

NN31545.1972

ICW Nota 1972
June 1989



nota

— instituut voor cultuurtechniek en waterhuishouding . wageningen —

BIBLIOTHEEK
STANINGGEBOUW

MAPPING EVAPORATION FROM PLAYA'S IN THE WESTERN DESERT:
APPROACH AND PRACTICAL EXAMPLES

M.H. Abd El Karim*

*Research Institute for Groundwater (RIGW), Giza, Egypt

Nota's (Notes) of the Institute are a means of internal communication and not a publication. As such their contents vary strongly, from a simple presentation of data to a discussion of preliminary research results with tentative conclusions. Some notes are confidential and not available to third parties if indicated as such

7 SEP. 1989

ICW 501218*

ACKNOWLEDGEMENT

The author wishes to express his gratitude to Dr. Massimo Menenti, scientist of the Institute for Land and Water Management Research (ICW), Wageningen, The Netherlands, for his valuable information and guidance through the training period.

Many thanks for engineer W.G.M. Bastiaanssen, also of this Institute, for his continuous assistance during the training period.

Thanks for the people of ICW who helped directly or indirectly for implementation of this report.

CONTENTS

	page
INTRODUCTION	1
1. SURFACE ENERGY BALANCE	3
	3
2. SURFACE REFLECTANCE CALCULATIONS WITH SATELLITE DATA	8
3. ANALYSIS OF REFLECTANCE MEASUREMENTS	20
4. ESTIMATING EVAPORATION BY MEANS OF THE SURFACE ENERGY BALANCE - BOWEN RATIO METHOD	23
5. ACTUAL EVAPORATION FROM A DRY BARE SOIL	26
	35
6. ATMOSPHERIC CORRECTION OF THERMAL INFRARED SATELLITE MEASUREMENTS	36
6.1. Calculation of at-satellite temperature	37
6.2. Application of mathematical models to do atmospheric corrections	38

INTRODUCTION

Groundwater basins formed everywhere in the sandstone horizons which occupy an area about 2 millions km² in NE Africa. It covers a part of Libya-Sudan, Chad and Egypt. The sandstone horizons are the main source of water outside of the Nile valley in the Western Desert of Egypt. Large scale development is now occurring in Dakhla and Kharga Oasis.

At the United Nations conference on desertification held in 1977 a proposal was presented for a feasibility study called "Management of the Regional aquifer in NE Africa".

A broad investigation program recommended to assess the potentiality of natural resources, groundwater in particular, for the purpose of developing human and agricultural activities that could contribute to the fight against desertification.

For political reasons this feasibility study was carried out in Egypt and Sudan only, under the umbrella of United Nations between 1984 and 1988. The purpose of the study is to determine the hydrogeological characteristics of the aquifer and planning the best groundwater utilization schemes through landuse and groundwater development. In Egypt the feasibility study is carried out under the responsibility of RIGW.

In 1985 a proposal was submitted by the Institute for Land and Water Management Research (ICW) the Netherlands, dealing with measurement of evaporation in the playa's in the Western Desert of Egypt. Evaporation takes place in depressions with shallow groundwater tables and it amounts to more than the groundwater extracted by pumping.

ICW and RIGW started in 1986 this joint research project to map groundwater losses by evaporation in the playa areas in the Western Desert.

The scheme of work includes:

- analysis of satellite data
- field campaigns to collect data on:
 - surface energy balance
 - soil physical properties

- Groundwater table depth by means of solid state water level recorders;
- Determination of evaporation by using numerical simulation models of water flow in the saturate (FEMSAT) and unsaturated zone (SWATRE; EVADES; CAPSEV);
- Evaluation of results by means of groundwater simulation models, as developed to assess the groundwater resources in the Western Desert of Egypt (MIT model);
- Training of RIGW staff inside and outside Egypt;

In the recent years a number of procedures to analyse satellite data to estimate actual evaporation have been proposed in the literature.

To this purpose surface reflectance and temperature are obtained with thematic mapper measurements. Field measurements data are needed.

An explanation of some theories and examples of application are given in this report.

This report has been prepared during a study visit at the ICW in The Netherlands (5th of September through 7th of October 1988).

1. SURFACE ENERGY BALANCE

Solar radiation is the driving force for all atmospheric motions through heating of the atmosphere and of the land surface. Particularly, solar radiation is the basic driving force of evaporation.

Natural radiation is a superposition of electromagnetic waves spreading in different directions. The sun behaves like a full radiator with surface temperature about 6000 K. Most of radiation emitted at that temperature is confined to the wave band from 0,3 - 3 μm (short wave radiation). The radiation, which reaches the earth are short wave radiations. The earth surface and the atmosphere radiate energy at a temperature of approximately 300 K, which corresponds to the thermal infrared spectral range (8 - 14 μm). The atmosphere effects radiation transfer through scattering in the atmosphere absorbtion, of a part of the solar radiation. Solids and liquids particles and gases emit energy as a long wave radiation (infrared).

The energy budget at the soil surface is formally written as:

$$R_n + H + LE + G_o = 0 \quad (\text{W.m}^{-2}) \quad [1]$$

where:

R_n = net radiation

H = sensible heat flux

LE = latent heat flux

G_o = soil heat flux

The net amount of radiant energy received by the earth's surface per unit time and area is called net radiation.

R_n = difference of incoming and out going short wave radiation + difference of incoming and outgoing long wave radiation

K_1 = incoming short wave radiation (Global radiation) Fig.1.

K_2 = outgoing short wave radiation (reflected)

L_1 = incoming long wave radiation from air

L_2 = outgoing long wave radiation from soil

$$R_n = (K_1 - K_2) + (L_1 - L_2) \quad (\text{W.m}^{-2}) \quad [2]$$

R_n could be measured directly in the field by net radiationmeter or indirectly from solarmeters readings shortwave and application of Stefan Boltzmann law.

$$L = \epsilon \cdot \sigma \cdot T^4 \quad (\text{W.m}^{-2}) \quad [3]$$

where:

T = absolute temperature of a body in K

σ = Stefan Boltzmann constant = $5.67 \times 10^{-8} \text{ W.m}^{-2}$

ϵ = emissivity of a body it is value between zero and one

A practical example of calculation will now be presented; the values applied to develop the example were measured at Bir Qfar on June 15, 1988 at 10 a.m.

K_1 = incoming short wave radiation (Global radiation) = 650 W.m^{-2}
(measured by Solarimeter)

K_2 = outgoing short wave radiation = 132 W.m^{-2}
(measured by Solarimeter)

L_1 = long wave radiation = $\epsilon \cdot \sigma \cdot T^4$

$T(^{\circ}\text{C}) = 40^{\circ}\text{C}; \epsilon = 0.85 \quad T(\text{K}) = 313 \text{ K}$

$L_1 = 0.85 \times 5.67 \times 10^{-8} \times (313)^4 = 462.5 \text{ W.m}^{-2}$

$T_0(^{\circ}\text{C}) = 50^{\circ}\text{C}; \epsilon = 0.95 \quad T(\text{K}) = 323 \text{ K}$

$L_2 = 0.95 \times 5.67 \times 10^{-8} \times (323)^4 = 586.2 \text{ W.m}^{-2}$

$R_n = K_1 - K_2 - L_2 + L_1$

$R_n = 650 - 132 - 586.2 + 462.5 = 640.7 \text{ W.m}^{-2}$

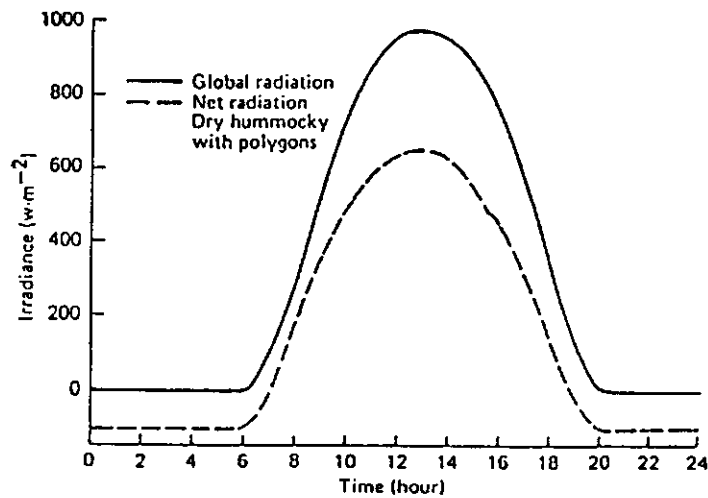


Fig. 1. Global radiation = Incoming short wave radiation

H = Sensible heat flux is the heat flux exchange between atmosphere and soil. It depends on the turbulent motion in the atmospheric layer. It is a function of temperature, humidity, wind speed at the surface and at certain altitude.

$$H = \frac{-\rho_a C_p}{r_a} (T_a - T_0) \quad (\text{W.m}^{-2}) \quad [4]$$

ρ_a = air density $\approx 1.25 \text{ kg.cm}^{-3}$

C_p = air specific heat $\approx 1004 \text{ J. kg}^{-1}.\text{k}^{-1}$

r_a = turbulent transfer resistance S.m^{-1} (10 - 200 S.m^{-1})

T_a = air temperature (10 - 50°C) (see Fig. 2)

T_0 = surface temperature (10 - 70°C)

r_a = mean turbulent transfer resistance S.m^{-1} is not a constant value, changes with surface roughness and difference between T_a , T_0 because of the contribution of buoyance to turbulent transfer.

Only two of the variables in eq., i.e.

α_0 , T_0 can be remotely measured, the remaining variables have to be measured in the field.

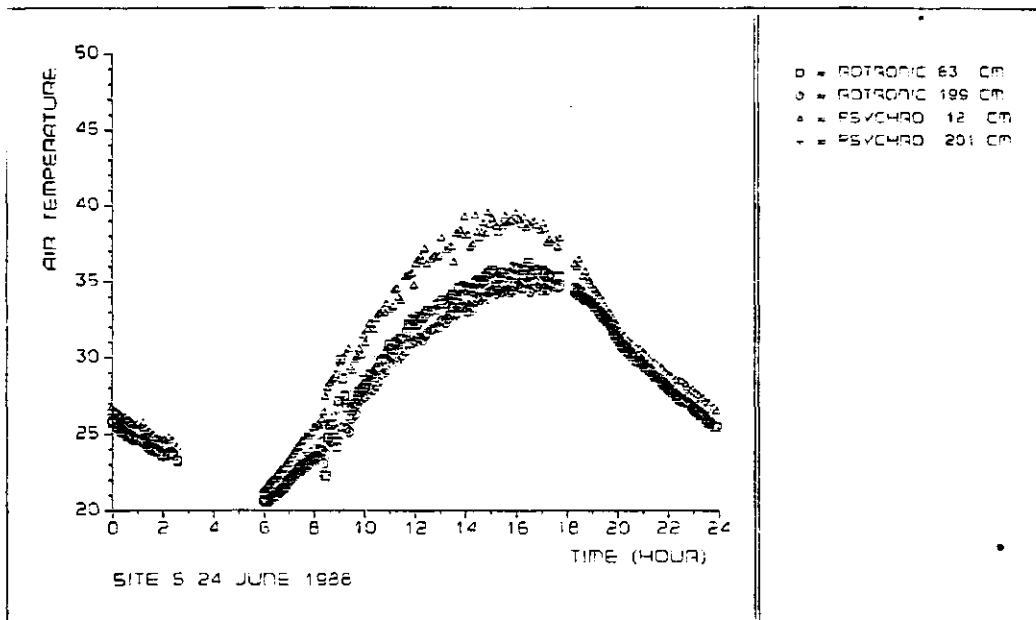


Fig. 2. The relation between air temperature and time

Ex: given local time 11.00 h.

$$R_{sw} = 785 \text{ W.m}^{-2}$$

$$\alpha_o = 0.21$$

$$\epsilon' = 0.883$$

$$\epsilon = 0.95$$

$$r_a = 60 \text{ S.m}^{-1}$$

$$\phi_{su} = 40^\circ\text{C}$$

$$T_a = 41.3^\circ\text{C}$$

$$T_s = 50$$

$$G_o = 0.25 R_n \text{ (see Fig. 3)}$$

What is the latent heat flux?

