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Research Article

A Spatial Analysis of Surface Energy Fluxes and Evapo-transpiration in the Northern-east of Niger W National Park

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Abstract: The aim of this study is to contribute to the development of a simple and quick methodology of extracting surface energy fluxes and evapo-transpiration, from remote detection data in the Northern-east of National W Park of Niger republic, where based ground data are practically unavailable. The methodology adopted is based on the algorithm METRIC in solving the surface energy balance equation using remotely-sensed data of Landsat7 ETM+ and few ground based data. The algorithm involves NDVI, surface temperature and albedo in the input. The obtained results permit the analysis of surface energy fluxes in function of land occupation/use. Areas subject to severe hydrous stress are identified by analysing the correlation between surface temperature and NDVI. The methodology developed here is an important tool for a diachronic study of surface energy fluxes by using many Landsat7 images. Such study is preponderant for a good management of vegetal and hydrological resources of the Park, which is facing, nowadays, to combined effects of natural climate variability and anthropogenic actions.

Keywords: Albedo, evapo-transpiration, Landsat7, NDVI, SEBAL/METRIC

INTRODUCTION

Spatialization of land surface energy fluxes and evapo-transpiration from remote detection data in visible, near infrared and thermal infrared regions of the electromagnetic spectrum has been at the centre of many meteorological approaches during the last past years. Globally, close to the two-third of precipitation on immerged land returned to atmosphere by evapo-transpiration (Brutsaert, 2010). It is therefore necessary to obtain at the large scale, reliable information on land surface fluxes and evapo-transpiration. Many methods using remote detection for calculation of such fluxes have been in focus (Bastiaanssen *et al*., 1998; Roerink *et al*., 2000; Su, 2002; Allen *et al*., 2007; Hamimed *et al*., 2009; Assefa and Vijyay, 2005; Pënualas, 1993; Seguin and Itier, 1983). The most used algorithms are: SEBAL, SEBI, S-SEBI, SEBS and METRIC.

In Niger, studies using remote data have been conducted in order to improve the management of the park (Couteron, 1992; Benoit, 1998; Inoussa *et al*., 2011). Still, no study allowing the obtainment of quantitative data of surface energy fluxes and their relationship with the state of the soil has yet been conducted.

It is so necessary to fill these gaps and thus, contribute in the development of simple and quick methodology of diachronic study of surface energy fluxes at the large scale. Such study is preponderant in the management of vegetal and hydrogenous resources of the Park. It allows also a better comprehension of meteorological phenomena and the prevision of their evolutions. Nevertheless, a good diachronic study of the surface energy fluxes required a good evaluation of impacts of climate variability and the associated risks, which themselves dependent on the availability and-correct interpretation- of pertinent meteorological formations. In this regard, the capacities of research in Sahelian region are problematic: The first limitation of such research is generally the scattered spatial repartition -and often the bad quality of records- of observations. National's meteorological stations such as National Meteorological of Niger (DMN in French) which are in lack of resources have difficulties to face maintenance of the stations and the high cost of large campaign of data records. In this effect, satellite imagery can be a praiseworthy alternative capable to complement and/or furnish observations records at a local or a regional scale. Satellite imagery is privileged tool for diachronic study of the surface energy fluxes, because it furnishes information's that are linked with transfer of mass and energy and in particular evapo-transpiration.

The main objective of our study is to contribute to the development of a simple and quick methodology of

