EVAPORATION FROM OPEN WATER SURFACE AND GROUNDWATER

V.S. Vuglinsky

State Hydrological Institute, Russian Federation, Russia

Keywords: Evaporation, water surface, groundwater, physical principles of the process, history, instruments, computation methods

Contents

1. Evaporation from open water surface
1.1. Introduction
1.2. Brief historical survey
1.3. Instruments to study evaporation from water surface
1.4. Methods for evaporation measurements from open water surface
1.4.1 Method of pans
1.4.2 Energy balance method
1.4.3 Aerodynamic method
1.4.4 Computation of evaporation from empirical formulas
1.5. Evaporation from water surface in different physiographic features
2. Ground water evaporation
Glossary
Bibliography
Biographical Sketch

Summary

Evaporation is a process of water vapor formation from a free water surface. As distance from the evaporating surface increases, the water vapor concentration reduces. Transfer of water vapor molecules from the evaporating surface to the environment is accomplished by a vertical turbulent exchange of air masses. Evaporation from a water surface has been investigated by scientists since ancient times. In the Middle Ages, however, it was possible to obtain the first quantitative assessments of evaporation by experiments. In the middle and end of the nineteenth century two trends in studying evaporation from free water surfaces prevailed, i.e. the use of evaporimeters and empirical formulas to determine evaporation rate from meteorological data. Early in the twentieth century two new trends were developed, i.e. an approach based on analysis of water vapor turbulent diffusion in the atmosphere, and a method of energy balance. At present different methods are applied for evaporation computation. The water balance method provides a direct integral value of evaporation from a water body, but this method may be applied only in cases when the absolute evaporation value is compatible with the other water balance components. Also, the method of evaporimeters, energy balance method, turbulent diffusion method and empirical formulas are widely applied. Space distribution of evaporation from free water surfaces follows the principle of geographical zonality and vertical altitudinal belts (in mountains). Water losses from the surface of a water table and identified as evaporation have another physical essence. With a shallow water table, the moisture is lost for transpiration and evaporation from

soil and it is recharged by capillary water rise from the subsurface water table. This process is conventionally termed "subsurface water evaporation" or "subsurface water outflow to the unsaturated zone". The amount of moisture inflow to the unsaturated zone during subsurface water evaporation is much less than evaporation from a free water surface. Mean monthly evaporation of subsurface water does not exceed 30 mm.

1. Evaporation from open water surface

1.2. Introduction

Evaporation is a process of vapor formation from a free water (or snow, ice) surface. The reverse process of vapor transition to the liquid state is condensation. Boiling differs from evaporation; during boiling, vapor is formed not only on the surface but inside the liquid and vapor bubbles go upward. Evaporation occurs at any temperature at different rates, but boiling occurs only at the temperature at which the pressure of the saturated vapor in the liquid attains the value of the atmospheric pressure. According to the molecular-kinetic theory evaporation is characterized by three interrelated stages: evaporation of molecules from the evaporating surface; absorption of some molecules by the evaporating surface; diffusion of the remaining molecules into the surrounding space. Molecules in the inner water layers move sporadically in any direction, because they are affected by the attraction of the surrounding molecules, which is similar on average. Meanwhile molecules in the surface water layer are affected by less attraction of the air molecules than the molecular attraction in the inner water layers due to the lower concentration of the air molecules. The rates of molecular motion are different; those molecules which reach the evaporating surface at high speeds and at big angles, overcome the attraction of other water molecules and, when separating from the evaporating surface, they escape into vapor. The higher the temperature, the more molecules with high speeds, and the more intensive is molecule diffusion into the surrounding space. Also, mean distance between molecules tends to increase with temperature rise; this leads to reduced cohesion forces and evaporation heat, which also stimulates a greater flux of molecules separated from the evaporating surface. The evaporation process is accompanied by losses of some energy to overcome forces of cohesion and for the work connected with the increase of the specific volume of the fluid during its transformation into vapor. The total energy required for this, depends on the latent heat of evaporation. If, during the evaporation process, energy does not reach water, the water is cooled, resulting in lower evaporation. In Nature, energy losses during evaporation are completely or partly compensated due to the environmental energy. As a result of evaporation a layer enriched by vapor molecules is formed above the evaporating surface. Migrating in different directions, these molecules partly diffuse into the air and partly return into water when they touch the evaporating surface. With an equilibrium, the quantity of molecules springing out of water is equal to the quantity of molecules which return back. If the quantity of molecules transformed into vapor exceeds the quantity of molecules simultaneously transformed into liquid, the evaporation process occurs; in the opposite case condensation is observed. Thus, evaporation and condensation are two facets of one process of molecular exchange between water and air above the water surface. As distance from the evaporating surface increases, water vapor concentration gradually decreases. A condition close to saturation is observed only in that part of the layer which touches the water surface.

