SIMPLE MODEL AND REMOTE SENSING METHODS OF EVAPORATION ESTIMATION FOR RIFT VALLEY LAKES IN ETHIOPIA

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ABSTRACT

In most arid regions of the world, evapotranspiration (ET) is a major component of the water budget. Accurate estimation of ET has been a challenge for hydrologist mainly because of the spatiotemporal variability and also most available models rely on intensive metrological information for ET estimation. Such data are not available at a desired spatial scale in less developed parts of the world. Measurement and estimation methods of ET usually provide different results as is the case for the Rift Valley Lakes of Ethiopia. Such limitations have necessitated the development of simple models that are less data intensive and also the use of remote sensing that can be applied to large areas where metrological data are not available. In areas like the Rift Valley regions of Ethiopia, the applicability of the Simple Method of lake evaporation estimation and surface energy balance approach using remote sensing was studied. The Simple Method of potential ET, lake evaporation and wetland ET estimation from a single parameter, solar radiation, has been successfully applied in South Florida. The Simple Method and a remote sensing evaporation estimates for Rift Valley Lakes were compared to the Penman, Energy balance, Pan, Radiation and CRLE methods. Results indicate a good correspondence of the model outputs to that of the Penman, Energy balance, CRLE and Radiation methods. Comparison of the 1986 and 2000 monthly ET from the Landsat images to the Simple and Penman Methods show that the remote sensing and surface energy balance approach is promising.

Key Words: evaporation, evapotranspiration, Simple Method, remote sensing, Rift Valley Lakes

INTRODUCTION

Evapotranspiration (ET) is one of the hydrologic parameters and has least variation on monthly and annual basis. It is a major component of the water cycle and important in water resource development and management. Measurement and estimation of this parameter usually provides different results. Evapotranspiration estimation models range from the complex as Penman Monteith to the simple, Pan method. Complex models require many meteorological measured and estimated input parameters which incur high monitoring cost. The error in measurement and estimation of input parameters increase the error in ET estimation. The adaptability of simpler methods especially in geographical areas where there is limited resource for monitoring is worth investigation. A Simple Method of potential ET, lake evaporation and wetland ET estimation has been successfully applied in South Florida (Abtew, 1996; Abtew, 2001, Abtew et al. 2003; Abtew, 2005). Preliminary analysis shows that this model can be applied at other locations. The coefficient, K_1, can be adjusted to the region if needed.

Lake evaporation (E_o) depends on the availability of energy and the mechanism of mass transfer, depth, and surface area of the lake. Evaporation is a function of solar radiation, temperature, wind speed, humidity, atmospheric pressure, and the surrounding environment. The most commonly used and the simplest method is the Pan method (Eq. 1) where evaporation from large surface area lake is related to evaporation from a small pan. The common problems with the pan method are errors caused due to difference in environment between the pan and the lake and errors in pan evaporation measurement. The use of pan data requires the development of a coefficient (K_p) to relate pan evaporation (E_{pan}) to lake evaporation. As the settings and operations of pans differ, different pan coefficients would be required for each pan to relate it to a single lake's evaporation. Abtew (2001) developed pan coefficients for seven pans in South Florida correlating monthly pan evaporation to evaporation from Lake Okeechobee and developed annual average pan coefficients ranging from 0.64 to 0.95.

$$E_o = K_p E_{pan} \qquad (1)$$

Energy balance, mass and momentum transfer methods require measurement and estimation of several parameters and coefficients. The energy balance method requires input data of net radiation, sensible heat flux and change of energy storage in the lake. Mass transfer and momentum transfer methods need differences in specific humidity, wind speed at different heights and mass and momentum coefficients. Combination methods as the Penman and Penman-Monteith methods are input parameter intensive. The Penman-Monteith method input requirements include measured parameters solar radiation, air temperature, humidity, wind speed and atmospheric pressure. The method also requires derived parameters as air density, canopy resistance, aerodynamic resistance, vapor pressure deficit, psychrometric constant, slope of saturation vapor pressure curve and heat storage. Additionally, estimated parameters as stomatal resistance, leaf area index, cover height, displacement height, aerodynamic roughness, momentum roughness and heat capacity are needed. Radiation and temperature based methods require fewer input data.

