INPE-340-RI/116

SERE Project

UTILIZATION OF SCANNER THERMAL INFRARED DATA IN STUDYING THE WATERSHED MANAGEMENT

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Maio/1973

cc.: 30

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UTILIZATION OF SCANNER THERMAL INFRARED DATA IN STUDYING THE WATERSHED MANAGEMENT

Mostafa K. Nosseir

This report is the result of the developing research in the Program of Natural Resources Survey using remote sensing techniques. This program is in implementation by the SERE Project of this Institute. Its publication was authorized by the undersigned.

Fernando de Mendonça
General Director

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ABSTRACT

Watershed management is one of the more important studies to look for the most efficient policy for water management. This work is an attempt to consult the thermal infrared remote sensing techniques to be applied in this field. A survey of the available method for calculating the PET has been made with emphasis on methods which depend on the surface temperature or energy budget of the targets.

The possibility of applying remote sensing is discussed throughout the report. Further studies and a continuing exchange of ideas are needed.

Prezado Senhor:

Um dos assuntos de pesquisa deste Instituto, dentro de seu Programa de Sensoriamento Remoto, é o emprego de imagens colhidas no infravermelho termal, com vistas a estudos sobre o manejo de bacias hídricas. Estamos enviando em anexo, para a apreciação de V. Sa. um relatório sobre a matéria.

Muito apreciaríamos receber seus comentários sobre o relatório ou qualquer outra informação adicional que V. Sa. julgue conveniente.

Dear Sir:

One of this Institute research subject within its Remote Sensing Program is the utilization of Scanner thermal infrared imagery in watershed management. We are sending you enclosed a copy of one technical report about this subject. We would appreciate very much any comments from you about this report or any other information you think would be applicabe. The application of such techniques would lead to either the possibility of water use in arid and semi-arid regions, or a more efficient management of water use in the humid regions.

INTRODUCTION

This activity is in development within the agreement among the Instituto de Pesquisas Espaciais (INPE), Universidade Federal de Viçosa (UFV) and the Laboratory for Applications of Remote Sensing (LARS). The main objectives are:

- Determination of the best hour during the day and the night to obtain thermal infrared data.
- Determination of the relation between the field surface temperature and the scanner data, by calculating the correlation between the two temperatures.
- Correlation of the energy measured by thermal infrared and the Potential Evapotranspiration (PET) of different vegetation covers.

The working plan for 1972, the progress report of the work done during that same year, and the working plan for 1973, describe in details the steps already accomplished in the project, the difficulties encountered and the activities yet to be developed. In this report we will consider the following:

a. To present from a technical point of view the results of a scientific survey of the literature in order to choose a suitable method for calculating the PET through measurement of the energy emitted from the different surfaces using a thermal infrared sensor (Scanner).

b. To make clear why we are interested in PET in watershed management studies.

c. To explain the advantages of using the thermal infrared remote sensing techniques in calculating the PET.

d. To describe the remote sensing approach for calculating the PET.

e. To explain the need to get the regional and seasonal vegetation constants and meteorological constants.

CHAPTER I

IMPORTANCE OF THE PET IN THE WATERSHED STUDY

The watershed studies take care and follow the movement of water from the time it falls on the head of the river basins (or in general on the catchment area of the basin) until it is absorbed by soil surfaces, evaporates, transpirates through plants and is discharged into the drainage basin. This type of study is not only important for efficient management planning of water use in the arid or semi-arid regions, but also for the humid regions to plan the use of excess water more than the needs of the vegetation. The total amount of the water evaporated and transpirated by the plants is called the evapotranspiration.