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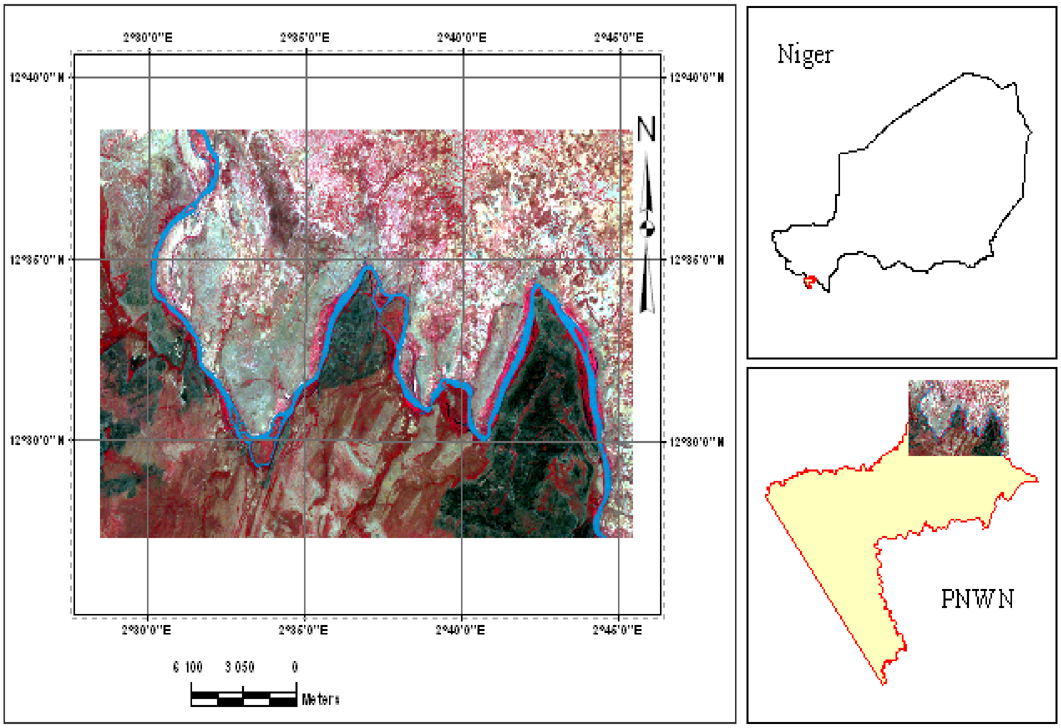

Fig. 1: Geographic position of the study area

extracting surface energy fluxes and evapo-transpiration, from remote detection data in the Northern-east of Niger republic national W Park, where based ground data are practically unavailable. To spatialize the surface energy fluxes and evapo-transpiration, we used the algorithm named METRIC (Mapping evapo-transpiration with Internalized Calibration) because of its simplicity and rapidity. It is also derived from SEBAL (Surface Energy Balance Algorithm for Land), algorithm validated in Niger and in others semi-arid areas (Tasumi *et al*., 2005). In addition, these two algorithms departed at maximum from ground data (Bastiaanssen *et al*., 1998; Allen *et al*., 2007) which are quasi non-existent in our area of study.

Characteristics of the study area: The study area (Fig. 1) is located in Niger (West Africa), between longitudes 2°25'E and 2°45'E and latitudes 12°25'N et 12°40'N. It covers a surface of 63.000 ha. It is composed of a protected area in the south, inside the Park and a non protected area in the North, outside the park. The two areas are separated by a natural border, the Niger River.

It is a tropical type with soudano-sahelian climatic system. Four types of geomorphologies are identified and mapped in the area: rocky plateaux, pediments and drains; battleships plateaux and the intermediary forms (Benoit, 1998).

Table 1: Solar parameters values on November 17, 2002 at 9:55 GMT

Astronomiques parameters	Unit	Value
Solar declination	Rad	-0.341846
Earth-sun distance	U	0.988319
Solar hour angle	Rad	-0.500037
Solar zenithal angle	Rad	0.734278

MATERIALS AND METHODS

The data used in this study are constituted with seven spectacles bands of ETM+ (Enhanced Thematic Mapper Plus) detector of Landsat-7, path 192 row 051, acquired on 17 November, 2002 at 9:55 am, GMT.

