Journal Homepage: - www.journalijar.com
INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)
ISSN NO. 2320-5407
Article DOI: 10.21474/IJAR01/5604
DOI URL: http://dx.doi.org/10.21474/IJAR01/5604

RESEARCH ARTICLE

ESTIMATING HEAT AND MASS QUANTITIES TRANSFERED BETWEEN FREE SURFACE WATER AND THE ATMOSPHERE USING THE ENERGY BALANCE METHOD.

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Manuscript Info

Manuscript History

Received: 12 August 2017
Final Accepted: 14 September 2017
Published: October 2017

Key words:-
Evaporation, Thermal transfer, energy balance, surface temperature.

Abstract

We hereby present a study on heat and mass transfer between free surface water and the atmosphere in Burkina Faso. We preferentially chose the city of Ouagadougou to conduct this study.
One of the major problems in studying evaporation is how to determine water surface temperature and the flow of water evaporated. We calculated this surface temperature using the dichotomy method (Saighi, 2002) applied to the energy balance formula. The calculation of this temperature enabled us to draw the evolution of the evaporation according to the time and surface temperature for a period of ten years considered in the study. The results obtained are satisfactory because we now have the minimum (23.64 °C) and maximum (36.64 °C) values of surface temperatures.
Concerning the evaporated water flows, we got extreme values like 6.25 mm for the minimum value and 12.7 mm for the maximum one for the ten years considered. We compared the values of the water flow calculated using the energy balance formula with that measured by the Burkina Faso Meteorology Department using an "A" class BAC. We were able to calculate an average error between both values of 12.7%; an error that we consider acceptable.

Nomenclature:-
R_n : Net radiation) (W/m²
L_v : Vaporization latent heat (J/kg)
H : Sensible heat (W/m²)
G : Heat flow in soil (W/m²)
E : Evaporation (mm)
P_{vs} : *Saturating heat pressure(Pa)*
P_v : *Heat pressure (Pa)*
K_E : *Mass transfer coefficient (m/s)*
h_c : *Thermal exchange coefficient (J/m^2/K)*
C_p : Water calorific capacity (J/K)
ρ : Water volume mass (kg/m^3)

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H_r : Relative moister (%)
T_s : Surface temperature (K)
Ta : Ambient temperature (K)
M_w : Water molar mass (kg/mol)
L_c : Characteristic length (m)
v : Wind speed (m/s)
R_g: *Overall radiation* (W/m^2)
α : *Surface albedo*
ε : *Emissivity*
σ : *Boltzmann constant* (5,6697.10^{-8} Wm^{-2}K^{-1})

Introduction:-

Heat and mass Transfers by evaporation from a free surface and atmosphere are a major issue in a hot and dry country like Burkina Faso. Quantifying these exchanges becomes an important task to be accomplished. Among all the components of the hydrological cycle, mass transfer (evaporation) remains the most difficult element to estimate. There are then a multitude of methods for measuring and estimating evaporation. Among these we have the Dalton Approach which that is the oldest. Another approach is that used by Arnaud et al. (2000) and Singh and Xu (1997) in their studies. Direct measurements of evaporation can be seen in the work by Perlat and Petit (1961) with an "A" class BAC and that by Called (1967) with a "Colorado" Bac. Evaporation losses in water storage facilities are estimated to be at least 40% (Burkina Faso GIRE Program, 2010), and 20-30% for Lake Nasser (M. A. Mosalam Shaltout and al, 1997): this is huge. How to minimize these water losses by evaporation? The study was conducted to investigate this issue. Its objective is to determine climatic variables such as temperature at the free surface of water and the amount of water evaporated. This flow of evaporated water obtained numerically was compared with that measured by Burkina Faso weather service.

Energy Balance Method:-
General Equation:-
The general equation of energy balance is given as follow:

$$R_n = L_v E + H + G \quad (1)$$

With R_n : Radiation balance (net radiation) (W/m^2) ; $L_v E$: latent heat of vaporization (J/kg) ; *H : Sensible heat (W/m^2) ; G :Heat flow in the soil (W/m^2)*.