Penman (1965) defined the PET as: "The amount of water transpirated in unit time by short green crops completely shading the ground, of uniform height and never suffered from the water shortage". This explains why all the studies were done on vegetation under an irrigated system, thus avoiding the problem of water shortage. On the other hand, in highly humid areas, the same studies are possible because of the absence of a water shortage for the plants. Even if there are significantly different climatic seasons there would exist the need for a special constant, calculated to specify the crops, regions, and season to be able to calculate the PET. In other words this can be explained as the capacity of the plant to loose water, which depends on the energy of plant canopy. The PET will reflect the plant nature and condition, under the existed climatic conditions. The rate of the PET depends on the evaporation power of the air determined by temperature, wind speed, radiation and air relative humidity. The relative importance of radiation, humidity, and wind speed in determining the pan evaporation are 80:6:14. Evaporation is proportional to the vapor pressure deficit, only when the temperature of the air is equal to that of the evaporating surfaces. In the absence of this equality the evaporation is proportional to the vapor pressure gradient between the evapotranspiration rate of the infected plant significantly well developed, large differences in vegetative growth could cause only relative small difference in the evapotranspiration rate when soil moisture is adequate. From the ecological point of view, the boundary between grassland and forest marks the transition from the humid to arid climate. As the aridity of the climate increases the difference in water needs between a tall and a short plant is accentuated to such a degree that they render the survival of tall vegetation in arid climates most difficult. This result could be applied in Brazilian ecological studies to put the definite boundary between the short cerrado[1], tall cerrado and forests.

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(1) Cerrado is called in some references wrongly "Brazilian Savana".

From the previously mentioned reasons the PET can be considered a parameter to calculate the water requirements for the different vegetation covers, but essentially after considering all the factors which influence the results of PET calculation.

CHAPTER II

THE ADVANTAGES OF APPLYING A TECHNIQUE OF THERMAL INFRARED REMOTE SENSING IN CALCULATING THE POTENTIAL EVAPOTRANSPIRATION (PET)

To discuss these points there are some definitions that should be clear:

II.1 - ADVICTION: (Philips, 1957)

The exchange of energy, moisture or momentum as a result of horizontal heterogeneity. A divected energy resolving itself into the "Clothesline effect and the Oasis effect" (Tanner, 1957).

a. Clothsline effect: when the warm air is blown through a small plot with little or no guard area, a very severe horizontal heat transfer occurs.
b. Oasis effect: the vertical energy transfer from the air above to the crop inside a large field.

The thermal infrared sensors can measure the radiation emitted by the plant canopy cover. This means it measures the energy used by the plant in doing its physiological activities. This can be translated into the capacity of the plant to loose water which is called PET. By using the Stefan-Boltzmann law:

$$E = \varepsilon\sigma T^4$$

where,

E = the flux of radiation emitted by the surface

ε = the emissivity of the emitting body

σ = Stefan-Boltzmann constant

T = the surface temperature of the body

One can see that the output of sensing in the thermal infrared wavelength (8-14μ) is either, the plant net energy or the plant surface temperature.

The previous definition of PET formed by Penman (1956) faces three critical points:

a. The short green crops are non specific, not only in the dimensions but also in the crop growth conditions (green crop). From the agrometeorological point of view the unspecified plant canopy will give error because of the Oasis effect, and the diversity of the plant condition will create a Clothsline effect because this will divide the field of the same crop into smaller fields of different conditions. From the remote sensing point of view it is easy to put the boundaries between the different plant condition in the same field and also to isolate the areas which are suffering from the Clothsline effect. The Oasis effect could be avoided by separating the field into similar textual plots from black and white photographs with suitable scale.

b. The complete ground cover is not well explained. The agrometeorological takes into consideration the canopy cover shading the ground completely when it receives all the incoming radiation. In fact even the tall, dense plant with a high leaf area can hardly absorb 95% of the incident radiation. From the remote sensing point of view this does not make any difference. The area of the completely ground shading could be calculated within the field, and even for the incomplete ground cover the emitted radiation per area or the surface temperature shows the quantity of the energy per area.

c. Penman does not specify the size of the field or the condition of the surrounding area. This is very important in the micro studies. But in the remote sensing applications it is possible to see and to measure the effect of the surrounding field and calculate the adviction effect. Also it is possible to choose the size of the field that will be adequate for PET studies of each crop.

Another advantage of remote sensing application is the possibility of obtaining the particular PET for each area; not to calculate for a sample area, then to generalize the results for the PET from the ground covered areas, the evaporation from the bare soil, and the water runoff from the basin catchment areas. Together with hidrological studies of water loss, from the basin plant cover areas, accurate water management will possible with high precision results.

