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# Application of Satellite Remote Sensing for Irrigation Management Practices in Sri Lanka - A Case Study of Performance Assessment in the Kirindi Oya Project

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**Abstract:** The potential use of space borne remotely sensed data to obtain accurate information on land surface processes and conditions has been spreading widely in the international research field of water resources management. Such studies have demonstrated that quantitative assessment of the transfer processes between the land surface and the atmosphere can lead to a better understanding of the relationships between crop growth and water management. As fresh water becomes an increasingly scarce resource, the application areas of these research tools are more important for the water managers, for the benefit of society.

This paper presents how to assess the performance of irrigation systems using space borne remotely sensed data associated with regular field measurements. The results of a case study carried out by the author for a large irrigation scheme in Sri Lanka are analyzed and presented to assess the feasibility of applying remote sensing techniques as a tool for irrigation practices. The wetness parameters such as actual evapotranspiration, potential evapotranspiration, above ground biomass growth, and volumetric soil moisture content are estimated using satellite measurements.

**Key words:** Remote sensing, crop growth, water management, evapotranspiration, soil moisture

## Background

Obtaining repeated objective evaluations about actual field conditions required for irrigation performance assessment is difficult. Remote sensing may now provide viable solutions in several situations, allowing repeated sampling of field conditions in units as small as 100 ha. By regularly monitoring field wetness indicators, system managers can modify decisions throughout the irrigation season based on field moisture depletion and evaporation deficit. In systems of gravity irrigation, such monitoring would assist managers to identify persistent deviations from scheduled deliveries enabling more rapid diagnosis of causes of deviations from target.

In addition, regular feedback of information from the field into water management decision making can improve the performance of water delivery services. Information from remote sensing is objective and unbiased. Irrigation system water allocations are, most often, based on assumptions about the irrigated area, crop types, and the near-surface meteorological conditions that determine crop water requirements. Remote sensing enables regular updating of irrigated areas that tend to deviate from the original estimates of irrigation command areas. In demand-based systems, knowledge from field conditions, including crop stress, can help managers forecast how much water should be released from the reservoir (Bastiaanssen et al, 2000).

Satellite images having spectral properties of visible range, near infrared range and thermal range are required for the computation of wetness parameters. High frequency, low spatial resolution satellite images (NOAA-AVHRR, MODIS) are now available almost free from cost. The prices of high spatial resolution satellite images (Landsat, ASTER) are decreasing. All these facilities bring opportunities for the irrigation managers to use the advance technology of satellite remote sensing for irrigation management practices, at a greater extent.

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## Study area

Kirindi Oya Irrigation & Settlement Project (KOISP), the study area of this research, consists of two subsystems, namely, the Old area and the New area. The irrigable areas of both systems are approximately equal. The Old area, having priority for water rights, is a composite system with five major irrigation tanks situated downstream of the New area. Because of this, a substantial amount of water has to be released initially to fill the downstream tanks. A part of the drainage water flowing out of the New area is collected in the tanks of the Old area, but a huge volume of drainage water flows to the sea without being reused in the Kirindi Oya system. Irrigation performances of the KOISP were assessed for the Yala season of 1999 using NOAA-AVHRR satellite measurements, associated with regular field measurements. The crop type of this season was paddy and the cultivated extent was about 9000 ha. A project map of the KOISP extracted from a satellite image is shown in Fig. 1.

## Satellite measurements and Climate parameters

The remote sensing input used in the study was AVHRR data from the day-time (early afternoon) ascending mode pass of NOAA 15 meteorological satellite, having a spatial resolution of 1.1 km x 1.1 km at satellite nadir, downloaded at the Department of Meteorology in Colombo, Sri Lanka. The suitability of images for processing was based on the degree of cloudiness over study area and the position of Sri Lanka in the image. The cloud free images with the view angle less than 5o from the vertical were selected for processing. The AVHRR channels used were; Channel 1 (0.58 to 0.68 (m in the visible), Channel 2 (0.72 to 1.00 (m in the near infrared), Channel 4 (10.3 to 11.3 (m in the thermal infrared) and Channel 5 (11.5 to 12.5 (m in the thermal infrared).