THE SIMPLE METHOD

A two-year lysimeter study of evapotranspiration in three wetland environments (cattails, mixed vegetation marsh, and open water/algae) was conducted in the Everglades Nutrient Removal Project, a constructed wetland in south Florida (26^{o} 38$^{'}$ N, 80^{o} 25$^{'}$ W). The design of the lysimeter system is presented in Abtew and Hardee, 1993. The results of the study were applied to test and calibrate six evapotranspiration estimation models: Penman-Monteith, Penman-Combination, Priestly-Taylor, Modified Turc, Radiation/Tmax, and Radiation (Simple) methods. The performance of each method was compared. The Simple Method required a single measured parameter, solar radiation, and achieved comparable performance to the complex methods with numerous input requirements.

Input data requirements increase from the Simple Method to the Penman-Monteith Method. In south Florida, most of the variance (73 percent) in daily evapotranspiration is explained by solar radiation alone. The effect of humidity and wind speed in estimating ET is relatively minimal. The Simple Method (Eq. 2) requires a single measured parameter, solar radiation, and is less subject to local variations (Abtew, 1996). The Simple Method is also cited as Abtew Equation and Simple Abtew Equation in published literature.

$$ET = K_1 \frac{Rs}{\lambda} \quad (2)$$

Where ET is daily evapotranspiration from wetland or shallow open water (mm d^{-1}), Rs is solar radiation (MJ m^{-2} d^{-1}), λ is latent heat of vaporization (MJ kg^{-1}), and K_1 is a coefficient (0.53). The Simple Method was further cross validated by comparing the estimates to four years of Bowen-Ratio ET measurements at nine sites in the Everglades of South Florida (Abtew, 2005).

Comparative application of the Simple Method further demonstrates its usefulness. In an effort to identify the most relevant approach to calculate potential evapotranspiration for use in daily rainfall-runoff models, Oudin et al. (2005) compared 27 potential ET models for stream flow simulation from 308 catchments in France, United States and Australia. Each potential ET model estimate was applied to four continuous daily lumped rainfall-runoff models. Comparison of the Nash-Sutcliffe (Nash and Sutcliffe, 1970) efficiency (Eq. 3) in validation of various potential ET methods as applied in the HBV0 model is shown in Figure 1. The model efficiency (*E*) goodness-of-fit measure is based on the error variance and is, defined as:

$$E = \left[1 - \frac{\sigma_\varepsilon^2}{\sigma_o^2}\right] \quad (3)$$

The error variance σ^2_ε is defined as

$$\sigma_\varepsilon^2 = \frac{1}{n-1}\sum_{i=1}^{n}(PE_{o,i} - PE_{p,i})^2 \quad (4)$$

The variance of the measured potential evapotranspiration (PE), σ^2_o defined as

$$\sigma_o^2 = \frac{1}{n-1}\sum_{i=1}^{n}(PE_{o,i} - \overline{PE_o})^2 \quad (5)$$

Where $\overline{PE_0}$ is average measured PE.

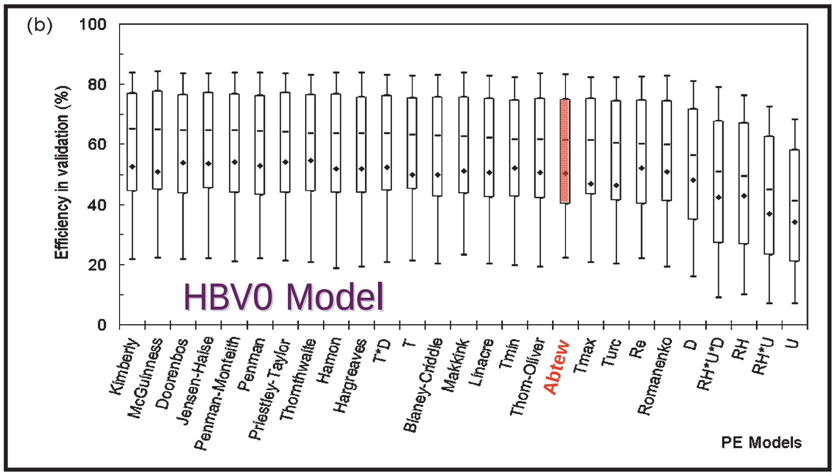

Figure 1. Average and 0.10, 0.25, 0.50, 0.75 and 0.90 percentile of Nash-Sutcliffee (E) Criteria obtained by 27 PE models in validation mode for HBV0 model (Oudin et al., 2005).