The previous reasons and advantages of applying the remote sensing technique in PET calculation lead to choose the formulas which depend on one of the two following approachs:

1 - The emitted energy by evaporating surface;

2 - The surface temperature.

CHAPTER III

COMPARISON OF THE DIFFERENT METHODS TO CALCULATE THE PET

In such a comparison as this, two manners will be used to present the advantage of each formula:

III.1 - THE WMO RECOMMENDATION

The WMO recommendation, published as the Technical Note nº 97, were prepared by the working group on Practical Soil Moisture Problems in Agriculture of the Commission for Agriculture Meteorology under the title "Practical Soil Moisture Problems in Agriculture", |WMO - Nº 235. TP . 128 |. The second chapter "Meteorological Aids to Efficient Use of Water for Irrigation" gives the recommendations and preference of each method.

The notes describe routine methods to calculate the PET in the following order:

III.1.1 - Methods based on measured open water evaporation

This report describes the pan and tank evaporimeters, their specifications, importance of standardization, ways of measurements, the care which must be taken during these measurements.

III.1.2 - Meteorological methods of estimating open water evaporating

There are two approachs to estimate the evaporation from the water surfaces:

a. Hypothetical large water surfaces, considering water surfaces infinitely large and shallow. Two equations could be used in this calculation. First is the Mass transfer method by Dalton. The second is the combination of energy balance and Mass transfer method by Penman (1948).

b. Actual small water surfaces. This is by using class A pan. It is suitable for areas with great variations in topographic, climatic and agricultural features.

III.1.3 - Atmometers

These include, Piche evaporimeters, Livingston atmometers and the Bellani disc atmometer.

III.1.4 - Determining the crop constant

III.1.5 - Empirical climatological methods

Many empirical formulae have been used to calculate the PET, but each formula has to be adapted and checked before application to a particular region because of the different climatological features of the region. These formulae are mainly:

a. Temperature methods

- Blaney - Criddle's formula (1962)

$$U = kf$$

where,

U = evapotranspiration referred to as comsumptive use,

k = the crop constant,

f = the main air temperature and daylight factor term.

$$= \frac{t \times p}{100}$$

t = the mean daily air temperature

p = hours of daylight as a fraction of 12 hours.

- Thornwaite's formula (1958)

$$PET = 1.6 \frac{(10)^a}{I}$$

where,

I = the annual heat index

a = a complex polynomial function of I

- Verigo's formula (1948) in U.S.S.R.

$$\Delta w = at + bm + cw + d$$

where,

Δw = the change in the soil moisture content in the root zone in mm.,

t = mean daily air temperature,

m = amount of precipitation (mm),

w = initial available soil moisture content of the root zone in (mm).

- Turc's formula (1961)

$$PET = 0.13 \frac{t}{t + 15} (T + 50)$$

where,

t = mean screen air temperature (^{o}C)

T = mean daily total short-wave radiation, gcal/cm^2

- Makkink's formula (1957)

$$PET = 0.61T \frac{\Delta}{\Delta + \gamma} - 0.12$$

where,

T = total short wave radiation in units of latent heat equivalent, mm/day;

Δ = the gradient of the saturated vapor pressure to air temperature relationship;

γ = the psychrometer constant.

- Inovo (1954) in U.S.S.R.

$$E = 0.0018 \ (25 + t)^2 \ (100 - a)$$

where,

E = evaporative power, mm/month

t = mean monthly air temp. ^oC

a = relative humidity of the air.

b. Humidity methods

These methods are aminly

- Blaney - Criddle's formula with air humidity term.
- Hargreave's methods (1948), using the same formula and the crop constant.

- Prescott's methods (1949), from Australian pan data

$$Ew = k\ (es - ed)$$

where,

k = vegetation constant ranging from 0.8 - 1.6

es = saturated vapor pressure at the mean air temp.

ed = actual vapor pressure measured at 09 hours.

$$PET = k\ .\ Ew^{0.75}$$

- All pat'ev (1954) in U.S.S.R.

$$E = 0.65\ D$$

where,

E = evaporative power in mm/day (PET)

D = saturation vapor pressure deficit (D)

The coefficient, 0.65 in this case, is not strickly constant but varies.

constant but varies.