Energy balance on the earth's surface written as:

$$R_n + H + LE + G_o = 0 \quad (\text{W.m}^{-2}) \quad [5]$$

so

$$LE = -R_n - H - G_o \quad (\text{W.m}^{-2}) \quad [6]$$

or

$$LE = - (1-\alpha_o)R_{sw} + \epsilon\delta T_o^4 - \epsilon'\delta T_a^4 - \frac{\rho_a \cdot C_p}{r_a} (T_a - T_o) - G_o \quad (\text{W.m}^{-2}) \quad [7]$$

$$R_n = + (1-0.21) \times 785 - 0.95 \times 5.67 \times 10^{-8} \times (323)^4 + 0.883 \times 5.67 \times 10^{-8} \times$$

$$(314.3)^4 = 620.15 - 586 + 488 = 522.15 \text{ W.m}^{-2}$$

$$H = \text{Sensible heat flux} = \frac{\rho_a \cdot C_p}{r_a} (T_a - T_o) = \frac{1.25 \times 1004}{60} (41.3 - 50) = -181.98 \text{ W.m}^{-2}$$

$$LE = -522.15 + 181.93 + 0.25 \times 522.15 = -209.7 \text{ W.m}^{-2}$$

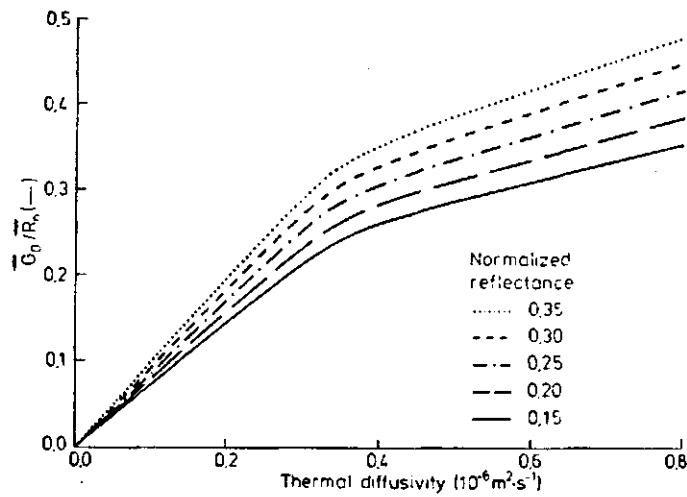


Fig. 3. Soil heat flux versus net radiation

2. SURFACE REFLECTANCE CALCULATIONS WITH SATELLITE DATA

The reflectance of a particular surface can be obtained by dividing the reflected irradiance by the incident irradiance ($0.3 - 3 \mu\text{m}$). Reflectance is dependent on surface characteristics (type), dew deposition and evaporation daily, sun altitude, evaporation daily cycles and the wave length of the incident radiant energy. (Fig. 4.)

Spectral reflected radiance at specific wavelength while the reflectance is integrated over the total spectrum.

Net radiation depends strongly on values of surface reflectance. To estimate actual evaporation through analysis of surface energy balance, it is necessary to obtain accurate values of surface reflectance, as net radiation depends strongly on the values of surface reflectance.

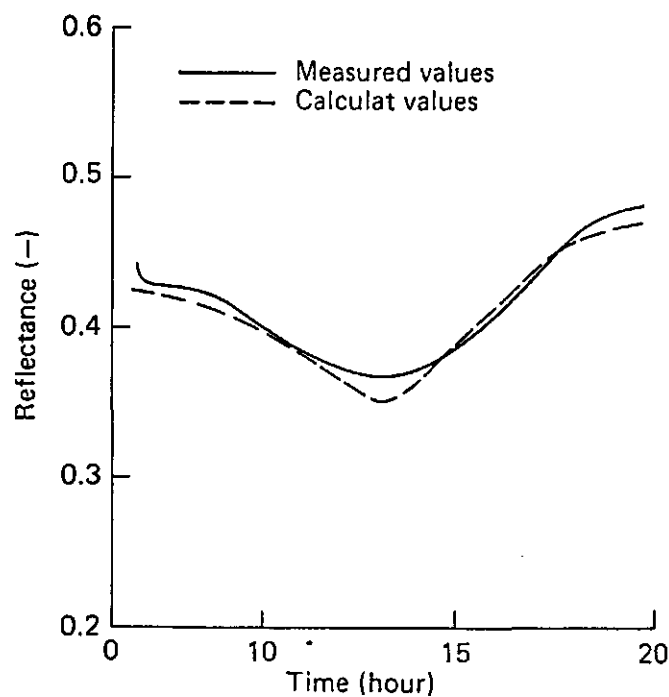


Fig. 4. Diurnal variation of bare soil reflectance

Surface reflectance = $\alpha_0 = \frac{\text{outcoming short wave radiation}}{\text{incoming short wave radiation}}$

Ex: $\alpha_0 = 0.5$ white salt crust

$\alpha_0 = 0.25$ Sabkha crust

(The wetter the soil the lower the reflectance)

Surface reflectance could be calculated from the field measurement using solarimeters to measure total and diffuse irradiance and reflected radiance.

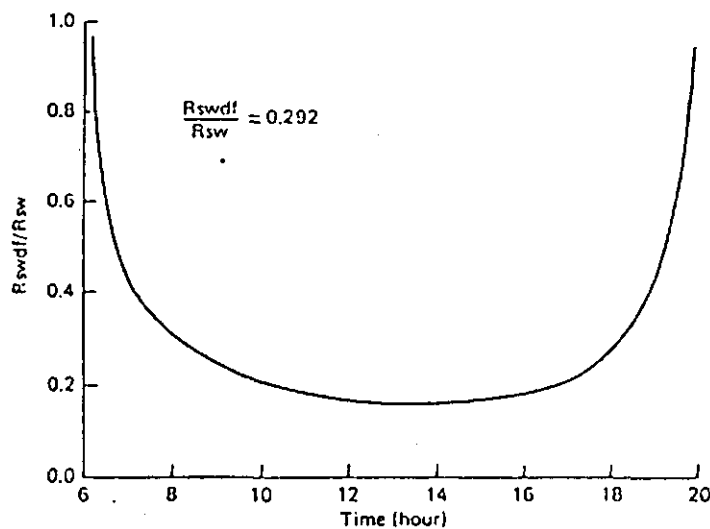


Fig. 5. Effect of diffusive radiation on the daily cycle of surface reflectance

To obtain surface reflectance with satellite measurements the following steps must be considered:

- A. From spectral radiance to spectral planetary reflectance
- B. From spectral planetary reflectance to planetary reflectance
- C. From planetary reflectance, surface reflectance can be calculated by applying formula to correct for atmospheric influence.

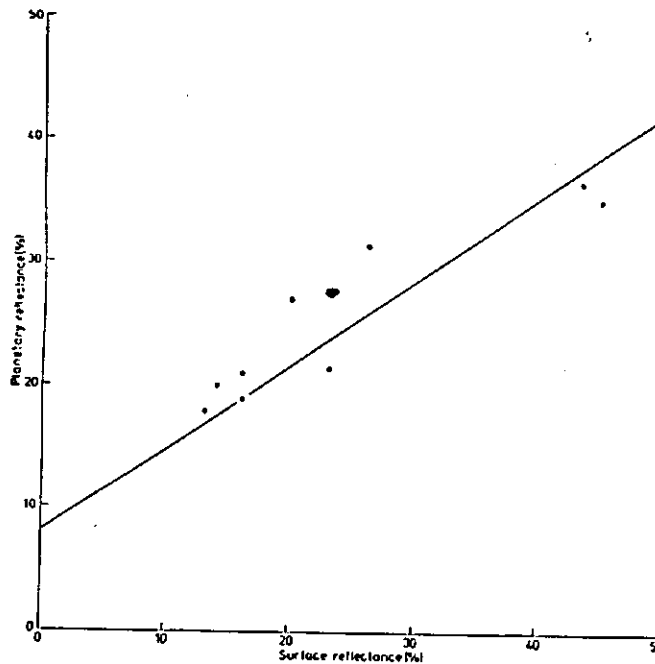


Fig. 6.

A. Calculating the spectral radiance L_i from standard tables of NASA as follows:

$$L_i = L_{min} + \left(\frac{L_{max\lambda} - L_{min\lambda}}{Q\text{ CAL MAX}} \right) Q\text{ CAL} \quad (\text{mW.cm}^{-2}.\text{ster}^{-1}.\mu\text{m}^{-1}) \quad [8]$$

where:

Q CAL = Calibrated and re-scaled radiance in units of DN, digital numbers.

$L_{min\lambda}$ = Spectral radiance at Q CAL = 0

$L_{max\lambda}$ = Spectral radiance at Q CAL = Q CAL MAX

Q CAL MAX = Range of rescaled radiance in DN

L_i = Spectral radiance

DN = Digital number

$$L_i = L_{mini} + \left(\frac{L_{maxi} - L_{mini}}{255} \right) \times \text{DN} \quad (\text{mW.cm}^{-2}.\text{ster}^{-1}.\mu\text{m}^{-1}) \quad [9]$$

Table 1 shows the spectral radiance $L_{min\lambda}$, $L_{max\lambda}$.