The Meteorology Department measures the climatic data namely, air temperature (maximum, minimum, and average), wind speed, sun shine records, relative humidity, and rain fall records on a daily basis from their weather station located close to the study area. The rainfall records were also obtained from the rain-gauge stations established in a few locations within and around the study area, by the Irrigation Department.

In this study, following wetness indicators were estimated using 10-day composites (average values of every ten day period) of NOAA-AVHRR satellite data associated with climate data.

i. Actual evapotranspiration
ii. Evaporative fraction (latent heat/net available energy)
iii. Potential evapotranspiration
iv. Volumetric soil moisture content
v. Accumulated biomass (above the ground)

The theoretical approach for deriving above parameters is briefly described in Annex 01.

The reservoir outflow measurements, the drainage outflow measurements, and the rainfall data were obtained from the Irrigation Department.

## Management perspective of performance assessment

The rationale behind the performance assessment is to diagnose any performance gap in the goal achieving process and to take remedial action to rectify the situation. Hence, both operational and strategic managers should identify the performance gap (if any), find the cause for the gap, and take corrective measures to cure below target performance, through a diagnostic approach. This implies that the performance assessment is not merely an administrative process. It is a managerial process, which needs continuous assessment of its performance through feed back controlling.

## Performance assessment of Irrigation systems

The function of irrigated agriculture is defined as the process by which individual water users, user organizations and irrigation management institutions use water to grow crops in relation to their goals, other resources and the environment (Bos, 2001). The performance of irrigated agriculture heavily depends on the water institutions in which the performances of an irrigation system should be assessed from the related disciplines of irrigated agriculture. Water institution determines the performance levels together with the boundary conditions i.e. certain

Fig.1 Project map of the KOISP extracted from a satellite image

physical limits from the environment. To identify the related disciplines, the function of irrigated agriculture can be analyzed under three distinct parts: inputs, processes, and outputs. The functional areas can be further generalized into three major disciplines as water balance, socio-economic, and environment whereas the sustainability of the system will become the cumulative outcome. Performance indicators for water balance and productivity of inputs (economic) are discussed in this study.

## Recommended indicators to assess the performance of the KOISP

### *Water balance*

The selected performance indicators are briefly described below. The mostly used wetness parameters; actual evapotranspiration ($ET_a$), potential evapotranspiration ($ET_p$), Evaporative fraction ($\Lambda$), accumulated biomass, soil moisture ($\theta_{act}$), were computed from satellite measurements using few field measurements. $ET_p$ is the amount of water needed for the process of photosynthesis whereas $ET_a$ is the amount of water actually used by the crop.

The schedule of system operations is computed from the crop water need for different growing stages. The effect of precipitation is also considered. *Relative water supply* (RWS) as presented by Levine (1982) can facilitate these requirements.

$$\text{Relative water supply} = \frac{\text{Irrigation supply + Gross precipitation}}{ET_p}$$

The aim of water use performance is to minimize the water stress by bringing actual evapotranspiration into a closer value of the potential evapotranspiration through the system performance and *relative evapotranspiration* describes;

$$\text{Relative evapotranspiration} = \frac{ET_a}{ET_p}$$

*Evapotranspiration deficit* is more meaningful than water deficit for irrigated agriculture being classically defined as supply minus demand (Bandara, 2001).

$$\text{Evapotranspiration deficit} = \left[ET_p - ET_a\right] \qquad \text{(mm/day)}$$

The *depleted fraction* (DF) was introduced by Molden (1997) to apply performance in the context of multiple irrigation systems or cascade systems.

$$\text{Depleted fraction} = \frac{ET_a}{\text{Irrigation supply + Gross precipitation}}$$

The usual target soil moisture level is field capacity, and the *relative soil wetness* (RSW) was introduced by Bastiaanssen et.al, (2001) to evaluate the deviation from this optimum moisture status as described in Eq. 9 of Annex1.