The solar conditions during the over pass of the satellite are calculated and the values obtained are presented in Table 1. They are used during the corrections of atmospheric effects and relief effects on réflectances detected by the satellites; they are also used in the parameterization of the surface energy balance equation given as:

$$Rn + H + G + LE = 0 \tag{1}$$

where,

Rn (W/m²): The net radiation flux at the surface
H (W/m²) : The sensible heat flux to the air
G (W/m²) : The soil heat flux
LE (W/m²): The latent heat flux

The original Landsat image used in this study is already geo-rectified (UTM, WGS 84 Zone 31). We have applied supervised classification by maximum likelihood method. The used of this method is due to

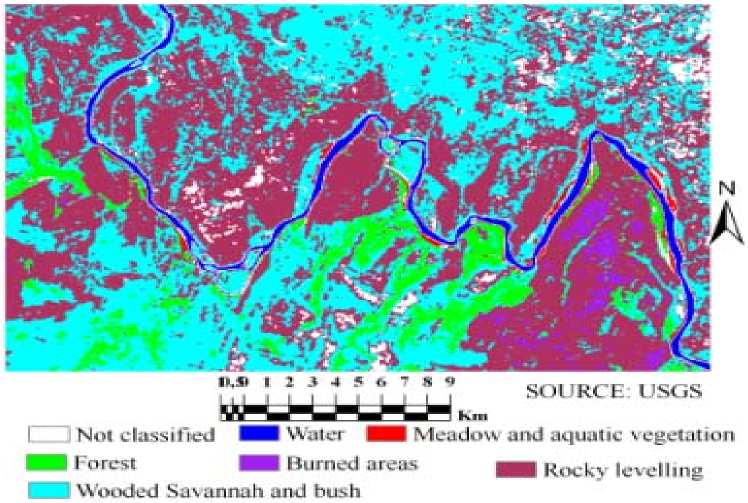

Fig. 2: Land-use/cover map

our well-known knowledge of the study's ground; it is the best method if the analyst has a good knowledge of the study's ground. The map of land-use/cover that results from this classification is shown in Fig. 2.

The elaboration of this Map is indispensable at the time of execution of Metric's model, precisely on the choose of dry pixels and cold pixels, pixels (anchor pixels) from which the thermal gradient dT and sensible meat flux are calculated.

We have converted the luminance of optic domains (Visible, near and mean infrared) in reflectance before realizing the Maps of surface energy fluxes and evapo-transpiration. Afterwards, we have corrected the image from the atmospheric effects using the radiate transfer model MODTRAN 4.0 (Berk *et al*., 1999) and the effects of relief are reduced using Duffie and Beckman (1991) formula. This formula requires Digital Elevation Model (DEM) and atmospherics parameters at the time of the image acquisition (Solar zenith, azimutal and hour angles Table 1). The corrected réflectances are then used to calculate the Albedo (α), Index of Vegetation (NDVI) and Surface Temperature (T_S) which are the main input parameters of metric's model. The theoretical basis of mapping evapo-transpiration from remote detection data are nowadays well documented (Bastiaanssen *et al*., 1998; Roerink *et al*., 2000; Allen *et al*., 2007; Crago, 1996). To spatialize the surface energy fluxes and evapo-transpiration we have followed the following steps (Allen *et al*., 2007):

- Corrections of atmospheric and relief effects on the luminance and reflectance detected by the satellite
- Calculations of surface Albedo; NDVI and surface temperature
- Calculation of net radiation
- Calculation of sensible heat flux using the gradient of air temperature; aerodynamic resistance by including the stability functions of the atmosphere and annual wind speed registered on the site of study
- Calculation of soil flux conduction

The basic Eq. (1) is that of surface energy balance. Thus, the equivalent energy of evapo-transpiration LE has been estimated as a residual of Eq. (1), applied to each image's pixel. It is calculated according to:

$$LE = Rn - H - G \tag{2}$$

where, Rn is given by:

$$Rn = (1 - \alpha)\, R_{global} + R_{atm}\downarrow - R_{suf}\uparrow \tag{3}$$

with,

R_{global} : The incident global radiation, partially reflected by the surface in function of surface albedo
$R_{atm}\downarrow$: The incident atmospheric longwave radiation
$R_{suf}\uparrow$: Shortwave radiation emitted by earth's surface