. Maude (1952) developed a coefficent which varies seasonally and regionally. His coefficient is highly correlated with mean wind speed which is represented by the air mass transfer.

. Hamon (1961) calculated the daily PET depending on the daylight hours (D), and the absolute humidity of the air (x):

$$PET = 0.0055\ D^2\ x$$

III.1.6 - Physical methods

The same WMO note has recommended three methods to be described has having future possibility for routine agriculture practice:

a. Eddy - correlation methods

It is also known by the "eddy-flux" or "eddy-transfer".

$$\overline{e_\omega q} = \overline{e_\omega}\ \overline{q} + \overline{(e_\omega)' q'}$$

where,

e= the density of the air

ω= air vertical velocity

q= air specific humidity

$\overline{e\omega q}$= average quantity of moisture transferred vertically through the horizontal plane on unit time.

The values denoted by bars are mean values, and by prime are instantaneous deviation from the mean value.

b. Aerodynamic profile method

The method is based upon the turbulent transfer of water vapor between two levels in the thin layer of air over the plant. Boltzmann equation can be used, namely:

$$E = \frac{-\rho k^2 \, (q_2 - q_1) \, (u_2 - u_1)}{(\ln \frac{Z_2}{Z_1})}$$

E= evaporation g/cm^2/sec

ρ= density of the air g/cm^3

q_1 and q_2= the specific humidities at height z_1 and z_2

k= Karman's constant = 0.41

u_1 and u_2= the wind speed at height z_1 and z_2.

This equation is applicable to aerodynamically smooth surfaces, thus is neededadaptation to be applicable for the rough vegetation covered surfaces.

c. Energy budget method

In the irrigated areas or in the crops without water deffichiencethe energy budget of the plant canopy is:

$$LET = Q_N - S - Q_h$$

where,

L= the latent heat of vaporization cal/cm^2
ET= evapotranspiration in $cal/cm^2/day$
Q_N= the radiation balance (net radiation) $cal/cm^2/day$
S= soil heat flux in $cal/cm^2/day$
Q_h= the sensible heat flux, $cal/cm^2/day$

This is a good approach where remote sensing technique can be applied in calculating the PET, namely as:

$$Q_N = Q_I - Q_E$$

where,

Q_I= the total incoming radiation could be measured by any radiometer and is equal for all the area at the same altitude without influence of the plant cover.

Q_E= the emitted radiation by the plant canopy cover. This is measured accurately by the multichannel scanner, or at least in the thermal infrared band (8-14μ) as in our case. Any advection influence or plant different shading canopy cover could be measured through the scanner detection.

While direct measurement of Q_N is difficult, and indirect approach could be used, consulting Bowen Ratio (B), we have:

$$ET = \frac{Q_N - S}{L.1+B}$$

where $B = K \frac{\Delta T}{\Delta e}$

The same WMO technical note recommended the value of k under agriculture condition to be 0.61, ΔT and Δe are the difference in air temperature in ^oC and pressure in mb. For the different crops and climatological condition the k value must be adapted. The use of this equation requires measurements of:

a. The radiation balance: measuring this parameter by the remote sensing technique has already been explained. If there is a problem in measuring the short wave radiation, a less accurate estimation process could be followed. Using the nearest measurement of the total short wave radiation and using the value of the crop albedo to calculate the net short wave radiation. This process lies outside the remote sensing field, but is essential for a study of that type.

b. The soil heat flux: this can be measured by the commercially available flux plates, or by a series of soil thermometer or thermographs for continuous 24 hours. From our previous measurement in latosol soil in Brazil the depth of 20cm was shown to be sufficient for calculating the soil heat flux.

c. The gradients of temperature and humidity: the most important advantage of the energy budget method is that the easiest, and most accurate parameter is the radiation balance, which can be measured with very high precision through the remote sensing techniques. The avail_ able sensor for this purpose is the thermal infrared scanner operating in the wave band (8-14μ).More up to date scanners with 24 multichannel detect from the ultraviolet wavelength to the thermal infrared (8-14μ).

d. The notes describe the different kinds of Lysimeters and irrigation gauges.