Component of The Energy Balance:-
Latent heat exchange (Stefan Law):-

$$L_v E = \frac{L_v K_E}{RT_a}(P_{vs}(T_s) - P_v(T_a)) \quad (2)$$

P_{vs} saturation pressure vapor at T_s, is defined by

$$P_{vs}(T_s) = \exp(25{,}5058 - \frac{5204{,}9}{T_s}) \quad (3)$$

P_v pressure vapor at ambient temperature T_a : $P_v(T_a) = H_r(P_{vs}(T_a))$ (4)

K_E mass transfer coefficient: $K_E = \frac{h_c}{\rho p_p}$ (5)

Sensitive Heath Exchange:-
This represents energy transportation between water surface and the atmosphere and is defined by:

$$H = h_c(T_s - T_a) \quad (6)$$

h_c the convection thermal exchange coefficient $h_c = 5{,}907V^{0{,}8}Lc^{-0{,}2}$ (7)

Conductive heat exchanges G≈ 0 *(8):-*
The net heat storage in water over a 24-hour period is generally negligible (zero) compared to the flow (Fenessy et al., 1996; Saighi, 2002).

Radiative Exchange:-

$$R_n = (1-\alpha)R_g + \varepsilon\sigma(T_a - 6)^4 - \varepsilon\sigma T_s^{\ 4} \quad (8)$$

α Surface albedo
R_g Overall radiation
ε Emissivity
σ Boltzmann constant

Resolution of the Balance Equation:-
The energy continuity equation becomes:

$$(1-\alpha)R_g + \varepsilon\sigma(T_a - 6)^4 - \varepsilon\sigma T_s^{\ 4} - h_c(T_s - T_a) = \frac{L_v K_E M_w}{RT_a}(P_{vs}(T_s - P_v(T_a)) \quad (9)$$

We draw a nonlinear equation so as:

$$A_1 T_s^{\ 4} + h_c T_s + A_2 \exp(-\frac{5204{,}9}{T_s}) = A \quad (10)$$

with $A_1 = \varepsilon\sigma$, $A_2 = \frac{K_E L_v M_w}{RT_a}\exp(25{,}5058)$

and $A = \frac{K_E L_v M_w}{RT_a} P_v(T_a) + (1-\alpha)R_g + \varepsilon\sigma(T_a - 6)^4 + h_c T_a$

where A_1, A_2, and A are constants that vary according to climate variables.
This relationship will be used as a condition at the upper boundary of the free water surface and enables us to calculate the temperature at this surface according to the prevailing temperature. The resolution of the equation makes it possible to calculate the temperature at the free water surface at each time of the day according to: the net radiation *Rn*, the temperature Ta of the ambient air, the mean relative moister of the water air Hr and wind speed v. This equation was solved using the dichotomy method (Saighi, 2002). Temperature T_S value calculated at each time enables us to have access to the surface density of the evaporated water flow at the surface.

Results and Discussion:-

Evolution of the surface temperature:-
We have analyzed heat and mass transfers by evaporation from an free water surface over ten year in the Ouagadougou City (from 2004 to 2013). This enabled us to estimate the temperature at the free surface of the bodies of water plans in this same city. The solving of the equation (10) using the dichotomy method enabled us to quantify the average surface temperature magnitude Ts for the ten years considered. The values of the temperature are those of three (3) years that we have chosen preferentially in 2005, 2011 and 2013. We also obtained a minimal value of the surface temperature which is 23.64 °C while the maximal value is 36.23 ° C (Figure. 1).