H is the sensible heat flux, obtained by an iterative approach from the aerodynamic equation which is given by:

$$H = (\rho_{air} Cp{*}dT)\, /r_{ah} \tag{4}$$

with,

ρ_{air} = The air density in Kg/m³
Cp = 1004 J/Kg/K (specific capacity of air)
dT (°K) = Thermal gradient of air (difference of temperatures between T_S at 0.1 m and T_{air} at 2 m from the ground)
r_{ah} = The aerodynamic résistance to heat transfer in sm^{-1}, between tow nearest surfaces separated by the distance Z_2-Z_1

G is soil conduction flux calculated according to Bastiaanssen (2000) formula:

$$G = [(T_S - 273.16) (0.0038 + 0.0074\alpha) (1 - 0,98NDVI^4)] Rn \quad (5)$$

With T_S the aerodynamic temperature: In Eq. (3) the surface albedo α is calculated using Liang *et al.* (2002) formula:

$$\alpha = 0.356r_1 + 0.13r_3 + 0.373r_4 + 0.085r_5 + 0.072r_7 - 0.0018 \quad (6)$$

where the r_i are the reflectance in the channels i (1; 3; 4; 5 et 7) of Landsat satellite, corrected from atmospheric and relief effects; these reflectance are deduced from the corresponding luminance $L_{\lambda i}$. The global radiance or incoming shortwave radiation is calculated according to the formula:

$$R_{global} = [(Gcs \times \cos\theta.img) /d^2] \times \tau_{sw} \quad (7)$$

with,

Gcs = 1367 W/m² (solar constant)

cosθ.img = (Integrate the solar declination; the latitude; the slope; the surface aspect angle and solar hour angle of our study area) is the spatial distribution of solar declination angle

d = The relative mean distance between the earth and the sun

τ_{sw} = The transmissivity of the atmosphere, calculated in function of air effective emissivity

The atmospheric radiation $R_{atm}\downarrow$ is calculated according to the Stefan-Boltzmann's formula:

$$R_{atm}\downarrow = \varepsilon_s \varepsilon_a \sigma T_a^4 \quad (8)$$

with,

ε_s : The surface emissivity (it corresponds to the conversion factor of thermodynamic energy to radiative energy; expressed in function of NDVI

ε_a : Air effective emissivity

σ : Boltzmann's constant

The radiation emitted by the earth surface $R_{suf}\uparrow$ is calculated according to Stefan-Boltzmann's formula:

$$R_{suf}\uparrow = \varepsilon_s \sigma T^4_s \quad (9)$$

With Ts is calculated from the radiative surface temperature T_{RS} (detected by the satellite) by simple inversion of Stefan-Boltzmann's; T_{RS} is given by the following formula:

$$T_{RS} = K_2/\ln [(K_1/r_{c(6)}) + 1] \quad (10)$$

K_1 and K_2 are specific constants of calibration for each type of Landsat satellite; their values are given in the header files of the image, downloadable at the same time with the image. $r_{c(6)}$ is the real radiance emitted by the surface, corrected from the atmospheric and relief effects.

The calculation of H from formula (4) requires the simultaneous existence of dry pixels and cold pixels on the site of study (Allen *et al.*, 2007). The supervised classified conducted on our image has permit the identification of such pixels: dry pixels are rocky levelling and burned area and cold pixels are meadow and aquatic vegetation.

To spatialize dT, we have first determined the values of H on dry pixels (H_{dry}) and on cold pixels (H_{cold}). They obtained values are then used to estimate the thermal gradient dT using an iterative process, starting by applying neutral stability conditions of the atmosphere until obtainment of dT convergence after successive corrections of the atmospheric stability, precisely on the aerodynamic resistance. The spatialization of dT is made possible by assuming a linear relation with T_S, given by Allen *et al.* (2007):