III.2 - CLIMATE AND AGRICULTURE

An ecological survey was published by JEN-HU CHANG in his "Climate and Agriculture" (1968). Chang in chapter 13 gave the definition of Evapotranspiration, and from chapter 14 to 18 he presented the different approachs of measuring or estimating the PET. In chapter 19, Chang discuss the water balance equation.

Chang's approachs to the PET problem divided the methods used in measuring or estimating the PET into 5 approachs:

Lysimeters: there is no need to discuss this here.
Empirical formulae.
Aerodynamic.
Energy budget.
Evaporimeters: not necessary in our survey.

This report will go over the different methods in each approach with special attention on the methods where remote sensing techniques can be applicable.

III.2.1 - Empirical formulae

a. Thornthwaite's method (1948)

$$E = 1.6 \left(10 \frac{T}{I}\right)^a$$

where,

E= (30 days/each 12 hours) PET in cm

T= the mean monthly temperature in ^oC

I= annual heat index = Σi

and $i = \left(\frac{T}{5}\right)^{1.514}$

$a = 0.675 \times 10^{-6}\ I^3 - 0.771 \times 10^{-4}\ I^2 + 0.1792 \times 10^{-1}\ I +$

$+ 0.49329$

PET is proportional to the mean monthly air temperature.

b. The Blaney-Criddle's formula (1942)

$$U = ktp\ (114 - h)$$

where,

U= monthly consumptive use in inches

k= crop coefficient 0.8 - 1.6

t= mean monthly air temperature in ^{o}F

p= monthly % of daytime hours in the year

h= mean monthly relative humidity.

c. Markkink's formula

$$E = 0.61\ Q \frac{\Delta}{\Delta+\gamma} - 0.12$$

E= PET

Q= in comming radiation in cal/day

Δ= the slope of the satured vapor pressure - temperature curve at the mean air temperature.

γ= psychrometric constant ($0.049/^{o}C$)

d. Turc's formula

$$\ell = 0.0437\ (T+2)\ \sqrt{a}$$

ℓ= evaporative power of the air

T= mean air temperature in ^{o}C

a= incoming solar radiation in lang/day

$$E = \frac{P + a + V}{\sqrt{\ell + (\frac{P+a}{\ell} + \frac{V}{2\ell})^2}}$$

E= evaporation calculated from soil

P= precipitation in mm

a= soil moisture available for evaporation from bare soil

V= additional soil moisture available for evaporation (through the vegetation)

The a(mm/week) = 35 - Δ

Δ= 0 in the field capacity

The method is available in irrigation schedules and water resources planning.

III.2.2 - The Aerodynamic Approach

Beside the WMO notes, Chang discuss Dalton equation. The molecular diffusivity of water vapor = 0,25cm^2/second in the very thin layer of the air over the evaporating surfaces.

a. Dalton - equation

$$E_0 = (e_s - e)\ f\ (u)$$

E_0= evaporation from water surface

e_s= vapor pressure at the evaporating surface

e= vapor pressure at some height above the surface

f (u)= function of the horizontal wind velocity gives accurate values of the evaporation from bare wet soil.

b. Thornthwaite - Holzman equation

$$E = \frac{\rho k^2 (q_2 - q_1)(u_2 - u_1)}{\ln \left(\frac{Z_2}{Z_1}\right)^2}$$

E= is evaporation

ρ= air density

k= von Karman's constant

u_1= wind speed

q_1= specific humidity

This equation fits well for the short vegetation. It is invalid under stable conditions.

III.2.3 - Energy budget approach

In this approach the Bowen ration and Penman equation will be discussed in greater detail than in the previous discussion under the WMO notes.

a. Penman's equation

Chang has presented the Penman equation as:

$$E_0 = \frac{Q_n + \gamma E_a}{\Delta + \gamma}$$

where,

E_0= evaporation from open water surface in mm

Δ= slope of the saturation vapor pressure - temperature curve (de_a/dt) at the air temperature T, in mb/^oC

e_s= saturation vapor pressure in mm of mercury at T

T= temperature in ^oK

$$Q_n = (1-r)\, Q_a\, (0.18+0.55\, n/N) - 5T^4\, (0.56-0.092\, \sqrt{e_d})\, (0.10+ + 0.90\, n/N)$$

Q_n = the net radiation expressed in evaporation units.

r= reflection coefficient (for mean annual values, Penman used 0.05 for open water, 0.10 for wet bare soil, 0.20 for fresh green vegetation)

Q_a= Angot's value

n/N= ratio between actual and possible hours of sunshine

σ= the Stefan Boltzmann constant

e_d= saturation vapor pressure in mm of mercury at the dew point temperature

γ= the psychrometric constant or the ratio of the specific heat of air to the latent heat of evaporation of water.