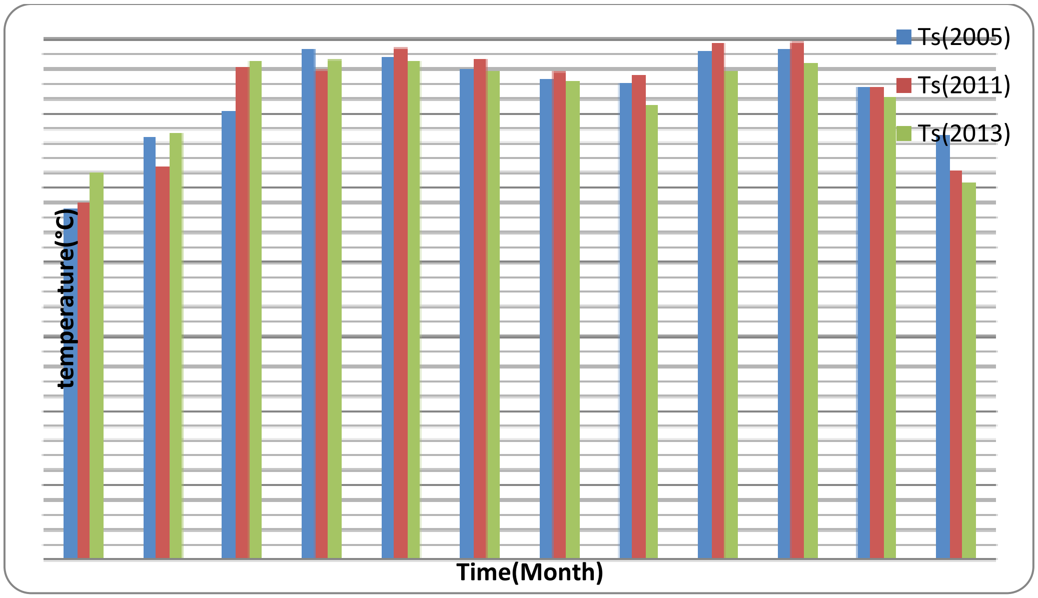

Figure 1:- Evolution of the surface temperature.

Evolution of the evaporated water quantity:-

Figure 2 is the flow of the calculated water and that of the measured water recorded by Burkina Faso Meteorology Department. To make it simple, we deliberately chose to show the results of three months among the ten considered. We note that the mean relative error between the values of the evaporation calculated using the energy balance method and that measured using the “A” class by the Burkina Faso Meteorology Department is nearly 12.7%. Such an error is considered satisfactory because, in good conditions, the Hydrological Practices Guide shows that average errors of nearly 10% can be expected in hot periods and 20% in cold periods. The minimum and maximum values are 6.25mm and 12.5mm respectively.

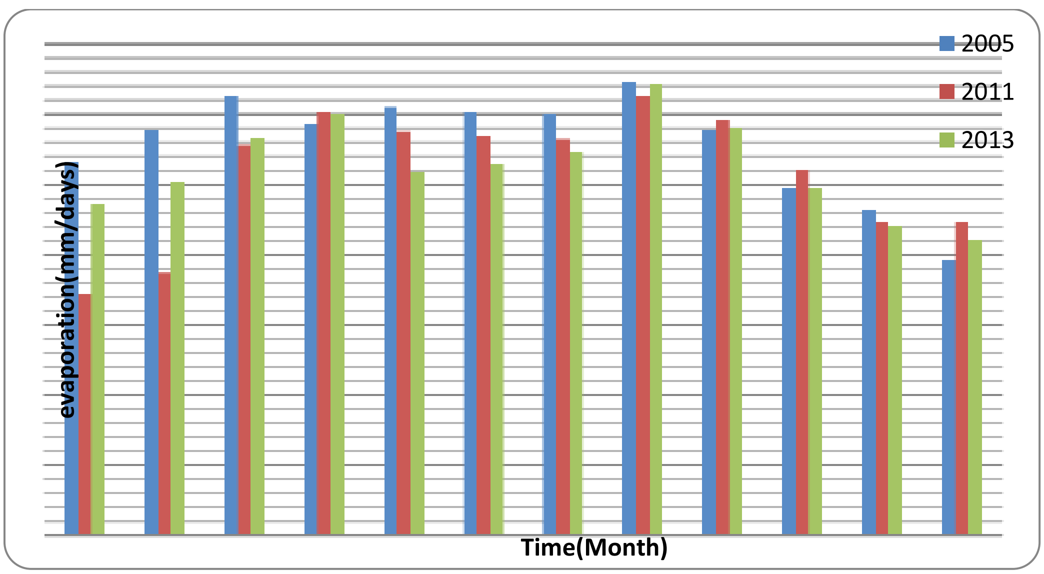

Figure 2:- Evolution of the evaporated water quantity

Comparison between ambient temperatures (Ta) and surface temperature (Ts)