The simple method was applied to estimate evaporation from Lake Titicaca, South America. Compared to eight evaporation models, it was found to be the best evaporation estimation model (Delclaux and Coudrain, 2005). Xu and Singh (2000) evaluated various radiation based methods for calculating evaporation and concluded that the Simple Method can be used when available data is limited to radiation data. The Simple Method is applicable to remote sensing where the input, solar radiation, is acquired through satellite observations (Jacobs et al., 2000).

LAKE EVAPORATION ESTIMATION METHODS APPLICATION TO LAKE ZIWAY, ETHIOPIA

The Simple Method Application to Lake Ziway

Lake Ziway (Figure 2) is located in the Ethiopian Rift valley with an average surface area of 490 km^2 at an elevation of 1636 m msl (Coulomb et al., 2001). Monthly and annual average Lake Ziway evaporation estimates have been published (Coulomb et al., 2001; Ayenew, 2003). The estimates vary from method to method of evaporation estimation. Annual lake evaporation estimates by Coulomb et al. (2001) were 1777, 1875 and 1728 mm, respectively estimated with the Energy balance, Penman and Complementary Relationship Lake Evaporation (CRLE) methods. Estimates by Ayenew (2003) were 2022, 1599 and 1769, respectively estimated with Penman, Radiation and Pan methods (Table 1).

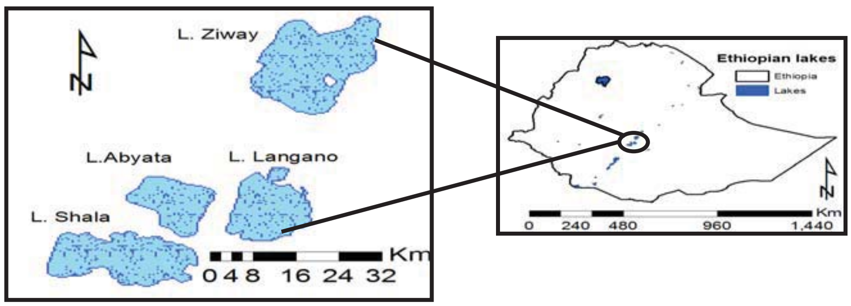

Figure 2. Ethiopian Rift valley lakes

Table 1. Lake Ziway evaporation estimations with various methods.

Month	Solar Radiation	Simple Method Lake Evaporation K=0.53	Coulomb et al. (2001) Lake Evaporation			Ayenew (2003) Lake Evaporation		
			Energy	Penman	CRLE	Penman	Radiation	Pan
	W/M^2	mm	mm	mm	mm	mm	mm	mm
January	245.8	142.4	143.2	153.8	132	150	135	159
February	250.1	130.9	149.1	162.2	135.3	128	120	144
March	249	144.3	151.7	166.1	149.2	148	142	192
April	252	141.3	155.5	165.6	154.6	188	138	142
May	259.2	150.2	163.2	170.3	159.9	188	138	156
June	243.4	136.5	147.4	167.6	154.6	135	107	137
July	208.3	120.7	127.7	135.8	146	139	115	126
August	219.2	127.0	136.3	137.1	136.3	135	115	123
September	225.5	126.4	141.1	136.4	137.4	164	124	112
October	260.3	150.8	158.9	162.4	140.6	200	151	170
November	262.7	147.3	159.6	161.1	143.8	223	157	178
December	249.4	144.5	143	156.5	138.5	225	157	130
Total		1662	1777	1875	1728	2023	1599	1769