Table 1. TM Post-calibration Dynamic Ranges for U.S. Processed Data (after Landsat technical notes)

Band	L_{mini}	L_{maxi}	<u>Bandwidth</u>
	m.w.cm. ⁻² .ster ⁻¹ .μm ⁻¹		μm
1	- 0.15	15.21	70.1
2	- 0.28	29.68	88.9
3	- 0.12	20.43	76.9
4	- 0.15	20.62	76.6
5	- 0.037	2.719	134.3
6	- 0.1238	1.560	226.5
7	- 0.015	1.438	268.2

The spectral planetary reflectance is calculated from spectral radiance:

$$\alpha_{pi} = \frac{\pi L_i \cdot d^2}{R_{out,i} \cos\phi} \quad (-) \quad [10]$$

where:

d = earth sun distance in astronomical units (from nautical handbook)

φ = solar zenith angle in degree

R_{out,i} = mean exo-atmospheric solar irradiance in band_i of the thematic mappes m.w.cm⁻²mm⁻²

α_{pi} = spectral planetary reflectance

Table 2. Mean solar Exo-atmospheric spectral irradiances

Table 2 TM Post-Calibration Dynamic Ranges for U.S. Processed Data Spectral Radiances, $L_{MIN\lambda}$ and $L_{MAX\lambda}$, in $mW \cdot cm^{-2} \cdot ster^{-1} \cdot \mu m^{-1}$						
Band	Prior to August 1983 (Scrounge-ERA processing) ^a		Prior to 15 Jan 1984 (TIPS-ERA processing) ^b		After 15 Jan 1984 (TIPS-ERA processing) ^c	
	$L_{MIN\lambda}$	$L_{MAX\lambda}$	$L_{MIN\lambda}$	$L_{MAX\lambda}$	$L_{MIN\lambda}$	$L_{MAX\lambda}$
TM 1	-0.152	15.842	0.000	14.286	-0.15	15.21
TM 2	-0.284	30.817	0.000	29.125	-0.28	29.68
TM 3	-0.117	23.463	0.000	22.500	-0.12	20.43
TM 4	-0.151	22.432	0.000	21.429	-0.15	20.62
TM 5	-0.037	3.242	0.000	3.000	-0.037	2.719
TM 6	0.20	1.564	0.484	1.240	0.1238	1.5600
TM 7	-0.015	1.700	0.000	1.593	-0.015	1.438

^a Barker, Ball et al., 1984 (Table 3)
^b Very little data were processed with these parameters because only small amounts of TM data were being collected at this time, e.g., TIPS "Long Term Parameter File" number TL4888.PAR was generated on 20 July 1983
^c Barker, 1984 (Table 1), and Barker, 1985 (Table 1-1 and Appendix 9), as carried in TIPS (TM Image Processing System at Goddard) Long Term Parameter File Number TL5027.PAR for in-band radiance from full-width half maximum band-width for Landsat-5 and generated on 23 August 1984

Table 3. TM Solar Exo-atmospheric spectral irradiances

Table 4 TM Solar Exoatmospheric Spectral Irradiances $ESUN_{\lambda}$ ($mW \cdot cm^{-2} \cdot \mu m^{-1}$) a,b			
Band	Satellite	Landsat-4	Landsat-5
	TM 1	195.8	195.7
	TM 2	182.8	182.9
	TM 3	155.9	155.7
	TM 4	104.5	104.7
	TM 5	21.91	21.93
	TM 7	7.457	7.452

^a Solar data from Neckel and Labs, 1984 (Bands 1-4) and from Iqbal, 1983 (Band 5 and Band 7)
^b Up-dated from Markham and Barker, 1985 (Table 11)

Table 4. Shows the values of earth sun distance in atmospheric units

EPHEMERIS OF THE SUN

Date	Declination	Longitude	Equation of time	Radius vector	Date	Declination	Longitude	Equation of time	Radius vector
	° ' "	° ' "	m. s.			° ' "	° ' "	m. s.	
Jan. 1	-23 4 280	1	- 3 14	0.98324	Feb. 1	-17 19 311 34	-13 34	0.98533	
5	22 42 284 5	5	5 6	.98324	5	16 10 315 37	14 2	.98593	
9	22 13 288 10	6 50		.98333	9	14 55 319 40	14 17	.98662	
13	21 37 292 14	8 27		.98352	13	13 37 323 43	14 20	.98738	
17	20 54 296 19	9 54		.98378	17	12 15 327 46	14 10	.98819	
21	20 5 300 23	11 10		.98410	21	10 50 331 48	13 50	.98903	
25	19 9 304 27	12 14		.98448	25	9 23 335 49	13 19	.98991	
29	18 8 308 31	13 5		.98493					
Mar. 1	- 7 53 339 51	-12 38	0.99284	Apr. 1	+ 4 14 10 42	- 4 12	0.99928		
5	6 21 343 51	11 48	.99182	5	5 46 14 39	3 1	1.00043		
9	4 48 347 51	10 51	.99287	9	7 17 18 35	1 52	1.00160		
13	3 14 351 51	9 49	.99396	13	8 46 22 30	- 0 47	1.00276		
17	1 39 355 50	8 42	.99508	17	10 12 26 25	+ 0 13	1.00390		
21	- 0 5 359 49	7 32	.99619	21	11 35 30 20	1 6	1.00500		
25	+ 1 30 3 47	6 20	.99731	25	12 56 34 14	1 53	1.00606		
29	3 4 7 44	5 7	.99843	29	14 13 38 7	2 33	1.00709		
May 1	+14 50 40 4	+ 2 50	1.00759	June 1	+21 57 69 56	+ 2 27	1.01405		
5	16 2 43 56	3 17	1.00859	5	22 28 73 46	1 49	1.01465		
9	17 9 47 48	3 35	1.00957	9	22 52 77 36	1 6	1.01518		
13	18 11 51 40	3 44	1.01051	13	23 10 81 25	+ 0 18	1.01564		
17	19 9 55 32	3 44	1.01138	17	23 22 85 15	- 0 33	1.01602		
21	20 2 59 23	3 34	1.01218	21	23 27 89 4	1 25	1.01630		
25	20 49 63 14	3 16	1.01291	25	23 25 92 53	2 17	1.01649		
29	21 30 67 4	2 51	1.01358	29	23 17 96 41	3 7	1.01662		
July 1	+23 10 98 36	- 3 31	1.01667	Aug. 1	+18 14 128 11	- 6 17	1.01494		
5	22 52 102 24	4 16	1.01671	5	17 12 132 0	5 59	1.01442		
9	22 28 106 13	4 56	1.01669	9	16 6 135 50	5 33	1.01384		
13	21 57 110 2	5 30	1.01659	13	14 55 139 41	4 57	1.01318		
17	21 21 113 51	5 57	1.01639	17	13 41 143 31	4 12	1.01244		
21	20 38 117 40	6 15	1.01610	21	12 23 147 22	3 19	1.01163		
25	19 50 121 29	6 24	1.01573	25	11 2 151 14	2 18	1.01076		
29	18 57 125 19	6 23	1.01530	29	9 39 155 5	1 10	1.00986		
Sept. 1	+ 8 35 157 59	- 0 15	1.00917	Oct. 1	- 2 53 187 14	+10 1	1.00914		
5	7 7 161 52	+ 1 2	1.00822	5	4 26 191 11	11 17	1.00801		
9	5 37 165 45	2 22	1.00723	9	5 58 195 7	12 27	0.99688		
13	4 6 169 38	3 45	1.00619	13	7 29 199 5	13 30	.99574		
17	2 34 173 32	5 10	1.00510	17	8 58 203 3	14 25	.99459		
21	+ 1 1 177 26	6 35	1.00397	21	10 25 207 1	15 10	.99344		
25	- 0 32 181 21	8 0	1.00283	25	11 50 211 0	15 46	.99233		
29	2 6 185 16	9 22	1.00170	29	13 12 214 59	16 10	.99126		
Nov. 1	-14 11 217 59	+16 21	0.99249	Dec. 1	-21 41 248 13	+11 16	0.98604		
5	15 27 222 0	16 23	.99150	5	22 16 252 16	9 43	.98546		
9	16 38 226 1	16 12	.99054	9	22 45 256 20	8 1	.98494		
13	17 45 230 2	15 47	.98960	13	23 6 260 24	6 12	.98446		
17	18 48 234 4	15 10	.98869	17	23 20 264 28	4 17	.98405		
21	19 45 238 6	14 18	.98784	21	23 26 268 32	2 19	.98372		
25	20 36 242 8	13 15	.98706	25	23 25 272 37	+ 0 20	.98348		
29	21 21 246 11	11 59	.98636	29	23 17 276 41	- 1 39	.98334		

B. From spectral planetary reflectance to planetary reflectance:

$$\alpha_p = \epsilon \frac{(R_{out,i} \times \alpha_{p,i} \times b_i)}{\epsilon_i R_{out,i} \times b_i} \quad (-) \quad [11]$$

where:

α_p = planetary reflectance

α_{pi} = spectral planetary reflectance

b_i = band width in micrometer

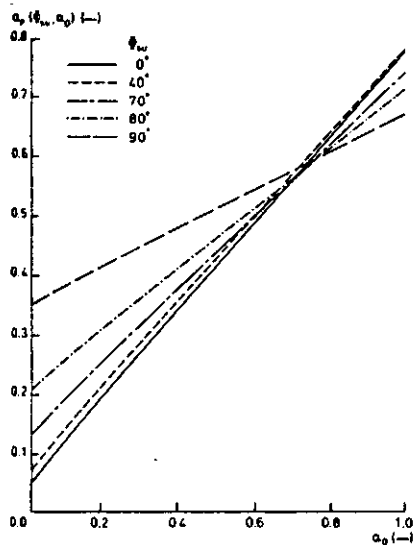
$R_{out,i}$ = the exo-atmospheric solar irradiance in band i of the thematic mapper

$\epsilon R_{out,i}$ = the sum of exo-atmospheric solar irradiance in the TM spectral bands

Measurement of surface reflectance can be done as follows:

WITHOUT MEASUREMENTS OF ATMOSPHERICAL OPTICAL PROPERTIES

- * Plot measurements of surface reflectance done with solarimeters vs. values of planetary reflectance obtained with landsat data.

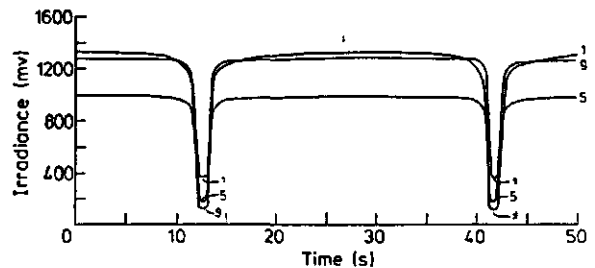


- * Simple atmospheric correction formula can be sufficient to match observed α_p with α_0 values.

- * For example a linear relationship between α_p and α_0 is given by the graphs of NACK and CURRAN (1978; Fig. 1). From the graphs it is possible to obtain the surface reflectance, for a given seen zenith angle and the atmospheric conditions and the atmospheric conditions applied to calculate the fluxes. A relation between planetary reflectance calculated with TM for an image of Siwa (2 April 1987) and measured values in the field was drawn. This linear relationship between α_p , α_0 matched with curves of Nack and Curran at ϕ_{su} 40°; which applies to the TM image acquired on 2 April 1987.