Relative soil wetness =

$$\frac{\text{Volumetric soil water content in the rootzone } \theta_{act} \ (cm^3 / cm^3)}{\text{Volumetric soil water content at field capacity } \theta_{sat} \ (cm^3 / cm^3)}$$

$$\text{soil water deficit} = \left[\frac{\theta_{sat} - \theta_{act}}{\theta_{sat}}\right] \times 100$$

$$= [1 - \text{Relative soil wetness}] \times 100$$

*Crop water stress* is the same as evapotranspiration deficit and can be computed as a percentage of ETp in dimensionless relative terms;

$$\text{Crop water stress} = \left[\frac{ET_p - ET_a}{ET_p}\right] \times 100$$

### *Productivity of inputs (economic)*

Satellite remote sensing can measure the crop growth which is expressed as above ground biomass growth (e.g kg per ha per month). The economic value per unit biomass can be calculated from the seasonally accumulated biomass with the market price of grain because grain yield and biomass yield are linearly related. The harvest index is the ratio of grain yield over biomass yield and lies essentially between 0.25 to 0.50 (Bastiaanssen et, al. 2001). The relative scales of biomass yield over irrigation supply and productivity of water are thus similar and also, substituting incremental values, could assess temporal variations within a season. Hence, the indicator *biomass over total water supply* can monitor the crop growth.

Biomass yield over water supply =

$$\frac{\text{Accumulated biomass (kg/ha)}}{\text{[Irrigation supply + Gross precipitation] } (m^3/ha)} \ (kg/m^3)$$

Agricultural researches are concerned with high yield crop varieties. Hence, *productivity of land* is so important that it determines the average seasonal production per unit area of land.

Productivity of land =

$$\frac{\sum \text{Seasonal crop yield in each sample area (kg)}}{\sum \text{Extent of each sample area (ha)}} \ (kg/ha)$$

The monetary value of water, which is used for agricultural product outputs, is more useful to assess the economic benefits of the country gaining from the irrigated agriculture. *Productivity of water used* describes the economic value of agricultural product per unit volume of water consumed by the crop.

Productivity of water used =

$$\frac{\text{Farm gate price of actual crop yield (Rs/ha)}}{\text{Accumulated } ET_a \ (m^3/ha)} \ (Rs/m^3)$$

## Results and interpretation

The cumulative average values of seasonal water balance for the KOISP during the Yala season of 1999 is shown in Table 1.

The temporal variations of Relative water supply (RWS), Evapotranspiration deficit, Relative evapotranspiration, and the Depleted fraction are graphically shown in Fig. 2.

The average value of the RWS for the whole season can be computed as 4.23 and which indicates that more water has been issued from the reservoir than required by the crops. Table 1 shows that only 20% of the net inflow has been utilized for evapotranspiration during the season. Under these circumstances, it has to be verified whether any extra amount of water issued from the reservoir against the requirement, may have been really wasted in conveyance, land preparation and as other field losses. As the five irrigation tanks of the old system receive their storage water during the initial stage of the season and the higher water requirement for land preparation, RWS indicates high values during the first seven ten-day periods. The cumulative average values of water balance, after the first seven ten-day periods are shown in the Table 2.

During the latter part of the season, i.e. crop growing stages, performance of the system had

Table 1.
The cumulative average values of seasonal water balance for the KOISP

| Components of seasonal water balance (in millimetres per season and as percentage values of the net inflow ) | | | | | Remarks |
|---|---|---|---|---|---|
| Irrigation supply | Precipitation | $ET_a$ | Drainage outflow | Seepage<br>+Percolation<br>+Tank storage | $ET_p$ (mm per season) |
| 1786<br>(98 %) | 39<br>(2 %) | 358<br>(20 %) | 204<br>(11 %) | 1263<br>(69 %) | 591 |