Evaporation, however, proceeds because the vapor molecules are constantly migrating to the environment. There will be no evaporation if water vapor concentration all over the space at a long distance from the evaporating surface corresponds to the concentration of complete water vapor saturation above the evaporating surface. Transfer of vapor molecules from the evaporating surface to the environment is accomplished by molecular diffusion and vertical turbulent air mass exchange. With absolutely quiet air condition the water vapor transfer is accomplished by molecular diffusion i.e. intrusion of molecules during their chaotic migration from sites of high water vapor concentrations to sites of lower concentrations. Diffusive water vapor flux through unit area per unit time, or evaporation rate, is presented by the following equation:

$$E = -\rho \, D \frac{\partial q}{\partial z} \quad \text{g/sq.cm s} \tag{1}$$

where: ρ is air density, (g/cm^3); D is coefficient of water vapor diffusion in the air (cm^2/s) constant over altitude; $\frac{\partial q}{\partial z}$ is vertical gradient of the specific air humidity (g/cm). Minus indicates that the water vapor flux is positive in the direction of decreasing specific air humidity. Integrating equation (1) within the limits of $z=0$ (the level of the evaporating surface) up to a certain level of z, we derive:

$$E = \frac{\rho \, D}{z}(q_0 - q_I) \quad \text{g/sq.cm s} \tag{2}$$

where: q_0 is specific air humidity at the level of $z=0$. During computations this value is assumed to be equal to the specific humidity of the saturated air at the temperature of the evaporating surface. For the case of $z = 1$ cm, at air temperature of 0 °C and normal atmospheric pressure equation (2) is reduced to:

$$E = 0.286 * 10^{-3} (q_0 - q_1) \tag{3}$$

It follows from this equation that if the air is dry ($q_1=0$) the diffusive evaporation rate is maximum. In saturated air ($q_1=q_0$) evaporation rate equals zero. Increasing temperature of the evaporating surface q_0 causes an increase in evaporation rate. Under field conditions equation (3) is not valid because real evaporation rates turn out to be much higher at the same values of specific air humidity. This is explained by the fact that under field conditions the evaporation process occurs not in a quiet atmosphere but in air which is constantly moving; the nature of this motion is sporadic and turbulent. The turbulent air motion produces a vertical exchange (mixing) of the air mass, causing water vapor transfer. During the vertical exchange some eddies take wet air mass away from the evaporating surface while simultaneously bringing in air with less moisture content.

The turbulent exchange is usually intensified at higher wind speed and greater roughness of the underlying surface (dynamic mixing) as well when there is warming or cooling of the above air layer (convective mixing). In accordance with the ideas of

Taylor and Schmidt the vertical turbulent exchange (diffusion) can be presented by the following equation, similar to the equation for molecular diffusion:

$$E = -\rho \, K_z \frac{\partial q}{\partial z} \quad \text{g/sq. cm s} \tag{4}$$

where: K_z is coefficient of turbulence characterizing the exchange intensity. As to the coefficient of molecular diffusion (see equation (1)) the dimensionality of the turbulence coefficient K_z is in cm^2/s. But as to the magnitude, K_z exceeds D by thousands of times. Therefore, evaporation in a quiet atmosphere (diffusive evaporation) may be assumed to be negligibly small (practically equal to zero) when compared with that in a turbulent atmosphere. Coefficient K_z is constant in time and over altitude; it depends on wind speed, roughness of the underlying surface and on the rate of convection development. Taking the latter into account and integrating equation (4) from $z=0$ up to a certain value of z, we derive:

$$E = \frac{\rho \, (q_0 - q_z)}{\displaystyle\int_0^z \frac{dz}{K(z)}} \quad \text{g/sq. cm s} \tag{5}$$