Application of the Simple Method was tested with input of average monthly solar radiation data (Coulomb et al., 2001). With the original coefficient value (K = 0.53), the annual lake evaporation estimate by the Simple Method is 1662 mm (Table 1). The Simple Method estimate is 4 percent lower than the CRLE method estimates (Coulomb et al., 2001) and 3.8 percent higher than the Radiation method estimates (Ayenew, 2003). The coefficient of the Simple Method can be adjusted to much annual estimate of any of the methods as a way of calibration if it is believed those methods are more reliable. Monthly lake evaporation estimates by the Energy Balance and Penman Equation (Coulomb et al., 2001) were compared to the Simple Method with adjusted K values. Results are shown in Figure 3 and 4. Monthly lake evaporation estimates by the Simple Method with single measured parameter, solar radiation, has fitted well compared to estimates of the energy balance and Penman equation.

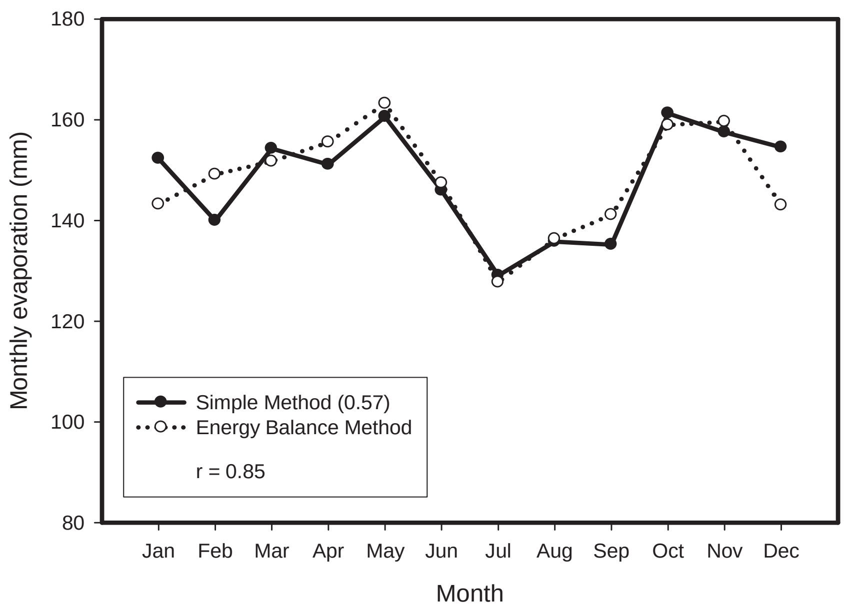

Figure 3. Comparison of Energy Balance and Simple Method estimates of Lake Ziway evaporation.

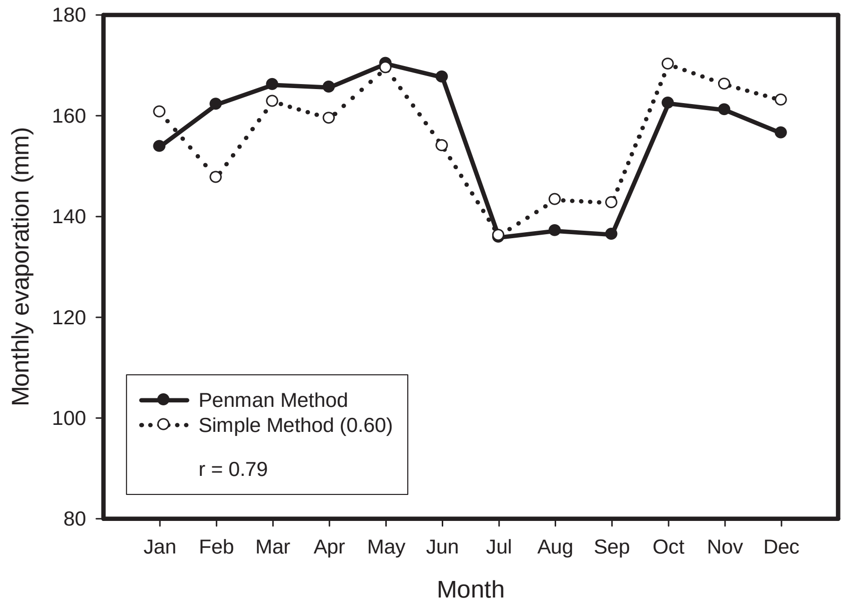

Figure 4. Comparison of Penman and Simple Method estimates of Lake Ziway evaporation.

