EVAPORATION FROM LAND, EVAPOTRANSPIRATION

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Contents

Summary

The basic physical principles of evaporation from land were founded in the nineteenth and early twentieth centuries. There are two groups of methods for determining evaporation from land. Experimental methods are based on special experiments in the study areas. Design methods are based on the use of standard hydrometeorological observation data. In the first group, the method of evaporimeters-lisimeters and energy balance method are most widely applied. A water balance method is often applied for small areas during a warm season when subsurface water is deep and surface runoff is not observed. It has been established that under the assessment of experimental methods for determining evaporation, quite reliable results for monthly intervals are provided by the standard version of the heat balance method based on the use of Bowen's equation. In the second group methods based on the solution of the equations of turbulent diffusion, heat balance or complex schemes are most suitable for computation of evaporation from land for particular months during the warm season. The use of a single model of water and heat regime formation within some territory with accounting its specific features is one of the basic ways to improve the accuracy of land evaporation computation.

1. Introduction

Landscapes greatly depend on the peculiarities of water cycle distribution on the land surface, where evaporation is one of the main links of the water cycle, together with precipitation and runoff. The problem of assessment of geosystem sustainability under the influence of the present intensive human activity is very important. In fact, this is one of the problems of predicting the development of the human society and its interaction with the geographic sphere. According to contemporary ideas the solution of this problem is possible on the basis of mathematical modeling methods. A number of approaches (statistical and system analyses, method of expert assessments, physical and mathematical models, etc.) is used to make such models. One of the approaches developed by academicians. A.A. Grigoriev and M.I. Budyko is based on the theory that evaporation in Nature is the main implementation mechanism of surface processes. Within the framework of this theory evaporation is considered as a bilateral process governed, on the one hand, by energy resources expressed as maximum possible evaporation (evaporativity or evaporation from water surface), and on the other hand, by water resources characterised by the quantity of precipitation. Hence, it follows that when creating models of geosystem development it is necessary to take into account the process of heat and moisture interaction in the "soil-plant-atmosphere" active layer. Evaporation of water from land surface is the key link in this process. In fact, a general model of water evaporation is the basis for a development of the surface process model. The first attempts to describe evaporation process were made in the sventeenth century. Edmund Halley was the first to prove by his experiments that the water cycle in Nature is closely connected to evaporation. Much was done by G.W. Richman to develop evaporation theory until the first mathematical description of the evaporation process was made by John Dalton in 1802, known as Dalton's Law. This law is valid for free water surface. Evaporation from land is a much more complicated process. The basic physical principles of evaporation from land were founded in the late nineteenth and early twentieth centuries. There are now seven groups of methods, which allow solution of the problem of estimation of evaporation from land.

Group 1: Evaporation from land is related to the regime of soil moisture content. P.S. Kossovich made a significant contribution to this trend by his discovery of three stages of evaporation. He proved that evaporation slightly depends on soil moisture content if this content is very high. As the soil becomes drier evaporation rate tends to decrease sharply and then it becomes much less subject to changes. Later studies of other scientists resulted in discovering the dependence of evaporation from land upon evaporation from an unrestricted wet surface (evaporativity or potential evapotranspiration) and soil moisture content. At present, these dependences are used in different schemes to compute evaporation. In particular, the methodology of V.G. Andrejanov—a complex energy-water balance method—some modifications of H.L. Penman's method, and the method of A.I. Budagovsky are based on these dependences.

Group 2: Evaporation is considered as a residual term of the water balance equation for a land area, say a river basin. is known as the water balance method.

Group 3: This group is based on studies of relations between evaporation and evaporativity, precipitation and other water balance components. These publications mainly describe background evaporation from watersheds. Earlier studies in this field were made by Shreiber and Oldecop. They analyzed data on water balances of different watersheds and derived equations in which evaporation depends on precipitation and potential evapotranspiration. Later, these studies were developed by L. Turc, N.A. Bagrov, V.S. Mezentsev, V.I. Babkin *et al*.

Group 4: Evaporation from land is considered as a process of water vapor transfer from the evaporating surface to the atmosphere. This research trend was initiated by Jeffreys who used a turbulent diffusion equation to describe evaporation. Later, the turbulent diffusion equation was modified by O. Setton, D.L. Lechtman, M.I. Budyko, M.P. Timofeev, A.M. Obukhov, A.S. Monin *et al.*

Group 5: this involves research on plant transpiration. In the nineteenth century it was assumed that water loss for transpiration was proportional to increment of biological mass of plants, and much work was done to determine the so-called transpiration coefficients. But during the 1890s K.A. Timiriazev demonstrated that plant transpiration, under usual conditions, greatly exceeded the true water demand of plants. On the basis of a number of tests Levingston came to the conclusion that the mechanism of transpiration was closely connected to the regime of stomata activity and with the saturation condition of leaves.