M.I. Budyko introduced the term "coefficient of external diffusion" which is derived from the following equation:

$$D = \frac{1}{\displaystyle\int_0^z \frac{\partial z}{K(z)}} \tag{6}$$

Substituting equation (6) into equation (5) we derive:

$$E = \rho \, D \, (q_0 - q_z) \quad \text{g/sq. cm s} \tag{7}$$

Equations (3) and (7) were known for a long time as empirical ratios, or Dalton law, according to which evaporation rate into a free atmosphere is expressed by the following equation:

$$E = \alpha \, (e_0 - e) \tag{8}$$

Where: e_0 is saturated water vapor pressure calculated from water temperature; e is water vapor pressure at a certain elevation above the water surface; α is a coefficient numerically equal to the evaporation rate if the difference of water vapor pressure equals unity. Equation (8) has been used as the basis for numerous empirical formulas for calculation of evaporation from the surface of water bodies based on the use of hydrometeorological information from the meteorological network. These formulas are presented as follows:

$$E = c \, (e_0 - e) \, f (\omega) \tag{9}$$

Where $f(\omega)$ is a certain function of wind speed; c is a coefficient taking complete account of the effect of those factors not taken into account but influencing the evaporation process. It should be noted that evaporation rate of salt water is lower than that of fresh water, other conditions being equal. This is explained by the fact that when salt water evaporates the vapor particles springing out of the salt water have to overcome not only the forces of water molecules gravity but the gravity of the matter dissolved in the water. Therefore, the salt water vapor pressure is lower than that of fresh water. Hence, for example, the pressure of saturated vapor of NaCl solution (340 $^o/_{oo}$), if compared with distilled water, is reduced by 22 %; for sea water (35 $^o/_{oo}$) this decrease is about 2%, and for brackish water (10 $^o/_{oo}$) it is only 0.5%. Thus, a significant decrease of evaporation rate occurs from solutions with high concentrations of admixtures. This factor is of no importance for natural fresh water. Increased evaporation rate may be observed at high wind speeds, when the wave crests are taken away by the wind and minute drops of water jumping in the air are taken by turbulent fluxes upward to less saturated layers where they evaporate. This evaporation, additional to the physical evaporation, is termed mechanical evaporation. It is most intensive where waves break as they approach a shore, and in the intertidal zone. Finally, there is a viewpoint that evaporation depends on atmospheric pressure. This view would be valid if water vapor transfer under natural conditions occurred through molecular diffusion, the coefficient of which is inversely proportional to atmospheric pressure. As noted above, however, the mechanism of water vapor transfer under natural conditions is based on turbulent mixing independent of atmospheric pressure. This viewpoint is therefore erroneous.

-
-
-

TO ACCESS ALL THE **21 PAGES** OF THIS CHAPTER,
Visit: http://www.eolss.net/Eolss-sampleAllChapter.aspx

Bibliography

Babkin V.I. (1984) *Evaporation from water surface,* 78 pp., Hydrometeoizdat, Leningrad [in Russian]. [Methods for the assessment of evaporation from water surface are given. Formulae are presented for the assessment of evaporation rate from a water surface on the basis of a molecular-kinetic theory of evaporation.]

Bowen I.S. (1926) *The ratio of heat losses by conduction and by evaporation from any water surface,* Phys. Rev., vol. 27, 779-787. [The ratio between turbulent heat flux to the atmosphere and heat loss for evaporation from a water surface (later termed 'Bowen's ratio') is validated.]