WITH MEASUREMENTS OF ATMOSPHERICAL OPTICAL PROPERTIES

- * Measure atmospheric properties (for example total and diffuse spectral irradiance with Guzzi-meter; measurements of total and diffuse irradiance with solarimeters in a broad spectral band; 0.3 - 2.8 m).



- * Apply radiation transfer models with the measured atmospheric properties to obtain relationships between planetary reflectance* and surface reflectance. For a given ϕ_{su} , such relationships are linear.
 - * planetary reflectance is obtained with Landsat digital data
- * Apply the thus obtained correction formula to obtain a α_0 -image, for Qara Oasis and Qattara depression.

EXAMPLE:

Local time 11.00 h

TM Data:

		Band width μm
Band 1	DN = 137	0.07
Band 2	DN = 97	0.089
Band 3	DN = 104	0.076
Band 4	DN = 52	0.134
Band 5	DN = 122	0.226
Band 6	-----	-----
Band 7	DN = 121	0.268

$$\phi_{\text{su}} = 40^\circ$$

Calculate the surface reflectance α_0

STEP 1

$$\angle\lambda = \angle_{\min\lambda} + \left(\frac{\angle_{\max\lambda} - \angle_{\min\lambda}}{255} \right) * DN$$

e.g. BAND 1 = : DN = 137

2 = : DN = 97

3 = : DN = 104

4 = : DN = 52

5 = : DN = 122

7 = : DN = 121

$$\text{BAND 1 } \angle_1 = -0.15 + \left(\frac{15.21 + 0.15}{255} \right) * 137 = 8.1 \text{ mW.cm}^{-2}.\text{ster}^{-1}.\mu\text{m}^{-1}$$

$$2 \angle_2 = -0.28 + \left(\frac{29.68 + 0.28}{255} \right) * 87 = 11.11 \text{ mW.cm}^{-2}.\text{ster}^{-1}.\mu\text{m}^{-1}$$

$$3 \angle_3 = -0.12 + \left(\frac{20.43 + 0.12}{255} \right) * 104 = 8.26 \text{ mW.cm}^{-2}.\text{ster}^{-1}.\mu\text{m}^{-1}$$

$$4 \angle_4 = -0.15 + \left(\frac{20.62 + 0.15}{255} \right) * 52 = 4.01 \text{ mW.cm}^{-2}.\text{ster}^{-1}.\mu\text{m}^{-1}$$

$$5 \angle_5 = -0.037 + \left(\frac{2.719 + 0.037}{255} \right) * 122 = 1.24 \text{ mW.cm}^{-2}.\text{ster}^{-1}.\mu\text{m}^{-1}$$

$$7 \angle_7 = -0.015 + \left(\frac{1.438 + 0.015}{255} \right) * 121 = 0.66 \text{ mW.cm}^{-2}.\text{ster}^{-1}.\mu\text{m}^{-1}$$

STEP 2

$$\text{BAND 1 } \alpha_{p,1} = \frac{\Pi. 8.1 \cdot 0.99508^2}{195.7 \cdot \cos 40^\circ} = 0.168$$

$$\text{BAND 2 } \alpha_{p,2} = \frac{\Pi. 11.1 \cdot 0.99508^2}{182.9 \cdot \cos 40^\circ} = 0.246$$

$$\text{BAND 3 } \alpha_{p,3} = \frac{\Pi. 8.26 \cdot 0.99508^2}{155.7 \cdot \cos 40^\circ} = 0.215$$

$$\text{BAND 4 } \alpha_{p,4} = \frac{\Pi. 4.01 \cdot (.99508)^2}{104.7 \cdot \cos 40^\circ} = 0.09$$

$$\text{BAND 5 } \alpha_{p,5} = \frac{\Pi. 1.24 \cdot (.99508)^2}{21.93 \cdot \cos 40^\circ} = 0.13$$

$$\text{BAND 7 } \alpha_{p,7} = \frac{\Pi. 0.66 \cdot (.99508)^2}{7.452 \cdot \cos 40^\circ} = 0.35$$

STEP 3

$$\alpha_p = \Sigma_i \frac{R_{out\ i} \times \alpha_{pi} \times b_i}{\Sigma R_{out\ i} \times b_i}$$

where: b_i = band width micrometer

$$\Sigma R_{out\ i} \times b_i = 195.7 \times 0.07 + 182.9 \times 0.089 + 155.7 \times 0.076 + 104.7 \times 0.134 + 21.93 \times 0.226 + 7.45 \times 0.268 = 62.792$$

$$\alpha_p = \frac{195.7 \times 0.168 \times 0.07}{62.792} + \frac{182.9 \times 0.246 \times 0.089}{62.792} + \frac{155.7 \times 0.215 \times 0.076}{62.79}$$

$$+ \frac{104.7 \times 0.09 \times 0.134}{62.792} + \frac{21.93 \times 0.13 \times 0.226}{62.792} + \frac{7.452 \times 0.35 \times 0.268}{62.79} =$$

$$\alpha_p = '.36 + '.06 + 0.04 + 0.02 + 0.0102 + 0.011 = 0.177$$

$$\alpha_p = 0.177 \approx 0.18$$

From the graphs (Fig. 1) we can get α_0

at $\phi_{su} 40^\circ$

$$\alpha_0 \approx 0.16$$

3. ANALYSIS OF REFLECTANCE MEASUREMENTS

The surface reflectance shows a diurnal variation which can be even different from day to day. In order to classify surfaces on the basis of reflectance, a reference surface reflectance has to be defined. During the field measurements in Egypt at each site solorimeters were applied to measure total and diffuse irradiance and surface reflectance related to sun zenith angle and atmospheric optical depth. By means of a non linear regression function of the following type (BASTIAANSEN, 1988):

$$T = A B^X \quad (-) \quad [12]$$

where: A = regression coefficient = α_0'
 B = regression coefficient = $B(\tau)$;
 τ = atmospheric optical depth

We can calculate the reference surface reflectance α_0'

$$\alpha_0 = \alpha_0' \cdot [m \cdot f_i(\phi_{su})] \cdot [g_i(\tau_i)]^{\sin \phi_{su}} \quad (-) \quad [13]$$

$$m = \frac{\alpha_0'(\text{morning})}{\alpha_0'(\text{afternoon})} \quad \text{is a constant} \quad (-) \quad [14]$$

$m \cdot f_i(\phi_{su})$ is a correction factor for dew; $f_i(\phi_{su})$ is equal to one at noon:

if $m \cdot f_i(\phi_{su}) = 1$ and $\phi_{su} = 0$

then $\alpha_0 = \alpha_0'$

then $\ln \alpha_0 = \ln \alpha_0' + \sin \phi_{su} \ln g_i(\tau_1)$

Through the empirical solution as a linear equation we can get the value of α_0' as regression coefficient and $g(\tau)$.

Table 5. Examples

α_0	ϕ_{su}	time	$\ln \alpha_0$	$\sin \phi_{su}$
0.51	80	7.00	0.67	0.98
0.49	60	9.00	0.71	0.86
0.46	15.34	11.00	0.77	0.78
0.38	20.7	13.00	0.96	0.35
0.40	43	15.00	0.92	0.68
0.44	70	17.00	0.82	0.93
0.49	88.89	18.00	0.71	0.99

What is α_0' and τ ?

Fig. 9 indicate the relation between $\ln \alpha_0$ and $\sin \phi_{su}$

From the graph

$$\alpha_0' = 0.33$$

$$\tau = 1.8$$

what is α_0 at $\tau_{su} = 70^\circ$

$$\alpha_0 = \alpha_0' \cdot \tau^{\sin \phi_{su}}$$

$$\alpha_0 = 0.33 \times 1.8^{\sin 70^\circ} = 0.57$$

which means a cloudy weather (see Fig. 10)

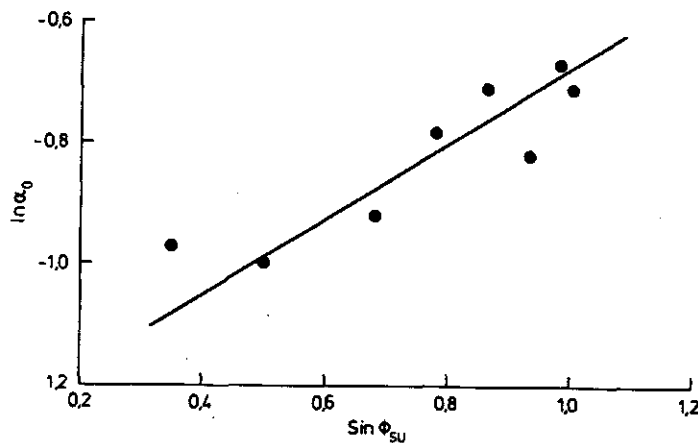


Fig. 9. The non-linear regression relation between $\ln \alpha_0$ and $\sin \phi_{su}$

Fig. 10 shows the relation between ratio of diffusive to total irradiance and $g(\tau)$ optical depth.

It is clear that $g(\tau)$ depends on the conditions of atmosphere and emface roughness.

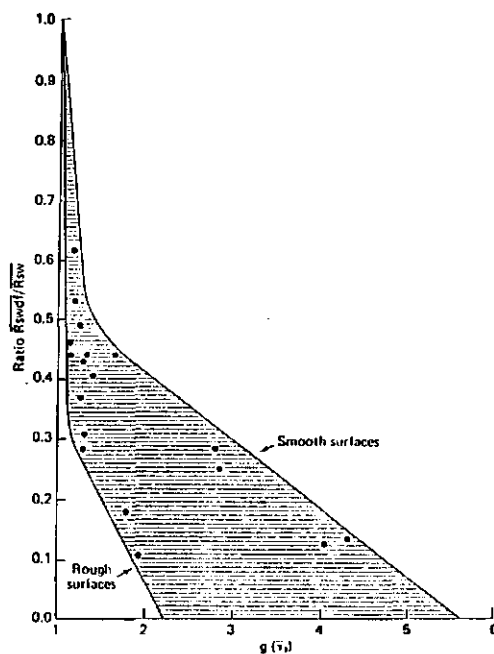


Fig. 10. Relation between $\frac{R_{swdf}}{R_{sw}}$ to the coefficient $g(\tau_1)$

4. ESTIMATING EVAPORATION BY MEANS OF THE SURFACE ENERGY BALANCE - BOWEN RATIO METHOD

Energy budget for a soil or water surface is:

$$R_n + G_o + H + LE = 0 \quad [15]$$

R_n is measured by means of net radiometers, G_o is measured with heat flux plates usually in conjunction with temperature measurements.