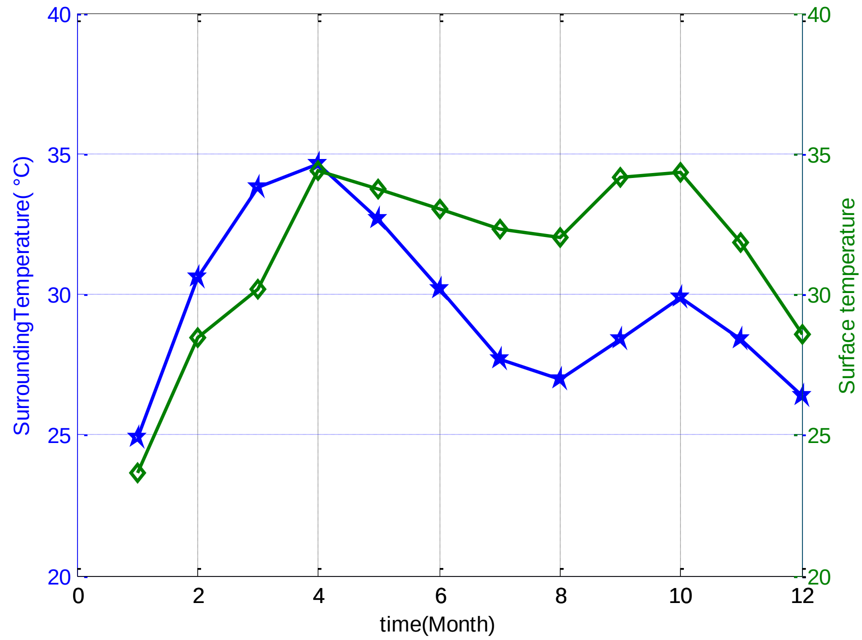

Figure 3:- Evolution of surface temperature and ambient temperature in 2005.

Figure 3 shows that the surface temperature Ts is above room temperature Ta almost in all wet periods and this temperature is below room temperature almost in all dry periods. This is due to the fact that at these times, wind speed and the overall radiation rate are very high

Comparison between temperature gap (T_s-T_a) and evaporation:-

Figure 4 shows that when the gap is maximal, evaporation is minimal; On the other hand, when the gap is minimal, the evaporation is maximal. The rise in the temperature gap increases the sensible heat flow; hence this minimum value of the evaporation recorded since the heat exchange coefficient decreases. However, the fall in the value of the gap makes the sensible heat flux decreases, giving therefore this maximum value of the evaporation because the heat exchange coefficient has increased.

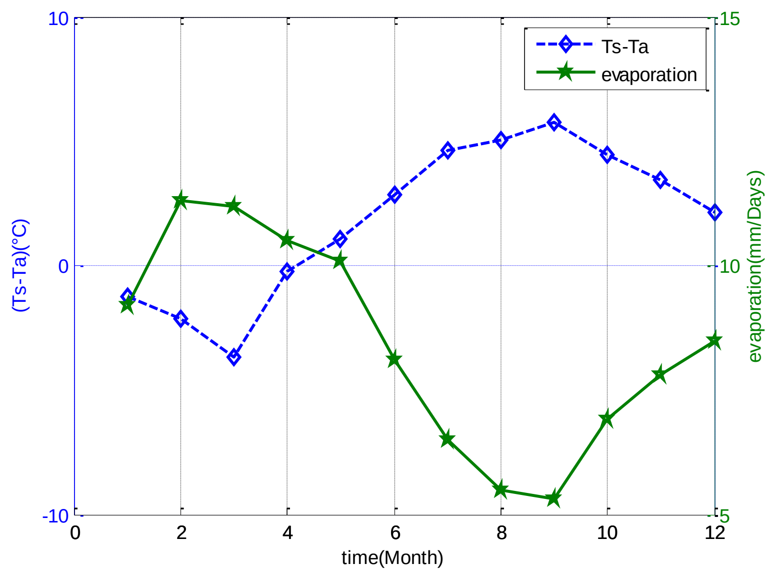

Figure 4:- variations of temperature and evaporation gap per month of the year in 2005

