

In the presence of nonequilibrium conditions, it is more expedient to estimate evaporation using the formula of V.A. Rymshi and R.V. Donchenko,[18] or by the formula of A.P. Braslavsky and S.N. Nurgaliev.[8]

Formula V.A. Rymshi and R.V. Donchenko looks like:

$$E = 0{,}104i(e_0 - e_{200})(k_0 + u_{200})..............(19)$$

Where: K_o - is a parameter depending on the difference between the surface temperatures of water and air (Δt_1).

The formula of A.P. Braslavsky and S.N. Nurgaliev.[9]

The problem of using empirical formulas for calculating evaporation from the surface of water bodies is still topical. Of the numerous empirical formulas for calculating evaporation, the most suitable are formulas (18) and (19) recommended by the "Guidelines for calculating evaporation from the surface of water bodies".[23]

4.0 CONCLUSION

Different methods for calculating evaporation from different water bodies are presented in this paper. An analytical review was done of these methods by discussing uses, applications, and problems faced by these methods. Finally, it was pointed out that this paper is an analytical review of different methods of evaporation, which in turn is considered as a background for other scientific papers to come in the future by the author.

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