The ratio of the sensible to latent heat flux is called the Bowen ratio (B). Substituting for H in eq. [1]:

$$LE = \frac{R_n - G}{1 + B} \quad [16]$$

LE and H can be expressed as:

$$LE = \frac{\rho c_p (e_1 - e_2)}{\gamma r_v} \quad [17]$$

where:

ρc_p = the volumetric heat capacity of air

ρ = air density $\approx 1.25 \text{ kg.m}^{-3}$

γ = the thermodynamic psychrometer constant

$$\gamma = \frac{P \cdot c_p}{\lambda \epsilon}$$

P = barometric pressure $\approx 1013 \text{ mbars}$

c_p = specific heat of air $\approx 1004 \text{ J.kg}^{-1}.\text{K}^{-1}$

e_1, e_2 = actual vapour pressures at two different altitudes

ρ = latent heat of vaporization = $2,500,000 \text{ W.m}^{-2}$

ϵ = the ratio of molecular weight of water vapour to molecular weight of dry air ≈ 0.662

psychrometer constant $\approx 0.66 \text{ mbar.K}^{-1}$

$$H = \frac{\rho c_p (T_1 - T_2)}{r_H} \quad [18]$$

r_v, r_H = the vapour and heat transfer resistance between two different altitudes.

T_1, T_2 = the actual air temperatures at two different altitudes.

Assuming $r_H = r_v$ the Bowen ratio is given by:

$$B = \frac{H}{LE} = \frac{(T_1 - T_2)}{(e_1 - e_2)} \quad [19]$$

B is obtained by knowing atmospheric pressure and measuring temperature and vapour pressure at two heights. Barometric pressure can be measured on-site or at a meteorostation and make necessary corrections.

Example:

Given the data of site 3 at Bir Qifar, 18 June 1988

1. net radiation $W.m^{-2}$ (Fig. 9)
2. soil heat flux $W.m^{-2}$ (Fig. 9)
3. Bowen ratio (Fig. 11)

Calculate the latent heat flux

$$1 W.m^{-2} = 1 J.s^{-1}.m^2$$

L_e latent heat of vaporization is at about 288 K, $2.46 \times 10^6 J.kg^{-1}$

So $1 W.m^{-2}$ enables the vaporization of $1/(2.46 \times 10^6) = 4.06 \times 10^{-7} kg.s^{-1}.m^2$ or $4.06 \times 10^{-7} \times 86,400 = 3.51 \times 10^{-2} kg.day^{-1}.m^2$

$$1 kg.m^{-2} = 1 mm$$

$$1 W/m^2 = 4.06 \times 10^{-7} kg/s.m^2 = 3.51 \times 10^{-2} mm/day$$

This value $3.51 \times 10^{-2} mm/day$ when the surface temperature is $288 - 273 = 15^\circ C$ which is not the average temperature in Siwa area. When water temperature increases water molecules need less energy to evaporate.

The latent heat of vaporization varies with temperature with the following formula:

$$L = (2501 - T \cdot \frac{71}{30}) \times 10^3 \quad [20]$$

where:

L = latent heat of vaporization (J.kg⁻¹)

T° = temperature in °C

Assume the average temperature is 40°C in site 3 Qifar

$$L = (2501 - 40 \times \frac{71}{30}) \times 10^3 = 2.41 \times 10^6 \text{ J.kg}^{-1}$$

$$\text{W.m}^{-2} = \frac{1 \times 86,400}{2.46 \times 10^6} = 3.58 \times 10^{-2} \text{ kg.day}^{-1}.\text{m}^2 \text{ or } 3.58 \times 10^{-2} \text{ mm/day}$$

$$\text{Evapotranspiration is } \frac{1103}{24} = 46 \times 3.58 \times 10^{-2} = 1.64 \text{ mm/day}$$

Example:

$$\text{Bir Qifar 18 June 1988 } L_e = \frac{R_n - G}{1 + B}$$

Hour	R _n (net radiation) W.m ⁻²	G (soil heat flux) W.m ⁻²	B (Bowen ratio) -	LE W.m ⁻²
0	- 90	- 50	0.20	- 33.3
1	- 88	- 55	0.20	- 27.5
2	- 85	- 60	0.20	- 20.8
3	- 85	- 60	0.20	- 20.8
4	- 85	- 60	0.20	- 20.8
5	- 85	- 60	0.20	- 20.8
6	- 85	- 60	0.20	- 20.8
7	- 15	- 82	0.20	+ 55.83
8	+135	+ 20	0.33	+ 86.46
9	+278	+ 45	0.60	+145.63
10	+385	+ 95	0.86	+155.9
11	+471	+140	1.13	+155.39
12	+507	+180	1.20	+148.63
13	+521	+190	1.13	+155.39
14	+492	+170	1.20	+146.36
15	+420	+150	0.86	+145.16
16	+335	+100	0.93	+121.76
17	+207	+ 72	0.66	+ 81.32
18	+ 90	+ 28	0.33	+ 46.62
19	- 21	- 20	0.26	- 0.81
20	-100	- 35	0.20	- 45.16
21	- 95	- 35	0.20	- 50.00
22	- 85	- 28	0.20	- 47.5
23	- 82	- 21	0.13	- 53.98
				+1103.01

5. ACTUAL EVAPORATION FROM A DRY BARE SOIL (Menenti's combination equation)

Soil evaporation is potential when the soil surface remains wet.

Evaporation from bare soils will take place either at the soil surface or below it. The evaporation front concept provides for restricted water movement away from the evaporation front towards the surface. Resistance factor for the transport of vapour and heat through the soil have to be taken into account.

To establish a clear separation between potential and actual evaporation, a new combination formula has been given by MENENTI (1984), which describes actual evaporation when it takes place inside the soil. The equation for potential evaporation is obtained by taking the limit, for a zero depth of the evaporation front of this new combination formula.

The transport equation for sensible heat in air is:

$$H = \frac{\rho_a c_p}{r_{ah}} (T(0) - T(z)) \quad (\text{W.m}^{-2}) \quad [21]$$

where

ρ_a = air density (kg.m^{-3})

c_p = air specific heat ($\text{J.kg}^{-1}.\text{K}^{-1}$)

$\rho_a c_p$ = heat capacity of air

r_{ah} = the resistance for sensible heat in air (s.m^{-1})

For the heat transport from the soil surface to the evaporation front:

$$G_0 = \lambda \frac{dT}{dz} = \frac{T(E) - T(0)}{r_{sh}} \quad (\text{W.m}^{-2}) \quad [22]$$

where

G_0 = soil heat flux

λ = soil thermal conductivity ($\text{W.m}^{-1}.\text{K}^{-1}$)

z_E = depth of evaporation front

r_{sh} = resistance for heat transport in soil

$$r_{sh} = \frac{zE}{\lambda} \quad (W^{-1}.m^2.K^{-1}) \quad [23]$$

For transport latent heat in air:

$$LE_a = -\frac{\rho_a c_p}{r_{av}} (e(0) - e(z)) \quad [24]$$

where

r_{av} = resistance for vapour transport in the air

$e(0)$ = actual vapour pressure at surface

$e(z)$ = actual vapour pressure at depth z

LE_a = latent heat in air

Resistance factor for transport of heat and vapour in the air:

r_{ah} resistance of heat

r_{av} resistance of vapour

In most situations there is no difference between r_{ah} and r_{av} so that

$$r_{ah} = r_{av} = r_a$$

$$r_a = k^{-2} \cdot u^{-1} \ln\left(\frac{(z_{reference} - d)}{z_0}\right)^2 \quad (S.m^{-1}) \quad [25]$$

where

k = wind speed at reference height ($m.s^{-1}$)

z = vertical depth or reference height (m)

d = factor for account on crop height = 0.63 x height of crop

z_0 = roughness of surface

Example:

$z(\text{ref}) = 1.85 \text{ m}$, $u = 2.2 \text{ m.s}^{-1}$ ($z_0 = 0.005$ in bare soil = 0.13 x height of crop)

$$\text{bare soil: } r_a = \frac{1}{(0.41)^2 \times 2.2} \ln\left(\frac{1.85 - 0}{0.005}\right)^2 \approx 32 \text{ S.m}^{-1}$$

For transport of latent heat in soil air holds:

$$LE_s = - \frac{\rho_a c_p}{r_{sv}} (e_{sat}(T_E) - e(0)) \quad (\text{W.m}^{-2}) \quad [26]$$

where

r_{sv} = the resistance for vapour transport in soil

$$r_{sv} = z_e / D_v$$

z_E = depth of the evaporation front

D_v = vapour diffusion coefficient

$e_{sat}(T_E)$ = calculated saturated vapour pressure at the evaporation front

$T(E)$ = temperature at evaporation front

Adding eqs. [3] and [4] which is eliminating $e(0)$:

$$r_{av} + r_{sv} = - \frac{\rho_a c_p}{\gamma LE} (e_{sat}(T_E) - e(z)) \quad (\text{S.m}^{-1}) \quad [27]$$

The saturation vapour pressure at the evaporation front can be expressed as a function of the saturation pressure in air at height z as follows:

$$1) S = \frac{\Delta e_{sat}}{\Delta T} \quad S = \text{slope of saturated vapour pressure curve}$$

$$2) e_{sat}(T_0) = e_{sat}(T_z) + \Delta(e)$$

$$3) \Delta(e) = s_a \cdot \Delta T \quad \text{where } \Delta T = T(0) - T(z)$$

$$4) e_{sat}(T_0) = e_{sat}(T_z) + S_a(T(0) - T(z))$$

$$5) e_{sat}(T_E) = e_{sat}(T_0) - \Delta(e')$$

$$6) \Delta e' = S_s \cdot \Delta T \quad \Delta T = T(E) - T(0)$$

$$e_{sat}(T_E) = e_{sat}(T_0) + S_s(T(E) - T(0))$$

$$e_{sat}(T_E) = e_{sat}(T_z) + S_a[T(0) - T(z)] + S_s[T(E) - T(0)] \quad (\text{mbar}) \quad [28]$$

Energy balance equation at earth's surface:

$$R_n + H + G_0^{in} = 0 \quad (\text{W.m}^{-2}) \quad [29]$$

where

G_0 = the heat flux reaching the soil surface

The energy balance equation at evaporation front where phase transition occurs can be formulated as:

$$G_E^{in} + LE + G_E^{out} = 0 \quad (\text{W.m}^{-2}) \quad [30]$$

where

G_E^{in} = the heat flux reaching evaporation front

G_E^{out} = the heat flux leaving the evaporation front

The flux G_E^{in} related to the flux leaving the soil surface by:

$$G_E^{in} = G_0^{out} - \int_0^{Z_E} c_s \rho_s(z) \frac{\partial T_s(z,t)}{\partial t} dz \quad (\text{W.m}^{-2}) \quad [31]$$

where

Z_E = the evaporation front depth

T_s = soil temperature

c_s = soil specific heat

ρ_s = soil bulk density

The integral term accounts for the heat storage. If the heat storage between $Z = 0$ and $Z = Z_E$ is neglected e.q. can be written as:

$$G_0^{in} - LE - G_E^{out} = 0 \quad (\text{W.m}^{-2}) \quad [32]$$

From the eq. [1], [2], [7] and [10] can be substituted in eq. [6]:

$$e_{\text{sat}}(T_E) = e_{\text{sat}}(T_z) + \frac{s_a r_{\text{ah}}}{\rho_a c_p} (R_n + G_E) + s_s r_{\text{sh}} G_E + \left(s_a \frac{r_{\text{ah}}}{\rho_a c_p} + s_s r_{\text{sh}} \right) LE \quad (\text{mbar}) \quad [33]$$

which can be substituted in eq [5] and finally in:

$$LE = - \frac{\rho_a c_p [e_{\text{sat}}(z) - e_{\text{act}}(z)] + s_a r_{\text{ah}} (R_n + G_E)}{\gamma (r_{\text{av}} + r_{\text{sv}}) + s_a r_{\text{ah}} + s_s r'_{\text{sh}}} + \frac{s_s \rho_a c_p r_{\text{sh}} G_E}{\gamma (r_{\text{av}} + r_{\text{sv}}) + s_a r_{\text{ah}} + s_s r'_{\text{sh}}} \quad (\text{W.m}^{-2}) \quad [34]$$

where

LE = latent heat flux (W.m^{-2})