Remote Sensing Application in ET Estimation

Remote sensing-based evapotranspiration (ET) estimations using the surface energy budget equation are proving to be one of the most recently accepted techniques for areal ET estimation covering larger areas (Morse et al. 2000). Surface Energy Balance Algorithms for Land (SEBAL) is one of such models utilizing Landsat images and images from others sensors with a thermal infrared band to solve equation (6) and hence generate areal maps of ET (Bastiaanssen et al. 1998a; Bastiaanssen et al. 1998b and Morse et al. 2000).

SEBAL requires weather data such as solar radiation, wind speed, precipitation, air temperature, and relative humidity in addition to satellite imagery with visible, near infrared and thermal bands. SEBAL uses the model routine of ERDAS Imagine, an image processing software, in order to solve the different components of the energy budget equations. In the absence of horizontally advective energy, the surface energy budget of land surface satisfying the law of conservation of energy can be expressed as,

$$R_n - LE - H - G = 0 \qquad (\text{W/m}^2) \qquad (6)$$

where R_n is net radiation at the surface, *LE* is latent heat or moisture flux (ET in energy units), *H* is sensible heat flux to the air, and G is soil heat flux. Energy flux models solve equation (6) by estimating the different components separately. Net radiation is estimated based on the relationship by Bastiaanssen et al. (1998a),

$$R_n = R_{s\downarrow}(1-\alpha) + R_{L\downarrow} - R_{L\uparrow} - R_{L\downarrow}(1-\varepsilon_s) \quad (\text{W/m}^2) \qquad (7)$$

where $R_{S\downarrow}$ (W/m^2) is the incoming direct and diffuse shortwave solar radiation that reaches the surface; α is the surface albedo, the dimensionless ratio of reflected radiation to the incident shortwave radiation; $R_{L\downarrow}$ is the incoming long wave thermal radiation flux from the atmosphere (W/m^2); $R_{L\uparrow}$ is the outgoing long wave thermal radiation flux emitted from the surface to the atmosphere (W/m^2), ε_s is the surface emissivity, the (dimensionless) ratio of the radiant emittance from a grey body to the emittance of a blackbody.

The soil heat flux is the rate of heat storage to the ground from conduction. Studying irrigated agricultural regions in Turkey, Bastiaanssen (2000) suggested an empirical relationship for *G* given as:

$$G/R_n = 0.2(1 - 0.98 NDVI^4) \quad (\text{W/m}^2) \qquad (8)$$

where *NDVI* is the normalized difference vegetation index (dimensionless).

Sensible heat flux is the rate of heat loss to the air by convection and conduction due to a temperature difference. Using the equation for heat transport, sensible heat flux can be calculated as:

$$H = \frac{\rho C_p (T_a - T_s)}{r_{ah}} \quad (\text{W/m}^2) \qquad (9)$$

where ρ is the density of air (kg/m^3), C_p is the specific heat of air (1004 J/kg/K), T_a is the air temperature (K), T_s is surface temperature (K) derived from the thermal band of Landsat images and r_{ah} is the aerodynamic resistance (s/m).

With R_n, G, and H known, the *latent heat flux* is the remaining component of the surface energy balance to be calculated by SEBAL. Rearranging equation (4) gives the latent heat flux where:

$$LE = R_n - G - H \quad (\mathrm{W/m^2}) \tag{10}$$

The detailed technique for estimating latent and sensible heat fluxes using remotely-sensed data from Landsat and other sensors is documented and was tested in Europe, Asia, Africa, and in Idaho in the US and proved to provide good results (Bastiaanssen et al. 1998a; Bastiaanssen et al. 1998b; Wang et al. 1998; Bastiaanssen 2000; Morse et al. 2000; Melesse et al., 2006).