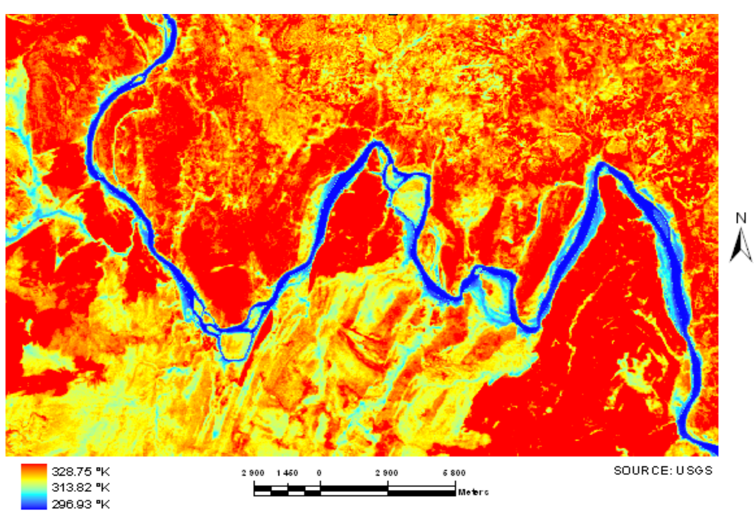

Fig. 3: Spatial distribution of surface temperature

Table 2: Mean values of energy flux and surface parameters

Surface parameters and fluxes	Unit	Instatntaneous means
NDVI	-	0.24
Albédo	-	0.19
Emissivity	W/m²	0.94
Température	°K	313.82
Net radiation	W/m²	445.42
Sensible heat flux	W/m²	170.75
Soil conduction flux	W/m²	77.86
Latent heat flux	W/m²	196.87
Evaporation-fraction	-	0.50

$$dT = 0.26 - (2.21)\ T_S \quad (11)$$

The spatial distribution of dT is utilised in another iteration process using Eq. (1), thus allowing the spatialization of H. Spatialization of other instantaneous fluxes obtained, allows the one of latent heat flux and then the one of instantaneous evapo-transpiration ET_{inst}. Calculated according to using formula:

$$ET_{inst}. = 3600\ (LE/\lambda\rho_w) \quad (12)$$

where,

ET_{inst}. = Instantaneous evapo-transpiration (mm/h); 3600 conversion of 1 h in minute

ρ_w = Water density (1000 kg/m³) and λ latent heat of water evaporation, estimated from surface temperature

Evaporation fraction used to characterize the hydrous status of our surface of study is calculated using the following equation:

$$F_{evapo}. = LE_{inst.}/\ (Rn - G) \quad (13)$$

F_{evapo} is the ratio of latent heat flux (LE_{inst}) and the energy available at the surface (Rn-G).

RESULTS AND DISCUSSION

Figure 3 represents the spatial distribution of surface temperature at pixel scale, in terms of different land-use/cover types. It varies between 296.93°K and 328.75°K with an average value of 313.92°K. Minimum values correspond to cold pixels (water; meadow and aquatic vegetation) and high values to hot pixels (rocky levelling and burned area). This is appropriate with Temperatures difference (dT), high on dry pixels and very low on cold ones, Table 2; this could be due to the fact that the vegetation areas reduce the surface resistance of evapo-transpiration which resulted in low surface temperature. The obtained mean value is in the same order of magnitude to one obtained in others areas having almost the same type of semi-arid climate (Hamimed *et al*., 2009; Pënualas, 1993).

The resolution of surface energy balance equation using Metric's algorithm allowed the spatial distribution of surface latent heat flux at pixel level, Fig. 4.

This flux varies between 0 and 823.39 (W/m^2) on the all area of study, with an average value of 196.87 (W/m^2). We notice that, they are more pixels with higher values of LE in the south than in the North. Therefore, the risk of hydrous stress is higher in the southern part of our area of study. The histogram of this flux represented at Fig. 5 shows that pixels with values near to the mean value (196.87 W/m^2) are more