ρ_a = air density (kg.m^{-3})

c_p = air specific heat ($\text{J.kg}^{-1}.\text{K}^{-1}$)

e_{sat} = air saturated vapour pressure (mbar)

e_{act} = air actual vapour pressure (mbar)

s_a = slope of air saturated vapour pressure curve (mbar.K^{-1})

s_s = slope of the soil saturated vapour pressure curve (mbar.K^{-1})

r_{ah} = air resistance for heat transfer (s.m^{-1})

r_{sh} = soil resistance for heat transfer ($\text{J}^{-1}.\text{K.m}^2.\text{s}$)

r'_{sh} = $\rho_a c_p r_{\text{sh}}$ (s.m^{-1})

r_{av} = air resistance for vapour transfer (s.m^{-1})

r_{sv} = soil resistance for vapour transfer (s.m^{-1})

R_n = net radiation (W.m^{-2})

G_E = soil heat flux leaving the evaporation front (W.m^{-2})

G_0 = soil heat flux leaving the evaporation front (W.m^{-2})

γ = thermodynamic psychrometric constant (mbar.K^{-1})

For zero depth of evaporation front with the assumption $R_{ah} = R_{av} = R_a$,
 $r_{sh} = 0$, i.e. $z = 0$.

The combination formula can be compared with common accepted potential formulae (PENMAN, 1948) for wet soils. With the above assumptions the terms $s_s \rho_a c_p r_{sh} G_E$, $s_s \rho_a c_p c_p r_{sh}$, $\bar{\gamma} \cdot r_{sv}$ lead to zero. The equation:

$$LE = \frac{\rho_a c_p [e_{sat}(z) - e_{act}(z)] / k_{ah} + s_a (R_n + G_0)}{\gamma + s_a} \quad (W.m^{-2}) \quad [35]$$

Example: Calculate LE and what is E

- coarse sand, gw1 110 cm
- $\lambda = 0.52 \text{ W.m}^{-1} \cdot \text{K}^{-1}$
- $d_v = 0.21 \text{ m}^2 \cdot \text{s.m}^{-1}$
- $R_{ah} = R_{av}$
- $Z_{ref} = 2.0 \text{ m}$, $U = 1.71 \text{ m.s}^{-1}$
- $\rho_{air} = 1.16 \text{ kg.m}^{-3}$
- $e_{sat} = 49.2 \text{ mbar}$
- $RH = 30\%$
- $R_{sw} = 802 \text{ W.m}^{-2}$
- $\alpha_0 = 0.241$
- $T_s = 41.8^\circ \text{C}$
- $T_a = 37.6^\circ \text{C}$
- $\epsilon = 0.97 \text{ soil}$
- $\epsilon' = 0.85 \text{ air}$
- $GE = -15.0 \text{ W.m}^{-2}$
- $\gamma = 0.667$
- $s_a = 1.75 \text{ mbar.K}^{-1}$
- $S_s = 2.61 \text{ mbar.K}^{-1}$
- evaporation front 72 cm from the ground surface (Fig. 11)

Applying the combination equation by MENENTI (1984) eg. [12].

$$\alpha = \frac{\text{outcoming short wave radiation}}{\text{incoming short wave radiation}} = \frac{R_{ref}}{R_{sw}} \quad (-) \quad [36]$$

$$R_{\text{ref}} = \text{total reflected radiation} = 0.241 \times 802 = 193.28 \text{ W.m}^{-2}$$

$$L_{\text{air}} = 0.85 \times 5.67 \times 10^{-8} \times (310.6)^4 = 448.53 \text{ W.m}^{-2}$$

$$L_{\text{soil}} = 0.97 \times 5.67 \times 10^{-8} \times (314.8)^4 = 483.26 \text{ W.m}^{-2}$$

$$R_n = 802 - 193.28 + 448.53 - 483.26 = 573.99 \text{ W.m}^{-2}$$

$$R_{\text{ah}} = R_{\text{av}} = R_a = \frac{\ln\left(\frac{2-0}{0.41}\right)^2}{(0.41)^2 \times (1.71)} \times 0.005 = 41.6 \text{ s.m}^{-1}$$

z_e evaporation front

$$r_{\text{sh}} = \frac{z_e}{\lambda} = \frac{\text{reference depth}}{\text{soil thermal conductivity}} = \frac{0.72}{0.52} = 1.38 \text{ J}^{-1} \cdot \text{K} \cdot \text{m}^2 \cdot \text{s}$$

$$r_{\text{sv}} = \frac{z_e}{D_v} = \frac{\text{reference depth}}{\text{vapour diffusion coefficient}} = \frac{0.72}{0.0021} = 342.85 \text{ s.m}^{-1}$$

$$LE = - \frac{1.16 \times 1004 \cdot 49.2 - 14.76 + 1.75 \times 41.6 (573.99 - 15.0) + 2.61 \times 1.16 \times 1004 (-15 \times 138)}{0.667(41.6 + 342.85) + 1.75 \times 41.6 + 2.61 \times 1.16 \times 1004 \times 1.38}$$

$$= \frac{40110 + 40694.5 - 62922}{256.42 + 72.8 + 4194.8} = \frac{17883}{4524} = 3.95 \text{ W.m}^{-2}$$

$$L = (2501 - \frac{41.8 \times 71}{30}) \times 10^3 = 2.4 \times 10^6 \text{ J.kg}^{-1}$$

$$^e \text{ W.m}^2 = \frac{1 \times 86400}{240 \times 10^6} = 3.6 \times 10^{-2} \text{ kg.day}^{-1} \cdot \text{m}^{-2} \text{ or } 3.6 \times 10^{-2} \text{ mm/day}$$

Evapotranspiration = $3.95 \times 3.6 \times 10^{-2} = 0.142$ mm/day. The calculated rate of evaporation 0.142 mm/day has a low value due to the depth of evaporation front inside the soil (72 cm) is big.

Assume that we have a medium sand profile instead of coarse sand profile with same groundwater depth like coarse sand (110 cm), then the evaporation front will be at 29 cm depth (Fig. 11).

$$r_{sh} = \frac{0.29}{0.52} = 0.56 \text{ J}^{-1} \cdot \text{K} \cdot \text{m}^2 \cdot \text{s}^{-1}$$

$$r_{sv} = \frac{0.29}{0.0021} = 138.0 \text{ s} \cdot \text{m}^{-1}$$

$$LE = - \frac{40110 + 40695 - 25533}{119.8 + 72.8 + 1141} = \frac{55272}{1333.6} = 41.4 \text{ W} \cdot \text{m}^{-2}$$

$$E = 41.4 \times 3.6 \times 10^{-2} = 1.49 \text{ mm} \cdot \text{d}^{-1}$$

From the calculations it is clear the importance of evaporation front: when it comes closer the surface the evaporation rate increases and vice versa. We can detect depth of evaporation front by means of simulation model (EVADES). Table 6 and 7 indicates the calculated values by EVADES Model Applying Menenti's formula.