Surface energy balance and remote sensing application to Lake Ziway

In this study, two Landsat images (Landsat TM from December 1986 and Landsat ETM+ from January, 2000) were used for the computation of energy fluxes and lake evaporation estimation. Images wee processed based on the procedures outlined in SEBAL model. Based on the daily lake evaporation estimates from the SEBAL model, monthly estimates were generated for comparison to the Simple and Penman Models. Table 2 shows statistics of the results of the remote sensing-based lake evaporation estimates. It is shown that the monthly estimates correspond well with the long-term averages of the monthly evaporation values from the Simple and Penman Method for Lake Ziway. Comparison of Lake evaporation estimates among lakes shows that, Lake Langano, the mercky lake with high sediment loads has lower average monthly evaporation than the other three lakes, which have less sediment loads and are clearer. Figure 5 shows the spatial evpotranspiration estimates from the two Landsat images.

Table 2. Monthly lake evaporation (mm)

Ziway	1986	2000	Langano	1986	2000
Min	121	121.8	min	110	100.4
Max	204	201	max	194	199
Mean	145	138.7	Mean	116.9	115
STD	7.3	2.13	STD	1.6	4.1

Abiyata	1986	2000	Shala	1986	2000
Min	129.6	129.7	Min	131.2	130.5
Max	148.22	185	Max	192	196
Mean	140.9	141.8	Mean	135.5	143.7
STD	2.1	2.1	STD	1.3	7.8

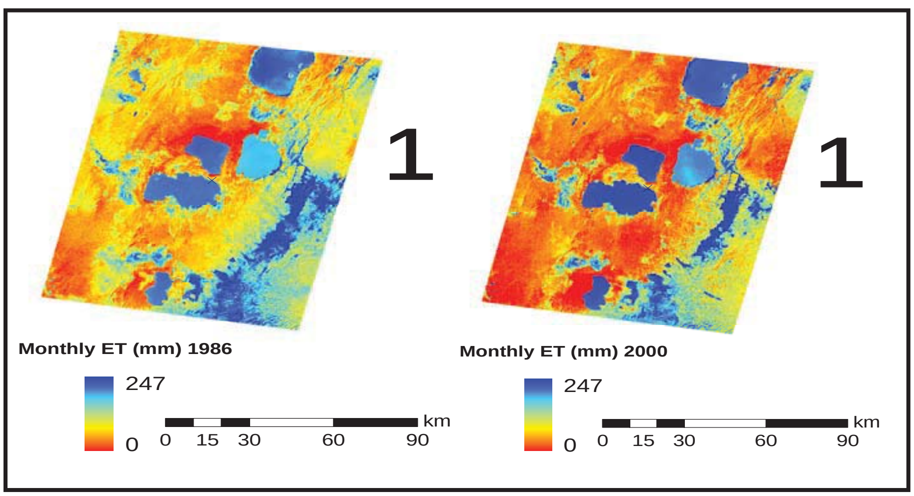

Figure 5. Spatial monthly evpoatranspiration map of Rift valley lakes, Ethiopia for December 1986 and January 2000.

SUMMARY

Evaporation from ponds, lakes and reservoir is a key hydrologic parameter and cost effective estimation method is desired specially in areas where monitoring resources are limited. Open water evaporation can be estimate of potential evapotranspiration. The Simple Method has been tested and applied in South Florida where it is currently the standard method for lake evaporation, wetland evapotranspiration and potential evapotranspiration estimation by South Florida Water Management District, a 47,000 square km complex water management system. Other applications are also cited. The method should do well in tropical and subtropical areas where humidity is high, wind speed is not high and temperature is correlated to radiation. In this study the Simple Method evaporation estimates with and without recalibration of the coefficient, K_1, are comparable to the estimate of the input data intensive methods.

The application of the Simple Method and surface energy balance approach using remotely-sensed data were applied to Rift Valley Lakes of Ethiopia, where other approaches are less effective due to limited observed metrological data and remoteness of the areas. The monthly lake evaporation estimates from the two approaches corresponds very well with Penman and energy balance approaches from previous studies.

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