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Variability of Soil Moisture in the Walawe River Basin: A Case Study in Sri Lanka Using Low-Resolution Satellite Data

Lal Muthuwatta and Yann Chemin
Research Officer (RS) and Remote Sensing/GIS Specialist
International Water Management Institute
PO Box 2075, Colombo
Tel: (94)-1-867404 Fax: (94)-1-866854
E-mail: l.mutuwatte@cgiar.org ; y.chemin@cgiar.org
SRI LANKA

Lalith Chandrapala
Ph.D. Student in Water Resources Management
International Institute for Aerospace Survey and Earth Sciences
Room 5-105, WRES, P.O. Box 6, 7500 AA Enschede
Tel: (31)-0-53 4874 233 Fax: (31)-0-53 4874 336
E-mail: chandrapala@itc.nl
THE NETHERLANDS

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ABSTRACT: Limited availability of freshwater and increasing demand for food require careful management of available resources. However, information on water utilization within river basins is often inadequate for comprehensive water management. Therefore, researchers are developing new tools and methodologies to overcome these data problems. A major concern for land use planning is the identification of suitable areas for different types of activities to enable optimal management of natural resources.
Satellite remote sensing technology opens new paths for studies on the management of river basins. Through information derived from satellite data, it is possible to monitor land surface conditions and the status of the water resources on daily basis. NOAA-AVHRR sensor supplies data at a relatively low resolution for every part of the world, also on a daily basis. By integrating these low-cost images in physically based models, soil moisture was estimated for every part of Sri Lanka at 1-km resolution.
This paper endeavors to show the relevance of soil moisture variation for water basin characterization, and ultimately for natural resources management. Walawe basin, one of the IWMI benchmarked basins in Sri Lanka has been selected for soil-moisture characterization and for the delineation of classes. Results show time variations and amplitude differences between different zones in the basin. When compiled with the *vegetation growth zones* of Walawe, the soil moisture highlights relevant land and water management lessons.

1. INTRODUCTION

Knowledge on actual evaporation and soil moisture conditions of crops, forests and natural vegetation is extremely important to initiate and evaluate water management practices (Bastiaanssen et. al., 1995). Crops require water mainly to meet transpiration demands (Kramer, 1969). The soil-moisture status influences transpiration rates. If the soil is dry, water cannot be transported into the leaves in sufficient quantities to meet transpiration requirements. At this stage, the stomata close and transpiration is reduced. Photosynthesis is also reduced when stomata are closed (Vaadia et al., 1967). Thus when plants are not supplied with sufficient moisture, crop growth and production are adversely affected.

Despite the scientific progress in hydrology and soil physics, deficit and excessive soil moisture in the root zone cannot be measured or calculated in a straightforward manner due to spatial heterogeneity in environmental conditions (Bastiaanssen et al., 1995). There have been some studies on estimating soil moisture using remote sensing data (Van Oevelen et al., 1996; Musiake et al., 1995). These studies mainly used high spatial resolution active microwave sensors, which have a relatively low temporal resolution. On the other hand, costs associated with these satellite images are high. This study, based on NOAA-AVHRR images for a 1-year period starting from June 1999, estimated soil moisture for every 1.1x1.1 km^2 area over Sri Lanka for every 10 days.

Accumulated biomass is dependent on water stress conditions, and it was estimated by Samarasinghe et al. (2001) for the study period (June 1999 to May 2000). As interesting as it is for monitoring environmental conditions, this yearly information permitted the delineation of vegetation growth zones (Muthuwatta et al., 2001), being the objective effect of the combination of land-water-atmosphere interplay on vegetation, as determined for all of Sri Lanka. This paper also addresses the combination of soil-moisture information for further description of the environmental conditions of biomass growth.

Sri Lanka, situated within 9^0 50’ N, 5^0 55’ N, 81^0 53’ E and 79^0 42’ E, has an aerial extent of 65,610 km^2. According to the modern scheme of climatic zonation employed in the World Soil Resources Map, 1991, the wet part of the country falls within the humid tropics and the dry part within the seasonally dry tropics. Small sections in the north and southeast of the island fall within the semiarid tropics. The country has a large human population and an agricultural economy. This study was carried out in the 2,471-km^2 Walawe river basin, which is the largest river basin in southern Sri Lanka. The Uda-Walawe reservoir, with a capacity of 250 million m^3 (MCM), was constructed across the Walawe river to provide irrigation facilities to an extent of 32,000 ha, and was commissioned in 1968. The estimated annual average inflow of this reservoir was 1,000 MCM.