Table 6. General result file with the simulated depth of the evaporation front

SIMULATION MODEL OF SOIL MOISTURE EVAPORATION (EVADES)
Version March 1968

Autotitle: EVADES.EX

day	hour	depth	temp	humid	evap	heat	rad	wind	atm	soil	total
no.	no.	cm	°C	%	cm/day	cal/cm²	cm/day	kg/m²	cm/day	cm/day	cm/day
54	1	-30	0.175	0.118E+00	0.431E+00	0.28E+04	0.455E+00	0.42E-03	-0.215E+03	-0.32E+06	
54	1	-30	0.175	0.118E+00	0.441E+00	0.225E+02	0.281E+01	0.221E-02	-0.215E+03	-0.32E+06	
54	2	-30	4.788	0.187E+00	-0.44E+00	0.44E+03	0.23E+02	0.27E-01	-0.147E+07	-0.327E+06	
54	3	-30	6.873	0.207E+00	-0.231E+00	0.322E+03	0.454E+02	0.47E-01	-0.552E+07	-0.331E+06	
54	4	-30	9.489	0.186E+00	-0.56E-01	0.325E+03	0.107E+04	0.95E-01	-0.177E+07	-0.328E+06	
54	5	-30	11.878	0.28E+00	0.103E-01	0.318E+03	0.787E+03	0.117E+01	-0.322E+07	-0.337E+06	
54	6	-30	13.979	0.128E+00	-0.199E-01	0.448E+03	0.44E+02	0.134E+01	-0.42E+07	-0.329E+06	
54	7	-30	16.049	0.342E+00	0.863E-01	0.279E+03	0.445E+03	0.144E+01	-0.28E+06	-0.331E+06	
54	8	-30	17.813	0.518E+00	0.189E+00	0.451E+02	0.44E+03	0.140E+01	-0.44E+07	-0.328E+06	
54	9	-30	19.477	0.726E+00	0.285E+00	0.317E+03	0.588E+03	0.177E+01	-0.32E+06	-0.322E+06	
54	10	-30	21.262	0.101E+01	0.38E+00	0.370E+03	0.422E+03	0.181E+01	-0.142E+06	-0.319E+06	
54	11	-30	23.423	0.132E+01	0.47E+00	0.58E+03	0.419E+03	0.181E+01	-0.153E+06	-0.317E+06	
54	12	-30	25.432	0.147E+01	0.472E+00	0.592E+03	0.408E+03	0.181E+01	-0.155E+06	-0.316E+06	
54	13	-30	27.439	0.140E+01	0.466E+00	0.592E+03	0.401E+03	0.181E+01	-0.155E+06	-0.316E+06	
54	14	-30	29.433	0.115E+01	0.405E+00	0.588E+03	0.398E+03	0.181E+01	-0.155E+06	-0.315E+06	
54	15	-30	31.427	0.841E+00	0.27E+00	0.571E+03	0.397E+03	0.181E+01	-0.153E+06	-0.315E+06	
54	16	-30	33.413	0.692E+00	0.122E+00	0.536E+03	0.402E+03	0.181E+01	-0.149E+06	-0.315E+06	
54	17	-30	35.399	0.591E+00	-0.547E-02	0.476E+03	0.428E+03	0.181E+01	-0.140E+06	-0.314E+06	
54	18	-30	37.385	0.545E+00	-0.822E-01	0.393E+03	0.428E+03	0.180E+01	-0.125E+06	-0.319E+06	
54	19	-30	39.378	0.648E+00	-0.148E+00	0.287E+03	0.444E+03	0.180E+01	-0.108E+06	-0.322E+06	
54	20	-30	41.363	-0.145E+01	-0.910E-01	0.262E+03	0.408E+03	0.180E+01	-0.794E+05	-0.337E+06	
54	21	-30	43.348	-0.102E+01	-0.170E+00	0.281E+03	0.423E+03	0.180E+01	-0.826E+05	-0.336E+06	
54	22	-30	45.332	-0.841E+00	-0.10E+00	0.276E+03	0.458E+03	0.180E+01	-0.882E+05	-0.335E+06	
54	23	-30	47.322	0.121E+01	-0.185E-01	0.207E+03	0.482E+03	0.180E+01	-0.922E+05	-0.336E+06	
54	24	-30	49.314	0.512E+02	-0.86E-01	0.315E+03	0.506E+03	0.180E+01	-0.956E+05	-0.335E+06	
54	1	-30	51.301	0.118E+00	-0.104E+00	0.326E+03	0.528E+03	0.180E+01	-0.979E+05	-0.335E+06	
54	2	-30	53.289	0.127E+00	-0.10E+00	0.227E+03	0.542E+03	0.180E+01	-0.101E+06	-0.335E+06	
54	3	-30	55.281	0.207E+00	-0.93E-01	0.32E+03	0.556E+03	0.180E+01	-0.102E+06	-0.336E+06	
54	4	-30	57.274	0.186E+00	-0.701E-01	0.219E+03	0.568E+03	0.180E+01	-0.101E+06	-0.336E+06	
54	5	-30	59.267	0.38E+00	0.125E-01	0.212E+03	0.583E+03	0.180E+01	-0.101E+06	-0.337E+06	
54	6	-30	61.259	0.128E+00	0.147E-02	0.304E+03	0.597E+03	0.180E+01	-0.982E+05	-0.337E+06	
54	7	-30	63.252	0.378E+00	0.444E-01	0.378E+03	0.612E+03	0.180E+01	-0.982E+05	-0.337E+06	
54	8	-30	65.245	0.552E+00	0.167E+00	0.465E+03	0.628E+03	0.180E+01	-0.114E+06	-0.337E+06	
54	9	-30	67.238	0.792E+00	0.317E+00	0.517E+03	0.646E+03	0.181E+01	-0.120E+06	-0.337E+06	
54	10	-30	69.230	0.112E+01	0.514E+00	0.570E+03	0.632E+03	0.181E+01	-0.143E+06	-0.339E+06	
54	11	-30	71.224	0.145E+01	0.691E+00	0.618E+03	0.618E+03	0.181E+01	-0.152E+06	-0.339E+06	
54	12	-30	73.217	0.161E+01	0.792E+00	0.692E+03	0.607E+03	0.181E+01	-0.155E+06	-0.338E+06	
54	13	-30	75.210	0.157E+01	0.772E+00	0.692E+03	0.612E+03	0.181E+01	-0.155E+06	-0.338E+06	
54	14	-30	77.203	0.128E+00	0.711E+00	0.596E+03	0.596E+03	0.181E+01	-0.155E+06	-0.338E+06	
54	15	-30	79.196	0.149E+00	0.531E+00	0.571E+03	0.597E+03	0.181E+01	-0.153E+06	-0.338E+06	
54	16	-30	81.189	0.762E+00	0.708E+00	0.526E+03	0.466E+03	0.181E+01	-0.149E+06	-0.338E+06	
54	17	-30	83.182	0.622E+00	0.80E-01	0.476E+03	0.428E+03	0.181E+01	-0.140E+06	-0.337E+06	
54	18	-30	85.175	0.588E+00	-0.551E-01	0.393E+03	0.432E+03	0.180E+01	-0.125E+06	-0.339E+06	
54	19	-30	87.168	0.648E+00	-0.18E+00	0.287E+03	0.445E+03	0.180E+01	-0.108E+06	-0.322E+06	
54	20	-30	89.161	-0.145E+01	-0.91E-01	0.242E+03	0.407E+03	0.180E+01	-0.794E+05	-0.337E+06	
54	21	-30	91.154	-0.102E+01	-0.170E+00	0.281E+03	0.423E+03	0.180E+01	-0.826E+05	-0.336E+06	
54	22	-30	93.147	-0.841E+00	-0.10E+00	0.276E+03	0.458E+03	0.180E+01	-0.882E+05	-0.335E+06	
54	23	-30	95.140	0.121E+01	-0.185E-01	0.207E+03	0.482E+03	0.180E+01	-0.922E+05	-0.336E+06	
54	24	-30	97.133	0.512E+02	-0.86E-01	0.315E+03	0.506E+03	0.180E+01	-0.956E+05	-0.335E+06	
54	1	-30	99.126	0.118E+00	-0.104E+00	0.326E+03	0.528E+03	0.180E+01	-0.979E+05	-0.335E+06	

Table 7. Example of an output file with the data required for the combination equation

..... SIMULATION MODEL OF BARE SOIL EVAPORATION IN DESERTS (EVADES)

..... version: march 1980

..... subroutines: EVAPDES,ACT

.....

day	hour	rh(t)	rh(0)	u(m/s)	u(z)	u(z)	u(z)	u(z)	u(z)	u(z)	u(z)	u(z)	u(z)	u(z)	u(z)	u(z)	u(z)	u(z)	u(z)	u(z)
1	1.251	7.0	0.81	1.78	271.66271.07856	-1.30851	-149.3	-13.0	-347.2	0.4250E-03	0.464	0.4551	-174.	10.497	0.418					
56	1.251	7.0	0.80	1.78	271.66271.07856	-1.30851	-149.3	0.0	-347.2	0.2250E-02	0.464	2.615	-132.	10.497	0.418					
54	2.122	6.3	0.77	1.68	211.70211.69667	-1.56669	-142.6	1.3	-144.6	0.2704E-01	0.464	23.65	173.	10.056	0.455					
53	1.252	5.9	0.77	1.57	211.70211.79326	-1.56673	-126.9	2.4	-144.0	0.4701E-01	0.464	45.37	66.3	10.056	0.491					
52	1.251	5.7	0.80	1.45	271.66271.09826	-1.30863	-126.2	3.6	-137.7	0.9554E-01	0.464	107.1	16.2	10.497	0.527					
51	1.249	6.0	0.80	1.32	52.69	52.68661	-0.12927	-112.6	5.0	0.1	0.1130	0.468	787.1	-2.95	12.526	0.544				
50	1.227	6.8	1.07	1.20	119.55119.54919	0.56683	-98.7	5.9	2.7	0.1264	0.468	448.5	3.97	15.500	0.600					
49	1.206	7.6	1.38	1.01	139.17129.17002	0.69157	-84.9	-22.6	-2.4	0.1456	0.471	448.0	-24.5	20.167	0.589					
48	1.187	13.4	1.75	2.61	156.51154.51117	0.89556	-71.2	-22.8	-7.8	0.1599	0.473	447.8	-52.5	24.562	0.538					
47	1.170	18.0	2.13	3.53	175.99170.99456	0.90321	-55.3	-21.6	-11.9	0.1748	0.476	568.0	-80.4	28.431	0.508					
46	1.152	22.9	2.49	4.47	182.18182.18204	0.98813	-506.2	-17.8	-67.0	0.1806	0.478	433.3	-85.3	31.548	0.477					
45	1.135	29.9	2.84	5.38	186.45186.45946	1.09978	-427.2	-7.0	-72.9	0.1806	0.479	418.6	-117.	22.728	0.466					
44	1.119	26.8	3.27	6.26	189.78189.78968	1.02215	489.8	-5.5	-77.5	0.1806	0.479	408.3	-122.	23.733	0.415					
43	1.104	21.5	3.69	7.10	192.24192.24709	1.04997	484.3	-4.0	-80.9	0.1806	0.481	401.0	-130.	24.433	0.385					
42	1.146	22.9	3.92	7.84	193.64193.64614	1.06014	610.9	-1.1	-81.7	0.1806	0.480	397.5	-113.	24.858	0.264					
41	1.147	25.5	3.72	8.67	193.64193.64648	1.06014	478.8	-1.3	-82.9	0.1806	0.480	396.8	-77.8	24.858	0.223					
40	1.152	34.9	3.77	9.50	189.60189.60868	1.02215	316.4	0.8	-82.9	0.1806	0.479	405.1	-74.2	23.733	0.297					
39	1.161	32.2	3.49	9.72	182.19182.18206	0.98816	151.0	7.2	-77.5	0.1806	0.478	419.8	1.60	31.549	0.267					
38	1.170	20.1	3.13	10.48	171.64170.99550	0.90325	12.2	13.2	-67.0	0.1806	0.478	424.2	23.2	28.432	0.231					
37	1.191	21.3	3.75	10.81	156.52154.51731	0.89461	-149.3	16.8	-52.1	0.1806	0.473	444.4	41.8	24.563	0.209					
36	1.229	12.7	4.07	1.46	439.75439.75214	1.57454	-177.3	89.3	1.7	0.1802	0.468	466.2	26.0	18.500	0.226					
35	1.228	12.1	4.07	1.46	439.75439.75214	1.57454	-168.9	-5.2	-5.8	0.1802	0.468	432.5	48.5	15.500	0.273					
34	1.236	10.4	4.98	1.99	231.65231.65100	0.89060	-144.6	-4.2	-12.0	0.1803	0.467	458.2	29.7	13.951	0.209					
33	1.242	9.0	6.90	1.91	52.63	52.62665	-0.12903	-100.1	-2.9	-14.5	0.1803	0.466	482.1	8.29	12.527	0.248				
32	1.247	7.8	6.86	1.86	106.01106.01177	-0.81496	-155.1	-1.2	-18.8	0.1803	0.465	504.7	24.8	11.243	0.282					

Table 8. Surface tension of water against air

B. Surface tension of water against air

T(°C)	σ_{wa} dynes/cm	T(°C)	σ_{wa} dynes/cm	T(°C)	σ_{wa} dynes/cm	T(°C)	σ_{wa} dynes/cm	T(°C)	σ_{wa} dynes/cm
0	75.69	11	74.07	21	72.59	31	71.02	41	69.40
1	75.46	12	73.83	22	72.44	32	70.86	42	69.23
2	75.32	13	73.78	23	72.28	33	70.69	43	69.07
3	75.18	14	73.64	24	72.13	34	70.53	44	68.90
4	75.04	15	73.49	25	71.97	35	70.37	45	68.74
5	74.90	16	73.34	26	71.81	36	70.21	46	68.57
6	74.76	17	73.20	27	71.65	37	70.05	47	68.41
7	74.63	18	73.05	28	71.50	38	69.88	48	68.24
8	74.49	19	72.90	29	71.34	39	69.72	49	68.08
9	74.36	20	72.75	30	71.18	40	69.56	50	67.91
10	74.22								

After Handbook of Chemistry and Physics, Table F-30

In the combination equation the soil resistance factors R_{sh} , R_{ah} can only be obtained when depth of evaporation front is known. At a given moisture content only pores comparable with the mean free path of a water molecule contribute to vapour flow. Below this moisture content, fast vapour movement becomes the main transport process.