A.M. Alpatiev proved quite convincingly that even at the optimal soil moisture content, the transpiration coefficients could be constant only in case of permanent climate, permanent soil fertility, constant type of plants, etc. The yield of plants primarily depends on nutrients, whereas transpiration depends on climate conditions, plant age and type, soil moisture content and soil aeration. He introduced a term "biological water consumption curve" (or biological coefficient) which characterizes relations between transpiration (or evapotranspiration) and meteorogical conditions. This approach has been widely applied for development of bioclimatic methods, developed by A.R. Konstantinov, A.M. Alpatiev, Grindley *et al*.

Group 6: Some methods were developed on the basis remote sensing data. Here evaporation is determined as a residual term of the water balance equation of the atmosphere through the difference between precipitation, atmospheric moisture discharge (income minus discharge of water vapor) and changes in moisture content in the air mass above the study territory. This method has been applied to study the water balance of the Great Lakes: it was used by O.A. Drozdov.

Group 7: There are methods based on the establishment of empirical relations between evaporation and hydrometeorological components. It includes the works of Mayer who established relations between monthly evaporation and air temperature, and works of P.S. Kuzin, Blaney-Kridl, Thornthwaite *et.al*.

According to the above groups of research trends, experimental and design methods were developed. Experimental methods of evaporation determination are based on special experiments directly in study areas. Design methods are based on the use of standard observation data received by different agencies, by hydrometeorological and hydrogeological networks in particular.

Experimental data provides a basis for evaluation of design methods, though the quality of experimental methods is rather low. Random errors in these methods are comparable with their temporal variability, even for monthly evaporation. Most research methods used at hydrometeorological stations and even during field experiments have high systematic errors. An analysis of presently used methods of determining evaporation from land is given below. Experimental methods are described first, and the basic design methods are then estimated on the basis of the experimental methods.

2. Experimental Methods for Determining Evaporation from Land

The method of evaporimeters-lisimeters and the energy balance method have been most widely applied in hydrometeorological studies to determine evaporation from land. The water balance method is often applied for small areas during a warm season when subsurface water is deep and surface runoff is not observed, e.g. for agricultural fields. Data on precipitation and soil moisture content is used as an experimental basis. In this scheme evaporation (E) is estimated from the water balance equation of the study area, say a field:

$$E = P - (W_f - W_b) \qquad (1)$$

where: P is precipitation during the design time interval; W_f and W_b are basic and final soil moisture storage, usually in the top soil layer 1m deep, estimated by any well-known method (thermostatic, gravimetric, neutron, gamma-indication, tensiometric, osmic, etc.). If there is a shallow water table (to 3-5 m deep) and available runoff, water balance plots are arranged. A plot of several square meters in area is selected; an impermeable wall is installed around the plot from its surface to the deepest position of the ground water or to the aquiclude. Special flumes are mounted along the wall to collect and measure surface and subsurface runoff. Precipitation gauges are also installed here to measure precipitation; regular measurements of soil moisture content are made to the groundwater table, so the depth of ground water table is fixed. Evaporation from the surface of the water balance plot is estimated by the following equation:

$$E = P - (W_f - W_b) - Q_s - Q_{gr} - \mu\ (H_{gf} - H_{gb}) \qquad (2)$$

where: Q_s and Q_{gr} are surface and subsurface (groundwater) runoff; μ is water yield coefficient; H_{gf} and H_{gb} are final and basic depths of the groundwater table. Evaporimeters and lysimeters are specific capacities with fixed areas of evaporating surfaces and fixed depth.

Soil evaporimeters of different size and design are used for experimental determination of evaporation from land surface where there is a deeper groundwater table (deeper than 2 or 3 m). They differ in the way of filling by loose soil or by an undisturbed soil monolith. Evaporimeters may not involve weighing when changes in soil moisture content is determined by special instruments. Alternatively, the change in soil moisture content can be determined by weighing soil monoliths on special scales (or weighing-machines) of high accuracy. To measure the amount of water infiltrated through a soil layer or through a soil monolith, the evaporating vessel in the bottom of the evaporimeter is equipped with a special weir or, more often, by a screened removable bottom. Evaporation in this case is calculated by the following equation:

$$E = P - (W_f - W_b) - I \qquad (3)$$

where: I is infiltration (water percolated through soil monolith).

Change in soil moisture content in soil monoliths for a design period of time is usually determined from the difference in the evaporimeter weight. Sometimes other methods are used to measure soil moisture content, in which extraction of soil samples (monoliths) is not required. When the groundwater table is shallow it is recommended to use lysimeters instead of evaporimeters. Unlike evaporimeters, lysimeters are equipped with special devices to maintain a specified water table in the soil. The appropriate equation for calculating evaporation is as follows:

$$E = P - (W_f - W_b) - I + E_{gr} \qquad (4)$$

where E_{gr} is groundwater outflow to the aeration zone (the term “evaporation from the surface of water table” is often used in the literature, see *Evapotranspiration from Open Water Surface and Groundwater*). When studying evaporation from land surface, particular emphasis should be focused on evaporation from swamps and forested areas. The water balance method can be used for a forested river basin where precipitation, surface runoff and soil moisture content are measured. This method is most useful for the case of a deep groundwater table. The method of water balance plots can be applied in special studies. These two methods are applicable to estimate monthly evaporation. For shorter time intervals large errors can be found if these methods are applied because of insufficient accuracy of soil moisture content measurements. In such cases the method of weighed evaporimeters or lysimeters is applied. Moreover, instruments with a large evaporating surface are used; e.g. in Valdai, V.A. Ouryvaev, in his experiments, used evaporimeters with an evaporating surfaces of 5 m^2 and weighed on hydraulic scales. In Australian studies evaporimeters with evaporating surfaces up to 28 m^2 were used and these evaporimeters were weighed on tensiometric scales. In the national network in Russia GGI-500 pans with evaporating surface of 500 sq. cm and the depths of the soil monoliths 50 or 100 cm are usually used. Hydraulic evaporimeters GR-19 and lysimeters GR-80 with evaporating surface of 0.3 $m^2$are also applied. Experimental methods for determining evaporation from land are based on a determination of water vapor flux from an active surface to the atmosphere, and the following equations are used:

1. Energy balance of the active surface

$$R = L_E + G + B_s \qquad (5)$$

where: R is radiation balance of the active surface; L_E is energy loss for evaporation; G is turbulent heat exchange; B_s is energy flux to soil.

2. Turbulent heat (energy), and water vapor and quantity of movements transfer in the lower atmospheric layer:

$$G = - C_p \rho K_\theta \cdot d\theta/dz \qquad (6)$$

$$L_E = - \rho \cdot L \cdot K_E \cdot dq/dz \qquad (7)$$

$$A = - \rho_a \cdot K_A \cdot d\omega/dz \qquad (8)$$

where: A is vertical transfer of the quantity of movements; C_p and ρ are heat capacity and density of the air; K_t , K_E and K_A are turbulence coefficients for heat and water vapor fluxes and for the quantity of movements; $d\theta/dz$, dq/dz, $d\omega/dz$ are vertical gradients of air temperature (θ), specific air humidity (q) and wind velocity (ω); z is a vertical coordinate.

3. Heat transfer in soil, water melting and freezing in soil and on the soil surface

$$B_s = - \lambda_\theta \rho_s d\theta_s/dz \pm L_i \Delta m \quad (9)$$

where: λ_θ,ρ_s are heat conductivity and density of soil; $d\theta_s/dz$ is vertical gradient of soil temperature (θ_s); L_i is heat of ice water melting; Δm is mass of melted or frozen moisture in soil and snow cover. The use of the above methods for experimental determination of evaporation from particular types of surfaces requires the following types of special observations to be taken. If only equations (6)-(8) are applied, this approach to determine evaporation is called the turbulent diffusion method, based on the account of vertical distribution of air temperature, air humidity and wind velocity at the elevation of 2 or 3 levels and higher above the active surface. It is difficult to apply the turbulent diffusion method, however, because the method of computation of turbulent coefficients for heat and water vapor fluxes and the quantity of movements has not been properly developed. If the system of equations (5)-(9) is used, this approach to determine evaporation is called the heat balance method. In addition to the turbulent diffusion method it is necessary to organize observations of radiation balance of the active surface, heat flux into the active surface, heat losses for water melting and freezing. A merit of this method is that does not require an accurate presentation of equations to determine turbulence parameters, but, if (R-B) is close to 0, its use results in great random errors in determining evaporation.

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Biographical Sketch

Anatoly Vershinin was born in 1941 in Russia. He graduated in 1964 from Department of Climatology, St. Petersburg State University. In 1974 he was awarded Doctor of Technical Science, and in 1996 Docent, St.Petersburg State University.

He has held the following positions:

Principal scientist (1976-1990), State Hydrological Institute;

Scientific secretary (1971-1980), Hydrology Commission of Geographic Society of the USSR;

Associate Director of Ecological Research (1990-1992), "Ecology" Scientific and Industrial Corporation;

Deputy Director for Science (1992-1996), Northwest Branch of Water Resources Institute;

Docent (1996-present), St. Petersburg State University.

He was a member (1983-1990) of the Working Group on Soviet Economic Mutual Aid on problem "Influence of Human Activity on Water Resources". He was also WMO Expert (1983-1991) for Hydrological and Meteorological problems in Syria and Mongolia.

He gives lecture courses at St. Petersburg University, on Meteorology; Climatology; Microclimatology, andEcological problems in meteorology. At St. Petersburg Hydrometeorological University, he lectures on Reclamation Hydrology.

His research activity involves microclimatology, evaporation in nature, heat and water balance, reclamation hydrology, and water resources.

He is a co-author of the following books:

Water and salt balance on reclaimed areas in South Kazakhstan, 1980, Co-authors: S.Kharchenco, K. Tsytsenko et al, Leningrad, Gidrometeoizdat (in Russian);

Casebook of calculation of evaporation from land, 1978, Co-authors: P. Kuzmin et al., Leningrad, Gidrometeoizdat, (in Russian);

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He has had ore than 70 publications in numerous national and international journals and proceedings of conferences and symposia.