2. METHODS

2.1. Satellite Images

The images used in this study were (Chandrapala et al., 2001) AVHRR data from the day-time (early afternoon) ascending mode pass of NOAA 14 meteorological satellite, having a spatial resolution of 1.1 x 1.1 km^2 at satellite nadir, downloaded at the Department of Meteorology, Sri Lanka.

The existing receiving facility in the National Meteorological Centre of the Department of Meteorology in Colombo consists of a PC-based system with the capability to automatically receive, process and archive AVHRR data from all the NOAA series meteorological satellites (Chandrapala et al., 2001). Acquired imageries were combined into 10-day equivalent composites, to rule out the constraint of cloud contamination, which is a constant in the latitude of the study (table 1).

Acquisition Decades	Acquisition Decades	Acquisition Decades	Acquisition Decades
June 2nd Dc., 1999	Sept. 1stDc., 1999	Jan. 1st Dc., 2000	Apr. 1st Dc., 2000
June 3rd Dc., 1999	Sept. 2nd Dc., 1999	Jan. 2nd Dc., 2000	Apr. 2nd Dc., 2000
July 1st Dc., 1999	Sept. 3rd Dc., 1999	Jan. 3rd Dc., 2000	Apr. 3rd Dc., 2000
July 2nd Dc., 1999	Nov. 1st Dc., 1999	Feb. 1st Dc., 2000	May 1st Dc., 2000
July 3rd Dc., 1999	Nov. 3rd Dc., 1999	Feb. 2nd Dc., 2000	May 2nd Dc., 2000
Aug. 1st Dc., 1999	Dec. 1st Dc., 1999	Feb. 3rd Dc., 2000	May 3rd Dc., 2000
Aug. 2nd Dc., 1999	Dec. 2nd Dc., 1999	Mar. 1st Dc., 2000	
Aug. 3rd Dc., 1999	Dec. 3rd Dc., 1999	Mar. 2nd Dc.,2000	
		Mar. 3rd Dc., 2000	

Note: Dc=Decade.

Table 1. Details of Satellite Images Decades Composed in This Study.

2.2. Definition of the Vegetation Growth Zones

Based on this dataset, monthly vegetation growth was estimated over the country during the study period (Samarasinghe et al., 2001). Using these estimates, the whole country was divided into 91 different zones with respect to the spatial and temporal variations of vegetation growth (Muthuwatta et al., 2001) namely vegetation growth zones. These 91 zones were named and described by the degree of wetness and the elevation. Wetness was determined, besides soil moisture, by the Moisture Availability Index (MAI) (Heargreaves, 1975). Areas where annual MAI below 1.0, from 1.0 to 1.4 and above 1.4 were classified as dry (D), intermediate (I), and wet (W) regions, respectively. Of these zones, 60 came under *low* country, 8 under *middle* country and 7 under *up* country. In addition to that, 10 zones were distributed between the *low* country and the *middle* country, and 6 zones were distributed between the middle country and the *up* country. Two letters and a number were assigned to each zone: The first letter refers to the MAI zone and the second to the elevation class (U for *up* country, M for *middle* country and L for *low* country), and the number refers to the MAI in ascending order. For example, WL1 gives the area with the lowest MAI in the wet areas of the low country (Muthuwatta et al., 2001).

2.3. SEBAL Application in the Meteorological Department of Sri Lanka

The application of the Surface Energy Balance Algorithm for Land (SEBAL, after Bastiaanssen, 1995) was operationalized in the Meteorological Department of Sri Lanka, through the collaboration of the International Water Management Institute (IWMI) and funded by the Programme Bureau Remote Sensing Netherlands (BCRS). SEBAL is a thermodynamically based model, looking towards finding the energy-balance terms at the land surface. While having a lot of empirically based steps, the physics of the core are robust thermodynamic equations. Extensive details of step-by-step considerations applied are provided for insight of the practical procedure in Chemin et al., 2000, Tasumi and Allen, 2000 and Tasumi et al., 2000. The application of the algorithm for Sri Lankan conditions is mentioned in Chandrapala et al., 2001. It has been satisfactorily validated in many places and situations, from Spain (Bastiaanssen, 1995) to Pakistan (Bastiaanssen et al., 2001).