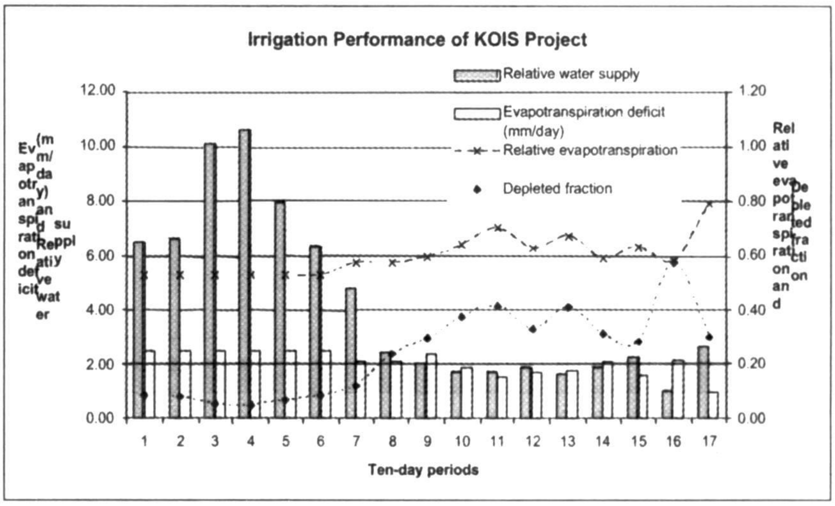

**Fig. 2 Temporal variations of performance indicators (set 1) of KOISP**

Table 2
Water balance of the KOISP after first seven ten-day periods

| Components of water balance after first seven ten-day periods (in millimetres per season and as percentage values of the net inflow ) | | | | | Remarks |
|---|---|---|---|---|---|
| Irrigation supply | Precipitation | ET_act | Drainage outflow | Seepage<br>+Percolation<br>+Tank storage | ET_pot (mm per season) |
| 826<br>(100 %) | 0<br>(0 %) | 279<br>(34 %) | 132<br>(16 %) | 415<br>(50 %) | 446 |

improved. The cumulative average of *RWS* has come down to 1.92 whereas $ET_a$ has increased to 34%. The absolute value of the evapotranspitation deficit fluctuates at the latter part of the season showing low values during the ten-day periods of 10,11,12,13, 15 and 17. As long as evapotranspiration deficit takes values greater than zero, there exists a water stress which is the ideal situation. In real practice, water stress has to be accepted within a feasible tolerance range.

The relative evapotranspiration takes values greater than 0.6 during the ten-day periods where evapotranspiration deficit has taken low values. This implies that the performances have been improving at the latter part of the season.

At the latter part of the season, the depleted fraction has taken values between 0.28 and 0.40 except the ten-day periods of 11, 13 and 16 of which the depleted fraction was above 0.40. This situation indicates a fairly low range for the actual crop water use with respect to its actual water need, except three ten-day periods. This brings a message to the irrigation manager that the total delivered amount of water had not reached the root zone bulb as and when it is required. In other words, the water deliveries were not effectively operated. Fig. 3 represents the Venn diagram for the upper range of the performance shown by three indicators as described.

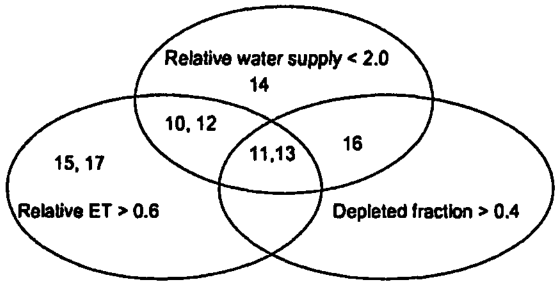

**Fig. 3: Venn diagram for the upper range of the performance shown by indicators in figure 2**

Fig. 3 describes that the relative performance during the ten-day periods 11 and 13 are better than the ten-day periods of 10, 12, and 16. The relative performance of the ten-day periods of 14, 15 and 17 are fairly good. This situation can be further analyzed by observing the temporal behavior of the indicators related to the soil moisture as graphically shown in Fig. 4.

The indicator values at the latter part of the season (after seventh ten-day period) describe the performance of the growing period of the crop. The relative soil wetness has taken values greater than 0.7 in all ten-day periods after the 9th. In most of the ten-day periods after the 9th, the crop water stress has taken values less than 40%. The soil water deficit has taken values less than 20% in the ten-day periods of 11, 12, 14 and 17. Fig. 5 represents the Venn diagram for the upper range of the performance shown by the respective three indicators.

Fig. 5 describes that the relative performance during the ten-day periods of 11, 12 and 17 are better than the ten-day periods of 10, 13, 14 and 15. The relative performance of the ten-day period 16 is fairly good..

The performance of the productivity indicators are shown in Table 3. Productivity indicators were computed using accumulated outputs with respect to the input resources utilized. Such indicator values assess the overall performance of the season and which are useful to evaluate the past season and to plan the forthcoming season based on past performances.