Brutsaert W. (1982). Evaporation into the atmosphere. Theory, history and applications, 346 p., D.Reidel Publishing Company. [This presents principles of the theory of evaporation to the atmosphere and recommendations on the practical application of this theory.]

Dalton I. (1802). Experiments and observations made to determine whether the quantity of rain and dew is equal to the quantity of water carried off by rivers, and raised by evaporation; with an inquiry into the origin of springs. Mem. Lit. Phil. Soc. of Manch., vol.5, part 2,346-372. [This presents principles of

contemporary evaporation theories. Dependence of evaporation from water surface upon air humidity and wind velocity above the evaporating surface is validated.]

Lebedev A.B. (1976). Methods of ground water balance investigation, 223 pp. M., Nauka.. [In Russian]. [This presents methods for study and computation of subsurface water balance.]

Penman H.L. (1948). Natural evaporation from open water, bare soil and grass. Proc. Royal Soc. London, A193, 120-146. [This is a theoretical substantiation of the formula for compilation of evaporation from a free water surface based on the data of measurements of water vapor, wind velocity and air temperature at the same elevation.]

Schmidt W. (1917). Der Massenaustausch bei der ungeordneten Stromung in Luft und seine folgen, 126 p., Akad. Der Wiss. Wien Math. - Nat. K1. Sitzber. Abt. 2a. [This presents estimates of the radiation balance of latitudinal ocean zones and total evaporation from these zones, as well as mean ratios between total heat lost for evaporation and total heat exchange between ocean and atmosphere.]

Shuleikin V.V. (1926). The kinetic theory of evaporation., Journal of the Russian phis-chem soc, phisic. part. **8**(3), 527-539. [In Russian]. [This presents a molecular-kinetic theory of evaporation process.]

Taylor G.I. (1915). Eddy motion in the atmospher, 215 pp. Phil. Trans. Roy. Soc., A. [This is a description of the mechanism of turbulent diffusion of passive substances in the atmosphere, including water vapor distribution.]

The CIMO (1976). International Evaporimeter Comparison,98 p., WMO 449, Geneva. [This presents the results of international inter-comparison of observation data on evaporation from water surface by evaporimeters of different designs.]

Biographical Sketch

Valery Vuglinsky was born in 1939 in Moscow, Russia. He graduated in 1966 from Department of Geography, St. Petersburg State University. In 1972 he gained his PhD from the State Hydrological Institute and in 1990 his Sc.D. from Moscow State University named after Lomonosov. Since 1994 he has been a Professor at St. Petersburg State University

Positions held:

Deputy Director for science (1982 - present), State Hydrological Institute;

Professor and Head (1989 - present), Department of Hydrology, St. Petersburg University

International experience:

- Member (1993 – present) International Informatization Academy;
- Member (1982 – present), Working Group on Hydrology RA-VI (Europe), World
- Meteorological Organization;
- Member (1993 – present), International BALTEX Science Steering Group

He gives the following lecture courses in St. Petersburg University:

- River runoff and water balance;
- Hydrology of lakes and reservoirs;
- Water resources inventory, etc.;

His research activities have focused on Water resources and water balance; Hydrology of lakes and reservoirs; Water resources inventory; and Hydroecology.

He has written the following books:
- "Water Balance of River Basins", 1982, Co-author: V.Babkin, Leningrad, Hydrometeoizdat, (in Russian);
- "Manual on hydrological computations for reservoirs under project", 1983, Editor and co-author; Leningrad, Hydrometeoizdat, (in Russian);

- "Water Resources and Water Balance of the USSR Large Reservoirs" 1991, Leningrad, Hydrometeoizdat, (in Russian);
- "Methodology for distinguishing between man's influence and climatic effects on the hydrological cycle", 1989, co-author, Technical Documents in Hydrology, UNESCO;
  "Casebook of Operational Hydrological Networks in RA-VI (Europe)",1995, WMO;
- "Basis of Geoecology" , 1994, Co-author, St. Petersburg University (in Russian)
- He has had more than 100 publications in numerous journals (in the USSR, in Russia, USA, etc.) and in the proceedings of different international and national conferences.