The matric pressure head (H_m) at evaporation front (z_E) can be calculated:

$$H_m = \frac{2 \tau_{wa}}{\rho_w \cdot g \cdot l_m} \quad (m) \quad [37]$$

where

τ_{wa} = surface tension of water against air ($N \cdot m^{-1}$)

l_m = free depth of water vapour = 4×10^{-8} mbar

g = gravitational constant = $9.81 \text{ m} \cdot \text{s}^{-2}$

ρ_w = the local density of liquid water ($kg \cdot m^{-3}$)

Example:

$\rho_w = 1100 \text{ kg} \cdot \text{m}^{-3}$ (salty water)

$\tau_{wa} = 0.07118 \text{ N} \cdot \text{m}^{-1}$

$$h_E = \frac{1}{100 \times 9.81} \times \frac{2 \times 0.07118}{4 \times 10^{-8}} = 329.8 = 32987 \text{ cm}$$

The values of surface tension of water against air are shown in Table 8. From the laboratory measurement of θ water content of soil samples and using tensiometers to measure the suction (pressure head) for samples we get the relation between moisture content and pressure head: pF-curve. From the profiles of θ and H in the soil we can get the depth of the evaporation front.

Table 9. Profile of θ and H in soil from laboratory measurements

$Z = -10 \text{ cm}$	$\theta = 0.07$	$h = -50,000$
-20 cm	$\theta = 0.12$	$h = -18,000$
-30 cm	$\theta = 0.16$	$h = -700$
-40 cm	$\theta = 0.25$	$h = -500$
-50 cm	$\theta = 0.35$	$h = 0$

g.w.l.

6. ATMOSPHERE CORRECTION OF THERMAL INFRARED SATELLITE MEASUREMENTS

In the spectral region between $\lambda = 10.5 - 12.5$ mbar (band r of T.M.) mainly water vapour affects radiation transfer. To estimate the effect of atmospheric water vapour on satellite measured earth surface temperature, thermal infrared radiation models are used. Indication of radiation absorption and emittance by atmosphere can be written as an integral function of optical depth.

$$I_{\lambda}(\tau) = I_{\lambda}(\tau+d\tau) \exp(-d\tau) + \int_{\lambda}^{\tau+d\tau} B_{\lambda} T(\tau') d \exp(-(\tau'-\tau)) \quad (\text{W.m}^{-2}.\mu\text{m}^{-1}.\text{sr}^{-1}) \quad [38]$$

where

I_{λ} = spectral radiant intensity at wave length λ ($\text{W.m}^{-2}.\mu\text{m}^{-1}.\text{sr}^{-1}$)

B_{λ} = Planck's function at temperature T (K) and wave length λ
($\text{W.m}^{-2}.\mu\text{m}^{-1}.\text{sr}^{-1}$)

τ = optical depth

Considering the atmosphere as one homogeneous layer this equation could be explained by:

$$I_{\lambda\text{top}} = I_{\lambda\text{bottom}} - I_{\lambda\text{absorption}} + I_{\lambda\text{emissivity}}^a \quad (\text{W.m}^{-2}.\mu\text{m}^{-1}.\text{sr}^{-1}) \quad [39]$$

where

$I_{\lambda\text{bottom}}$ = total spectral radiant intensity at the bottom of atmosphere
($\text{W.m}^{-2}.\mu\text{m}^{-1}.\text{sr}^{-1}$)

$I_{\lambda\text{top}}$ = total spectral radiant intensity at top of atmosphere

I_{λ}^a = total emittance for the whole atmosphere

The total emittance through the whole atmosphere:

$$I_{\lambda\text{top}} = I_{\lambda}(\text{transmitted}) + I_{\lambda}^a \quad [40]$$

$$I_{\lambda_{top}} = I_{\lambda} \text{ (bottom-absorption)} + I_{\lambda}^a \quad [41]$$

Example:

- Input 1) $I_{bottom} \lambda = 11.5 \text{ mbar} = 0.8872 \times 10^6$
 2) $I_{\lambda}^a = 0.2599 \times 10^6$
 3) $I_{\lambda} \text{ (transmitted)} = 0.5808 \times 10^6$

Output 1) $I_{top} = 0.5808 + 0.25 \times 10^6 = 0.8308 \times 10^6$

$$2) \tau = \ln \frac{I_{\lambda} \text{ (transmitted)}}{I_{\lambda_{bottom}}} = \ln \frac{0.5808}{0.8872} = 0.43$$

This parameter is an indication of absorption only.

$$3) T = \text{transmittance} = \frac{I_{\lambda_{top}}}{I_{\lambda_{bottom}}} = \frac{0.8303 \times 10^6}{0.8872 \times 10^6} = 0.94$$

This is a parameter for absorption and emittance.

$I_{\lambda} \text{ (bottom)}$ is calculated by the Plank's function; further the Plank function if applied in order to determine the atmospheric emittance.

The Plank function can be written as follows:

$$B_{\lambda}(T) = \frac{c_1 \lambda^{-5}}{\exp\left(\frac{c_2}{\lambda T}\right) - 1} \quad [42]$$

where

- $c_1 = 1.185 \times 10^{-5} \text{ erg.cm}^{-2}.\text{s}^{-1}$
 $c_2 = 1.4356 \text{ cm.K}$
 $\lambda = \text{wave length}$

6.1. CALCULATION OF AT-SATELLITE TEMPERATURE

To obtain the at-satellite temperature, the calibration formula of the specific sensor must be applied:

$$T_{\text{sat}} = \frac{k_2}{\ln\left(\frac{k_1}{L_i} + 1\right)} \quad (\text{K}) \quad [43]$$

where

T_{sat} = effective at-satellite temperature in Kelvin, K^{-1}

k_2 = calibration constant 2 in K from the following Table 10

k_1 = calibration constant 1 in $\text{mw.cm}^{-2}.\text{ster}^{-1}.\mu\text{m}$ from Table 10

L_i = spectral radiance in $\text{mx.cm}^{-2}.\text{ster}^{-1}.\mu\text{m}$

Table 10. LANDSAT TM thermal band calibration constants

Satellite	Constant k_1 (K)	Constant k_2 ($\text{mw.cm}^{-2}.\text{ster}^{-1}.\mu\text{m}^{-1}$)
LANDSAT4	67.162	1284.3
LANDSAT5	60.776	1260.56

With numerical methods at-sureface temperature can be estimated from at-satellite temperature

6.2. APPLICATION OF MATHEMATICAL MODELS TO DO ATMOSPHERIC CORRECTIONS

We used the WINNEW model by MENENTI (1984), built on the structure of model by PRICE (1977). This model enables to calculate atmospherical correction if radio-soundings, i.e. measurements of humidity (e.g. dew point) temperature, and atmospheric pressure are available.

The output of the model gives values of optical depth (τ), extinction ($T.\rho$) and total radiation intensity ($I_{D1}(\)$) for max. 50 layers. The final correction is given by the difference in surface and satellite temperature which can be fitted with linear regression function:

$$\text{e.g. } T_{(\text{ground})} = A + BT_{(\text{satellite})} \quad (\text{K}) \quad [44]$$

The required input data are:

- number of surface tempoeratures
- number of sounding levels

- the difference between air temperature and dew point temperature
(option 5 of model)
- viewing angle $0^\circ - 30^\circ$
- surface temperature: four values of surface temperatures were considered
- atmospheric pressure mbar

Satellites observe the earth with different view angles which are satellite dependent. Altitude and scene width modify this view angle. Therefore, a range between $0^\circ - 30^\circ$ degrees is in most cases considered for atmospheric corrections.

The WINNEW model was used to calculate the atmospheric corrections for the sounding data from Mersa Matrauh Station in the periods:

10 October 1984	GMT 12.00
28 October 1984	GMT 00.00
2 April 1987	GMT 00.00
13 November 1987	GMT 00.00
13 November 1987	GMT 12.00

The simulation results for 13 October 1987 gave a large correction for high surface temperature (315K). The correction of surface temperature must be increased with 12K with an optical depth of 0.43, while on the other hand the analysis of data on 2 April 1987 showed that correction of 7K was sufficient with optical depth 0.22. It can be concluded that the higher the optical depth (this means higher water vapour content in the atmosphere) the higher the correction. Also we conclude that the higher the view angle the higher the correction, which means a longer path length through air. Some parameters vary with view angle while others are independent on view angle. For example, the emitted radiance from atmosphere is independent. Transmittance and irradiation at top of atmosphere are dependent values. Optical depth and precipitable water and air temperature, and radiant intensity at bottom are independent factors.

Fig. 13 shows the relation between surface temperature and view angle and satellite temperature. Fig. 14 shows the vapour distribution in the atmosphere by plotting optical depth versus atmospheric pressure (mbar). Table 11 shows the simulation results of WINNEW model at 0° angle and 30° angle.

Hence the total calculation procedure of the remotely sensed surface temperature can be summarized as follows:

1. calculate L_i from D_n (see eq. [8])
2. calculate satellite temperature from L_i (see eq. [43])
3. calculate surface temperature from satellite temperature using the program WINNEW

Table 11. Simulation results WINNEW-model

	$I_{\lambda_{bot}}$ ($W.m^{-2}.\mu m^{-1}.st^{-1}$)	$I_{\lambda_{top}}$	I_{λ^a}	τ (-)	T (-)	Precipitable water (cm)	$T_{air_{bottom}}$ (K)
\emptyset view angle = 0.0							
Run 1	0.887E8	0.831E8	0.250E8	0.43	0.94	2.49	296.4
Run 2	0.747E8	0.723E8	0.18E8	0.38	0.97	2.28	288.5
Run 3	0.747E8	0.730E8	0.13E8	0.21	0.98	1.54	284.5
Run 4	0.858E8	0.822E8	0.26E8	0.43	0.96	2.17	294.1
Run 5	0.899E8	0.871E8	0.21E8	0.31	0.97	1.76	297.5
\emptyset view angle = 30.0							
Run 1	0.887E8	0.823E8	0.28E8	0.43	0.93	2.49	296.4
Run 2	0.747E8	0.720E8	0.21E8	0.38	0.96	2.28	288.5
Run 3	0.747E8	0.728E8	0.15E8	0.21	0.97	1.54	284.5
Run 4	0.858E8	0.818E8	0.29E8	0.43	0.95	2.17	294.1
Run 5	0.899E8	0.867E8	0.24E8	0.31	0.96	1.76	297.5