Temperature evolution curves calculated and measured:-
The two curves that follow (Figure. 5) represent the profile of the evaporated water amount calculated using the energy balance method and that measured by Burkina Faso Meteorology Department using the "A" class BAC. The first comment that can be made is that the appearance of both curves is similar. When both curves are superimposed, we realize through an error calculation that the mean relative error is nearly 12.7%. Such an error is acceptable according to the Hydrological Practice Guide.

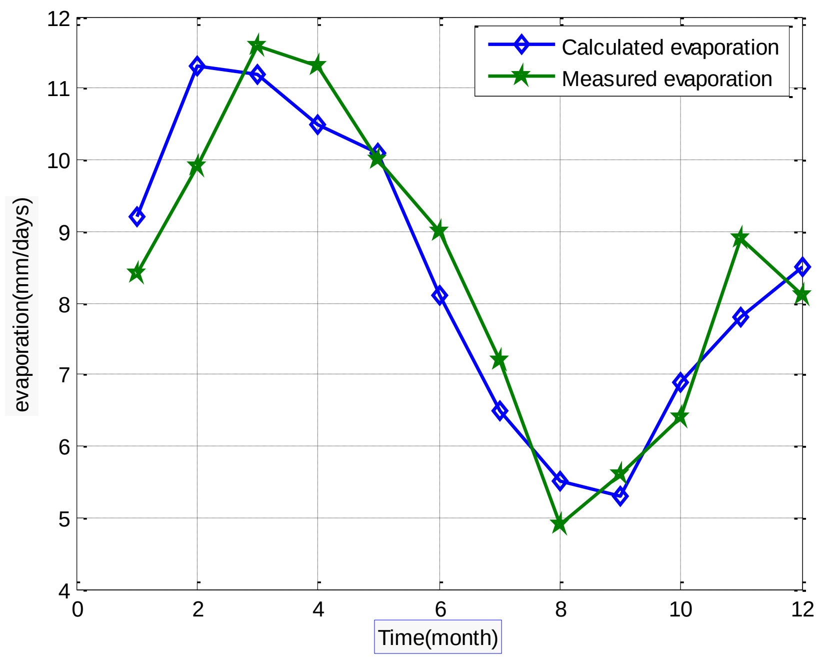

Figure 5:- Comparison between the calculated and measured evaporation

Conclusion:-
The modeling of mass and heat transport is still one of the issues to investigate, despite the diversity and multitude of research works performed. In this work, the objective is to estimate the average temperature at the surface of water bodies in order to assess water quantity evaporated on the same water bodies using the energy balance method.

Modeling requires the characterization of the system so as to identify its various physical and mechanical properties. Solving mass and heat transfer problem is therefore determining the characteristic variables, notably surface temperature (Ts), which enables to calculate the evaporated water flow.

To calculate the parameters abovementioned, we used the energy conservation principles, namely the energy balance equation and Darcy-Fick's empirical mass transfer laws. The energy balance equation was developed and solved with a numerical model, namely the dichotomy solving algorithm.

This program has enabled to simulate the free water surface body used and to show the impact of the surface temperature of heat and mass transfer on the water and diffusive characteristics of the water body.

Similarly, this program has enabled us to estimate the mean values of the temperature at the surface of a water body for the ten years considered, notable from 2004 to 2013.

These results have shown that the initial objective has been achieved by comparing it with works on the evolution of surface temperature carried out previously. The simulation was based on the mean values of outside environment, namely temperature, global solar radiation, relative moister and wind speed.

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