Table 3 indicates that the seasonal crop yield is close to the district average of 3809 kg/ha (Central Bank annual Report, 1999). "Productivity of water used" determines the economic value of water actually consumed by the paddy crop (only 20% of the net inflow) during the growing season. In the KOISP, the paddy crop has produced Rs. 16.39 worth of rice consuming one cubic meter of water during the 1999 Yala season. According to the figures of Table 1, 11% of the net inflow has gone out of the KOISP boundary as the drainage outflow. This implies that the balance.69% (100% - 20%-11%) remains within the system as ground water recharge and storage under five irrigation tanks of the old area. The ground water recharge stabilizes the water table eliminating salinity development and provides numerous environmental benefits to the system. There may be environmentally negative effects such as water stagnation. The tank storage can be used at the forthcoming season. This situation reveals that it is necessary to have a comprehensive economic evaluation over the net benefits to the system from the amount of water nonconsumptively used within the KOISP.

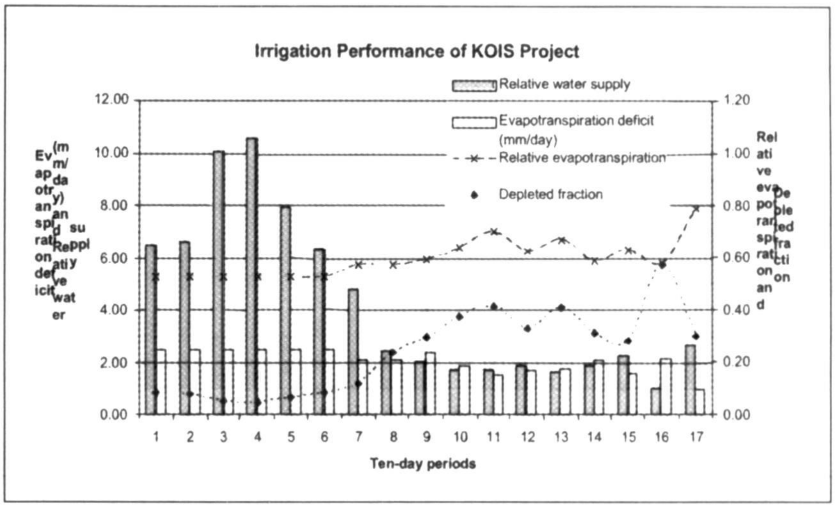

**Fig. 4 Temporal variations of performance indicators (set 2) of KOISP**

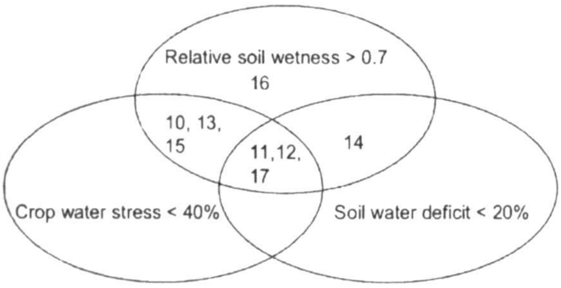

**Fig. 5 Venn diagram for the upper range of the performance shown by indicators in figure 4**

**Table 3**
**Performance of the productivity indicators**

| Performance Indicator | Seasonal output |
|---|---|
| Biomass yield over water supply | 0.36 kg / m3 |
| Productivity of land | 3526 kg / ha. |
| Productivity of water used | 16.39 Rs / m3 |

## Conclusion

Traditional methods of performance assessment will evaluate the overall performance of any irrigation scheme at the end of the cultivation season or within long span time intervals. Such information is rather useful for strategic planning than for operational monitoring. When a cultivation season has commenced, updated information on performance is necessary. Appropriate remedial actions could be made to the process if real-time data is available. Satellite measurements provide near-real-time data and figures 2 and 4 can be revised and updated for each ten-day period of forthcoming seasons. Remote sensing also provides an opportunity to measure the crop yield without field measurements and this opens the possibility to study the variability of water productivity within an irrigation scheme.

A set of performance indicators describes the system performance of irrigation schemes in different dimensions for the benefit of decision-makers. The temporal variations of such indicators will enhance the total quality of the irrigation performance.

Examination of spatial variation of performance indicators within a system using NOAA images is a rather difficult exercise for the irrigation schemes in Sri Lanka because the irrigation extent is relatively small compared to the spatial resolution of NOAA images, i.e., 1.1 km x 1.1 km. But the availability of satellite measurements at a high frequency (daily basis, and 10-day composites), will provide key information for the Irrigation Department. Therefore, temporal variations of performance indicators computed using remote sensing techniques can potentially make a vital contribution to the management of irrigation operations.