E_a= $0.35\ (e_d - e_a)\ (1 + u_2/100)$. E_a is an aerodynamic component

u_2= wind speed in miles/day at height of two meters

Two main terms govern the Penman equation.

The $\underline{Q_n}$ is the net radiation or the energy balance as it is used in the WMO technical note. The other term, $\underline{E_a}$, is the aerodynamic term. The first term makes possible the use of this equation by remote sensing application to calculate the PET. On the other hand, the equation has many constant which depend on local conditions. This makes the results very sensitive and the source of error is very big.

b. <u>Bowen Ratio: (1926)</u>

$$B = \frac{A}{E} = \gamma \frac{(k_h)}{(k_w)} \frac{(T_s - T_a)}{(e_s - e)}$$

where,

A= heat flux to the air

E= evapotranspiration

B= the Bowen ratio

γ= the psychrometric constant 0.49/^{o}C and mm of mercury

k_h= eddy diffusivites for heat

k_w= eddy diffusivites for water vapor

T_s= the temperature of the surface

T_a= the temperature of the air

e_s= vapor pressure of the surface

e= vapor pressure of the air.

III.3 - ADVANTAGE OF BOWEN RATIO METHOD

a - It is less sensitive to the errors in instrumentation for a gradient measurements and in assumptions concerning the eddy coefficient.

b - It does not need exact wind profile data.

c - Fetch requirements are not critical.

d - It depends mainly on the surface temperature. For meteorologists this is considered as a disadvantage because of the absence of an instrument to accurately measure the surface temperature. From the remote sensing point of view it is one of the big advantage, since by sensing the vegetation surfaces in the thermal infrared wavelength, and knowing the emissivity of the surface, accurate surface temperature can easily be obtained. This technique can also show the advection effect.

There has been sufficient research work done on the different methods of measuring the leaf surface temperature, by contact and non-contact methods. In Project SERE (INPE, Institute of Space Research - Brazil), the comparison between the results of these methods and the thermal infrared scanning of different times during the day and the night as well as at different flight altitudes is under study to learn the atmospheric influence. This scanning technique has an important advantage, since its output can be stored on magnetic tapes making it easy to digitalize the data and compute the radiation information.

CHAPTER IV

A DIFFICULTY IN APPLYING THE BOWEN RATIO IN THERMAL INFRARED REMOTE SENSING

The problem here is the vapor pressure of the vegetation surfaces (e_s), because the plant does not have 100% relative humidity. The solution to this problem is to calculate this parameters for the different vegetation covers during the different stages of growth . The seasonal value and regional value of this parameters should be considered. Although this is not including the remote sensing techniques, it is essential and must be developed before the application.

CHAPTER V

FURTHER WORK, EXTENSIONS DEVELOPMENT NEEDED

a - Routine work to calculate the crop constant regional and seasonal values.

b - To identify the different vagetation covers from the photographs, to be able to measure the geometric features of the plants and the area of each field. This can not be realized over the scanner image because of geometric distortion, and also because of the non-stereoscopic propoerties of scanner image to study the geometric features of the plants.

c - Digitalizing the image of scanner to calculate the isothermal areas and to define the advected areas.

d - Calculating the catchment area of the basin and the quantities of the rain falls on it.

e - Calculating the water requirements of the total area considering the soil properties, field capacity, etc.

f - Considering the water loss by runoff and other hidrological resources, from item d and item e, the water balance could be calculated.

These are application techniques of using the thermal infrared remote sensing in the watershed studies. It is clear that some of the work lies outside the area of remote sensing while other parts are related to the fields of agro-meteorology and hidrology.

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