When the SEBAL model is applied to the NOAA AVHRR images in Sri Lanka it produces a set of intermediary products. These transitory layers of information are the normalized difference vegetation index (NDVI), surface emissivity, surface albedo, surface temperature, radiative/conductive/convective energy fluxes at the soil surface, daily potential evapotranspiration, instantaneous evaporative fraction and daily actual evapotranspiration, the two last being the main outputs of running the SEBAL model. The Department of Meteorology is maintaining an archive of some of the transient and all of the final products in CDROM format.

2.4. Soil Moisture Calculation from SEBAL

Since there is no operationally feasible method to estimate soil water content of the root zone an empirical relationship between soil moisture and the heat fluxes partitioning ratio (called Evaporative Fraction: Λ) proposed in Bastiaanssen et al., 2000 was integrated with remote sensing data to estimate soil moisture. Λ is the output of SEBAL, and is defined as the ratio of latent heat to net available energy as in equation below:

$$\Lambda = \frac{lE}{Q^* - G_0} = \frac{Q^* - G_0 - H}{Q^* - G_0} \qquad (-) \qquad (1)$$

where, Λ = the Evaporative Fraction *(-)*, Q^* = the instantaneous Net Radiation *(W/m²)*, G_0 = the instantaneous Soil Heat flux *(W/m²)*, H = the instantaneous Sensible Heat flux *(W/m²)* and lE = the instantaneous Latent Heat of Vaporization *(W/m²)*. The empirical relationship between the root zone soil moisture and Λ, after Bastiaanssen et al., 2000, is as follows:

$$q = 0.0475 \times e^{2.3736 \times \Lambda} \qquad (cm^3/cm^3) \qquad (2)$$

Where, q = the root zone soil moisture and Λ = the Evaporative Fraction *(-)*. These results are valid for the experiments made under the conditions found in the USA and Spain; however it was the only information available for this study. Soil moisture was calculated assuming a constant soil porosity, across the island, of 0.51 $cm^3\ cm^{-3}$, being the upper limit of this empirical equation, setting the typical soil conditions at 100 percent soil water content saturation in the root zone of the soil when this value is reached.

3. RESULTS

Soil moisture was estimated for every day and prepared in 10-day composite images, and monthly and yearly averages were then calculated using these 10-day composites. During the study period (June 1999 to May 2000), the estimated average soil moisture ranged from 0.14 to 0.29 cm^3/cm^3 for Sri Lanka (figure 1). The entire wet zone demonstrated high annual average values as expected. Surprisingly, and as discussed in Muthuwatta et al. 2001, some areas in the dry zone also proved to have high soil moisture values, mainly due to groundwater and irrigation.

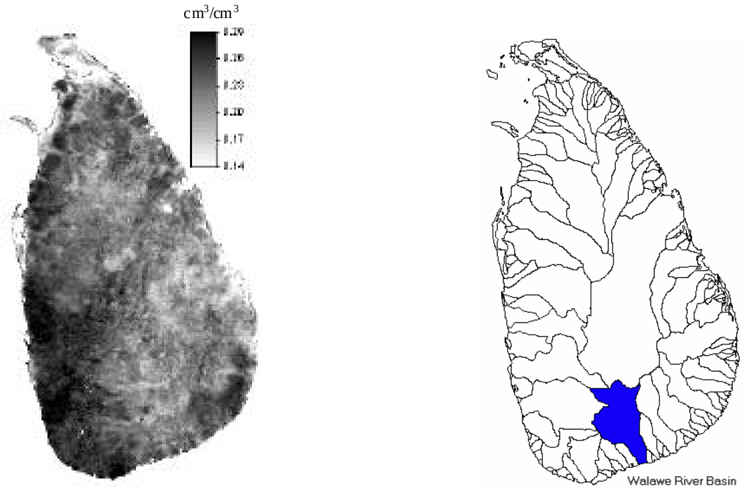

Figure 1. Average Soil Moisture (June 99 to May 00) and Map of River Basins of Sri Lanka.