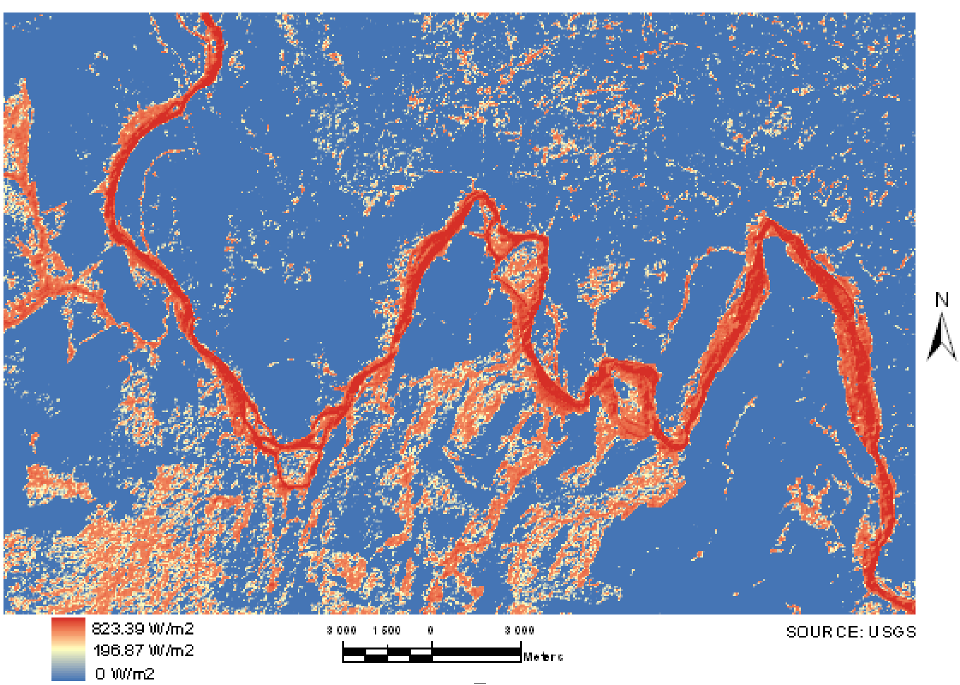

Fig. 4: Spatial distribution of latent heat flux (W/m^2)

Table 3: Instantaneous values of surface parameters and fluxes on dry pixels and on cold pixels

Surface parameters and fluxes	Unit	Dry pixels	Cold pixels
NDVI	-	0.090	0.72
Albédo	-	0.210	0.17
Emissivity	-	0 .930	0.99
H	W/m^2	285.890	0.04
LE	W/m^2	0.300	559.76
F_{evapo}	-	0.060	0.99
dT	°K	2.990	0.27

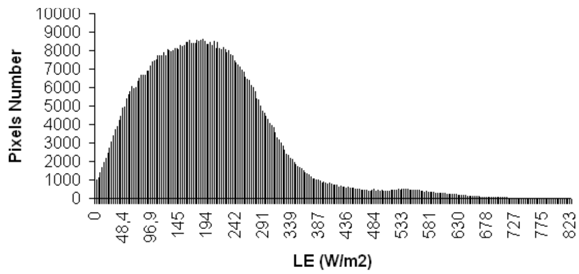

Fig. 5: Histogram of latent heat flux LE

abundant. This mean value is high at 9:55 am. This score is characteristic of semi-arid area where sunniness is high and wind speed is not neglected.

The mean instantaneous values of the remaining energy fluxes and surface parameters are given in Table 2.

The latent heat flux LE obtained was converted into instantaneous evapo-transpiration using Eq. (12) and daily evapo-transpiration ET_{day} was calculated using formula (14) supposing that fraction-evaporation F_{evapo} Is constant towards the day (Bastiaanssen *et al*., 1998):

$$ET_{day} = F_{evapo} * Rn_{day} \tag{14}$$

With Rn_{day} the daily net radiation given by:

$$Rn_{day} = (1 - \alpha) * Rg_{day} - 110 * \tau_{day} \tag{15}$$

With τ_{day} the daily transmissivity of the atmosphere expressed in function of the insulation fraction n/N, given by:

$$T_{day} = 0.25 + 0.50 * n/N \tag{16}$$

Rg_{day} the daily global radiation estimated using the daily exo-atmospheric radiation K_{exo} and the daily transmissivity of atmosphere given by:

$$Rg_{day} = K_{exo} * \tau_{day}$$

Then his daily evapo-transpiration obtained is represented at Fig. 6.