The performance of the Kirindi Oya project shows over-irrigation during the early part of the season. After that, less water is issued and the efficiency increases. The irrigation managers can diagnose the root cause for the poor performance using indicator values computed at closer intervals, using satellite measurements. For the surface irrigation systems like KOISP, productivity per unit of water cannot be defined as a simple ratio of paddy production to net inflow. Productivity of water used by the paddy crop is more meaningful until a comprehensive economic analysis is carried out for the consumptive and non consumptive uses of the net inflow.

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Annex - I

## SEBAL approach to determine the evaporative fraction and actual evapotranspiration

Remote sensing data provided by satellites are a means of obtaining consistent and frequent observation of spectral reflectance and emittance of radiation of the land surface on micro to macro scale. A physically based "multi-step" Surface Energy Balance Algorithm for Land (SEBAL) has been formulated (Bastiaanssen, 1995) mainly with remotely sensed measurements and a limited number of climate parameters as input data. The SEBAL approach was used to estimate the actual evapotranspiration and the evaporative fraction (latent heat/ net available energy) of the seasonal crop growing areas of the KOISP.

The conceptual scheme of SEBAL approach is presented in Fig.6 and which describes latent heat flux density ($\lambda E$) as the residual of the instantaneous surface energy balance;

$$\lambda E = R_n - G - H \ \text{Wm}^{-2} \qquad \text{Eq. 1}$$

The conversion of instantaneous flux values determined above, for the satellite overpass time, to daily evaporation rate is done by the evaporative fraction ($\Lambda$), which reads as:

$$\Lambda = \frac{\lambda E}{\lambda E + H} = \frac{\lambda E}{R_n - G} \qquad \text{Eq. 1}$$

Following Shuttleworth et al. (1989), the instantaneous evaporative fraction is considered similar to its daily counterpart (Brutsaert and Sugita, 1992; Crago, 1996; Farah et al., 2000; Chandrapala et al, 2001), and is used to compute the actual 24-hour evaporation from the instantaneous latent heat fluxes: The soil heat flux density which is a part of surface energy balance adds heat to the soil during daytime and extracts heat from the soil during nighttime (Bastiaanssen, 1995). Hence on a daily basis, soil heat flux density ($G_{24}$) can be neglected (Roerink, et al 1997), as it is minimal

$$\lambda E_{24} = \Lambda R_{n24} \qquad \text{W m}^{-2} \qquad \text{Eq. 2}$$

Where, $R_{n24}$ is the 24-hour net radiation. Farah (2000) recently tested the applicability of this assumption successfully for a tropical watershed.

Daily estimates of potential evapotranspiration (ETp) can be computed from the Priestley and Taylor (1972) method and satellite data, which is a simpler form of the Penman-Monteith equation for irrigation scheduling (Mekonnen and Bastiaanssen, 2000):

$$ET_p = 1.26 \ x \ R_{n24} \left[ \frac{S_a}{S_a + \gamma} \right] \text{mm day}^{-1} \qquad \text{Eq. 4}$$

where, $ET_p$ = potential evapotranspiration (mm day$^{-1}$); $R_{n24}$ = 24-hour net radiation (mm day$^{-1}$); Sa = slope of the vapor pressure deficit curve (mbar/K); and $\gamma$ = the psychrometric constant (mbar/K). Net radiation is based on surface albedo from NOAA channel 1 and 2.