There were 14 major vegetation growth zones in the Walawe river basin (figure 2). All ranges of classes of vegetation growth zones are represented in this river basin (dry, intermediate and wet, as well as all elevation classes). The average soil moisture for the study period was observed to be from 0.16 to 0.26 cm^3/cm^3, characterizing the river basin as relatively wet (mean yearly soil moisture=0.22 cm^3/cm^3).

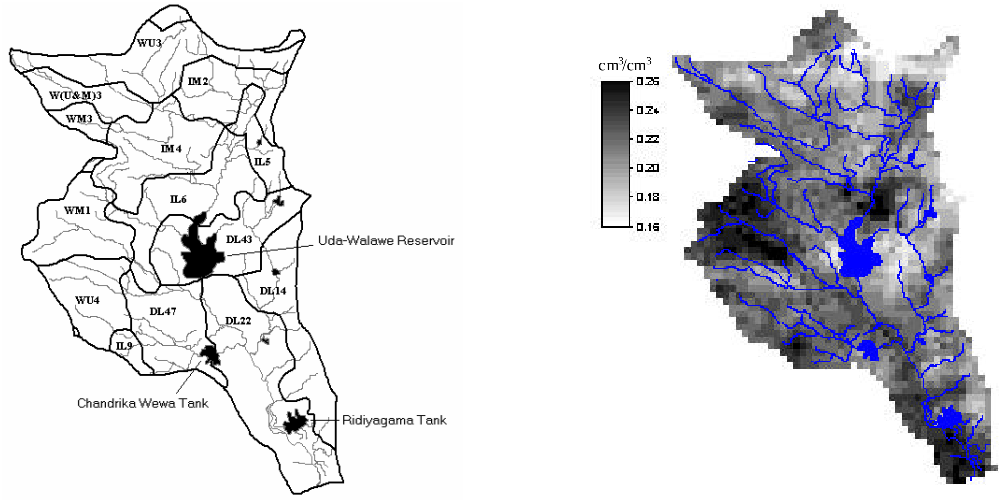

Figure 2. Vegetation Growth Zones and Average Soil Moisture (June 99 To May 00) in the Walawe River Basin.

According to the latest available soil map (Somasekaram et al., 1996), the predominant soil type of zone DL14, located in the lower part of the basin (figure 2), is of reddish brown earth, and according to the River Valleys Development Board, 1968, there was a relatively high infiltration rate of about 25 mm/h. Figure 3 shows that there was a high rainfall event in November with a break in December, and that between December and March, there was a gradual increase in the precipitation amount. From November to March, there was an increase in the soil moisture values and since there are many small tanks inside this area, it can be implied that in a large rainfall event rain collects in the tanks, which might help maintain the soil moisture of the zone. Hence, the relatively high amount of water in the soil between December and April (>0.25 cm^3/cm^3). These conditions supply a favorable situation for rain-fed agriculture in terms of water availability in the soil. During the other months, low soil moisture prevails (q=0.15 cm^3/cm^3), indicating the need for additional water for agricultural activities.

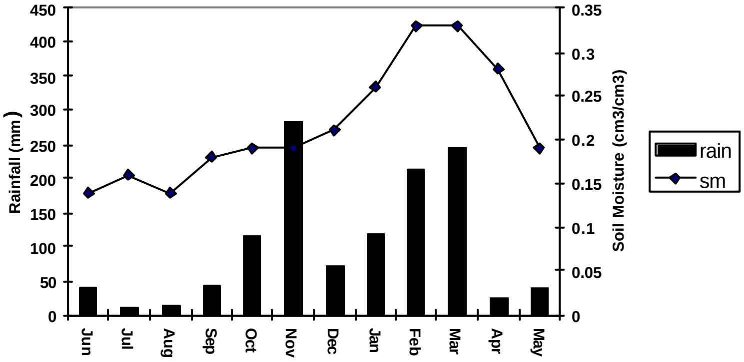

Figure 3. Monthly Variation of Soil Moisture and Rainfall in Zone DL14.

However, the amount of rainfall in some months during the study period deviates from the existing standard mean values for this area. A high rainfall is expected in November. But in the observation year, rainfall in January, February and March exceeded the standard averages. Further, the April and May values were found to be lower than the expected values. Therefore, to make final conclusions it is necessary to perform same analysis for a few more years. About 17 percent of the land in this zone is utilized mainly for paddy cultivation from small tanks and from some small diversion weirs (anicuts). Other parts are predominantly covered with sparse and open forest.