It varies between 0.4 and 7.12 mm, with an average value of 3.14 mm and with great dominance of pixels suffering from hydrous stress in the northern part, outside the park. Quite number of pixels subject to such degree of stress is observable on the frequencies distributions of latent heat flux, Fig. 5. We remark at Fig. 6 that the maximum values correspond to water pixels (Niger River principally), meadow and aquatic vegetation.

To analyse simultaneously the structure of the vegetation cover and the state of hydrous surfaces, we have represented at Fig. 7 the variation of TS with NDVI. We observe a negative correlation between these two variables. Indeed, when a surface presents a high NDVI it generally indicates a surface where vegetation is active and dense. The evapo-transpiration is important in such places and tends to reduce surface temperature TS.

Table 3 indicates the mean values of others surface flux and parameters. We remark a high value of

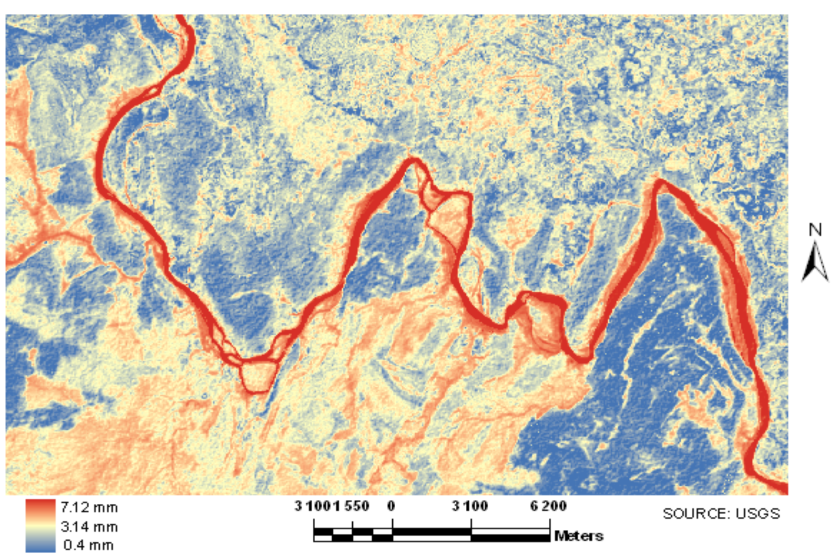

Fig. 6: Spatial distribution of the daily evapo-transpiration

Table 4: Values of energy fluxes and surface parameters in function of land-use/cover types

Land-use/cover	Rn (W/m²)	G (W/m²)	H (W/m²)	LE (W/m²)	F_{evapo}	Albedo
Water	598.14	49.55	0.71	547.87	0.99	0.10
Wooded savannah and bush	445.18	80.47	193.38	171.38	0.45	0.17
Meadow and aquatic vegetation	523.78	47.08	22.48	454.21	0.95	0.21
Forest	515.19	66.52	87.79	360.82	0.80	0.16
Rocky levelling	370.82	80.02	218.60	72.58	0.23	0.21
Burned areas	453.36	87.93	285.89	79.53	0.26	0.24

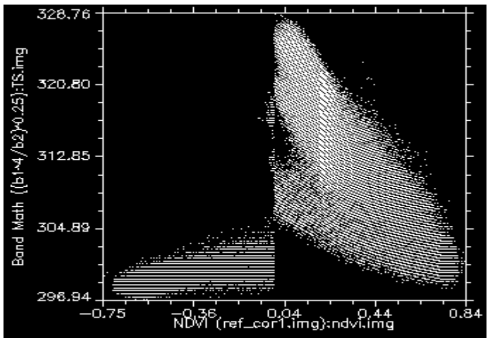

Fig. 7: Diagram defined by the relation between TS and NDVI

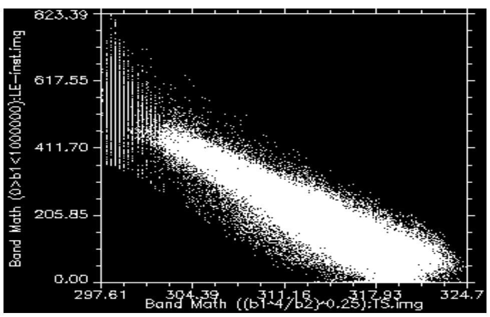

Fig. 8: Correlation between TS and LE

evaporation-fraction earlier at 9:55 am; this explains in part the high degree of hydrous stress that affected most pixels.