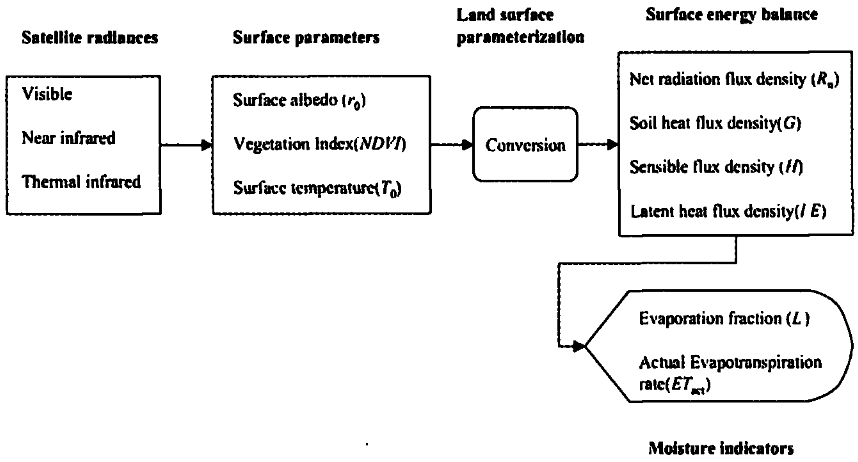

**Fig.6 Principal components of the SEBAL approach**

## Assessment of crop biomass using remote sensing measurements

The fraction of photosynthetically active radiation absorbed by green leaves in a canopy ($f_{PAR}$) can be remotely sensed. Remote sensing yields the opportunity to estimate $f_{PAR}$ directly as a linear function of *NDVI* (e.g. Hatfield et al., 1984; Asrar et al., 1992). Bastiaanssen et al, 2001a have used the following linear relationship by considering the experimental data from Daughtry et al. (1992: corn and soybeans), Joel et al., (1997: sunflower) and Myneni et al. (1997: cereals) and the same is used in this study.

$$f_{PAR} = -0.161 + 1.257\, NDVI \qquad \text{Eq. 5}$$

*NDVI* is an expression for chlorophyll related photosynthetic activity (e.g. Tucker, 1979) and expresses by that fresh and vigorous biomass, which is different from physical crop yields. Since *NDVI* can be calculated from most satellite multi-spectral sensors, the possibility arises to generate maps of $f_{PAR}$ at the regional scale using *NDVI*, even if land use is unknown.

Monteith (1972) pioneered the concept of calculating net primary biomass production as a function of absorbed photosynthetically active radiation (*APAR*). Experimental results (Gallagher et al, 1978; Legg et al, 1979; Kumar et al, 1981; Steven et al, 1983; Green et al; 1985, Kasim et al 1986; Wiegand et al, 1989; 1991; Casanova et al, 1998;) have shown that the amount of dry matter of a seasonal crop ($W_{DM}$) is a time integrated product of the and expressed as a function of the *daily incident radiation* of *PAR* above the canopy ($S_{PAR}$);

$$W_{DM} = \int \alpha\, f_{PAR}\, S_{PAR}\, dt \ \text{kg m}^{-2} \qquad \text{Eq. 6}$$

For rice crop, the conversion factor for intercepted PAR into dry matter (α) takes a constant value of 2.25 g MJ $^{-1}$ from seeding to maturity stages (Casanova et al, 1998). For the estimation of accumulated dry matter (above ground) using the remotely sensed data, Eq. can be simplified into the discrete variables (Bastiaanssen et al, 2001$^{a}$; 2001$^{b}$, Bandara 2001)

## Identification of crop water stress situation through the estimation of volumetric soil moisture content.

A direct application to retrieve soil water content of the root zone is not operationally feasible, but crop water stress indicators based on energy partitioning can be used as a first approximation. Volumetric soil moisture can be estimated from the evaporative fraction (latent heat / net available energy) using a statistical relationship between evaporative fraction and soil moisture. Bastiaanssen et al, 2000 have depicted a logarithmic relationship between volumetric soil water content in the root zone and the evaporative fraction obtained from the results for two large scale field campaigns dedicated to soil moisture-evaporation-biomass interactions, FIFE (Smith et al, 1992) and EFEDA (Bastiaanssen et al, 1997). The same relationship has been converted into a globally acceptable empirical relationship between volumetric soil moisture content (*θ*) and evaporative fraction (Λ) as follows (Bastiaanssen et al 2001$^{b}$):

$$\frac{\theta}{\theta_{sat}} = \frac{1}{\varepsilon} \exp\left[(\Lambda - a)/b\right] \ \text{cm}^3\,\text{cm}^{-3} \qquad \text{Eq. 9}$$

Values of constants "*a*" and "*b*" of the Eq. were obtained as 1.28 and 0.42 respectively for the porosity of $\varepsilon = 0.51$, from the tested area. Saturated soil moisture content ($\theta_{sat}$) has to be obtained from laboratory tests for the application area.

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