The upper catchment of Uda Walawe features sites of different environmental behavior compared to the lower part. Zone IM4 (figure 2) belongs to the mid-country intermediate zone and is relatively steeper (8–16%) than DL14. Conventionally, these areas are suitable for agroforestry and tree crops. The predominant soil type is reddish brown earth and red yellow podzolic soils.

In zone IM4 (figure 4), monthly soil moisture varies with respect to the rainfall patterns. But it receives higher rainfall than DL14. The soil moisture values are relatively low. This is certainly due to the higher slope and the high infiltration rate of the soil (River Valleys Development Board, 1968). Because it is a typical forested uphill area, soil moisture is not dependent on the monthly variations of potential evapotranspiration ($q \pm 0.05$ cm^3/cm^3), besides receiving regular rainfall except for September and October. In this later case of high precipitation and low soil moisture, it is shown that forested areas do not act as a soil moisture buffer. This contradicts the general belief about the environmental necessity of forested areas in water-harvesting upper catchments. This is believed to add significant information about erosion control in the forested area and mitigation of the sediment flow into the main hydrological network eventually reaching the main reservoir of the Uda Walawe basin as reviewed in Finlayson, 1998.

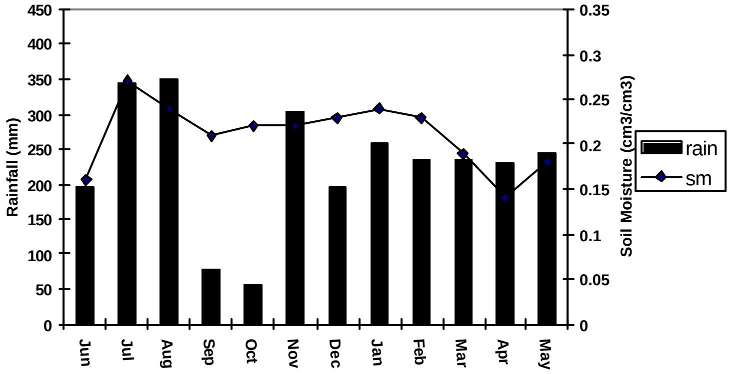

Figure 4. Monthly Variation of Soil Moisture and Rainfall in Zone IM4.

4. CONCLUSIONS

Even if the two vegetation growth zones studied here belong to the medium-high class of biomass growth for Sri Lanka (DL14=21,391 kg/ha/year; IM4=23,139 kg/ha/year), they still behave very differently according to the topographical and climatic patterns. Soil moisture is found to add substantial information to the understanding of prevailing hydrological processes and environmental conditions. The characterization of zones having stable and non-stable soil moisture regimes over the year, is a critical parameter in modeling the hydrological cycle of water basins. As stated in Vidal et al., 2001, for European conditions, “The users involved in water quality management (the domestic water distribution companies) were interested with soil moisture maps at the scale of small to medium watershed area.” This information provides the means for identifying and assessing the importance of water contributive areas, as input for water quality models. Because the accuracy level would be as low as 50 percent, the spatial distribution of such information would dramatically improve the output of such water quality models, especially for small to medium water basins. This would close the issue of accuracy.

Further, as discussed by Muthuwatta et al., forthcoming, water basin management can deal with environmental priority by using vegetation growth zones as a reference because it shows a way to delineate river basins into different areas based on actual biological activities taking place on the ground. Supplementing these zones with soil moisture information would improve water resources assessment and land management in river basins. This information permits to grasp and compare root zone soil moisture with respect to the different vegetative behaviors within and between river basins (benchmarking activity of IWMI for various basins around the world). Further, integration of spatially and temporally distributed information on soil moisture with other agronomic parameters would tremendously help agricultural planning such as crop selection.

NOAA-AVHRR overpasses every river basin on a daily basis. Once it is automated, deriving this information is not time-consuming (after 2 days in the case of Sri Lanka). Therefore, AVHRR supplies almost real time information on water basins, which helps planners and managers in water and agriculture sectors to a great extent.

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