We have used this figure to identify dry pixels and cold pixels by using the triangle method (Allen *et al*., 2007). Thanks to this identification, we have obtained the instantaneous values of surface parameters and fluxes for each category of pixels. These values are represented in Table 3.

Values of LE obtained on dry pixels (LE ~ 0) and on cold pixels (H ~ 0) is a proof of the existence of almost totally dry pixels and totally cold pixels on our sit of study. The existence of such pixels is vivaciously wished if someone wants to apply METRIC or SEBAL models (Allen *et al*., 2007).

It is important to notice that the correlation between TS/NDVI is largely determined the environmental conditions and vegetation and thus is linked to the energy fluxes partition.

The spatial analyse shows that the distributions property of energy fluxes and surface parameters are very variable at pixel's scale. This variability is in part due to the heterogeneous nature of the site of study. To understand the effect of this variability, we have estimated the mean values of these fluxes and surface parameters on the main types of land-use/cover. Obtained values are indicated in Table 4. This table shows that water and vegetation cover have higher values of LE than the rest of land-use/cover type; this results in very high evaporation-fraction for such pixels and very low albedo for the rest. Indeed, for these last ones an increase of albedo coincides with diminish of water content (bared soil), or diminish of vegetation cover and thus, an increase of dry surfaces (small or almost null water content). An increase of albedo induces diminish of energy absorbed by the surface and thus, lesser temperature; as regulation by latent heat flux is no more possible.

Surfaces that are not too covered have high evaporation-fraction and high latent heat flux; this has great consequences on soil humidity and vegetation drainage which will be more marked during dry season.

In order to investigate the relations between energy fluxes and surface parameters, we have conducted a correlation study between surface temperature TS and latent heat flux LE. A marked correlation has been found, Fig. 8.

Surface temperature TS is thus indirectly linked to latent heat flux LE by means of energy balance equation, it is inversely proportional to latent heat flux, it furnishes an important information on the hydrous state of the surface contrary to others surface parameters such as NDVI and albedo where any significant correlation has not been found.

Note finally those results of analysis correlation between TS, NDVI and LE show negative correlation (-) for all the land-use/cover types. Results show that slope of TS/LE curve, Fig. 8 is more accented (marked) than that of TS/NDVI, Fig. 7. The correlation between TS/NDVI is thus largely determined by environmental conditions and vegetation and is thus linked to the flux energy.

CONCLUSION

With data extracted from Landsat7 ETM+ image of November 17, 2002 at 9:55 GMT and few ground based data, the model METRIC has allowed us to spatialize surface energy fluxes and evapo-transpiration, thus resolving the energy balance equation by using tele-detection data essentially. Obtained values are in the same order of magnitude to those obtained by tele-detection in the regions having almost the same type of semi-arid climate as our area of study. In addition, since the model used was derived from a validated model in Niger, we can assert that our results are quite realistic; nevertheless, we are planning to initiate a project in which Micro-lysimeters will be buying and install in the study area, in order to measure the evapo-transpiration in the future. This will allow validating the model used in this study.

The analysis of spatial distributions of surface temperature in terms of land-use/cover, NDVI and evapo-transpiration has allowed the identification of pixels that suffer from hydrous stress. Such stress could impact the dynamic of vegetation. In this respect, we envisage to conduct a forthcoming work on a diachronic study of surface energy fluxes and evapo-transpiration by using many Landsat images. We will put in relations the evolutions of these parameters with vegetation's dynamic. This will contribute to better interpretation of such dynamic and a best comprehension of the biophysics mechanisms intervening in sol/plant's system. Then, it will be possible to make a steady control in order to help the Park's manager to identify regions at risks, requiring a putting plan of management and adequate conservation.

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