# Spatial Mapping of Actual Evapotranspiration and Soil Moisture in the Murrumbidgee Catchment: Examples from National Airborne Field Experimentation

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## EXTENDED ABSTRACT

Spatial knowledge of land surface evapotranspiration and root zone soil moisture is of prime interest for environmental applications, such as optimizing irrigation water use, irrigation system performance, crop water deficit, drought mitigation strategies and accurate initialisation of climate prediction models especially in arid and semiarid catchments where water shortage is a critical problem. The recent drought in Australia and concerns about climate change has highlighted the need to manage water resources more sustainably especially in the Murrumbidgee catchment which utilizes bulk water for food production.

This study focused on estimation of daily actual evapotranspiration and soil moisture in Yanco area including Coleambally Irrigation Area (CIA) area and Kyeamba creek, using the SEBAL model applied to a remote sensing TERRA/MODIS, NOAA AVHRR 18 and Landsat 5 TM sensor during different satellite over pass days in National Airborne Field Experimentation (NAFE) campaign, lasted over 3 weeks (October 30 to November 21, 2006). All ground truth data for calibration of model was collected during the field campaign. Instruments like a thermal imager and a tri-spectral scanner was flown onboard a small environmental research aircraft at different altitudes together with coincident ground data collection on soil moisture, surface roughness, skin and soil temperature, and vegetation water content.

Results showed that actual ET estimated from NOAA AVHRR 18 was always overestimating (range from 11.5% to 59.3%) as comparison to Eddy system (on average 37%) during the image acquisition dates. However, for the same image acquisition dates, TERRA/MODIS ET ranges from 9.8% lower to 14.3% higher than the Eddy system. Landsat 5 TM modeled ET results were comparable to the Eddy Covariance system having a minor error of -1.21%. Similarly, root zone soil moisture modeled results showed that soil moisture ranges from 0.3-0.7 degree of saturation for Yanco area and 0.3-0.5 degree of saturation for Kyeamba creek on November 14. The effect of rainfall on Nov. 12 was captured in soil moisture results because most of the pixels showing high degree of saturation.

It was proven possible to simultaneously use SEBAL for different sensors with the combination of high spatial and temporal resolution to estimate ET spatial distribution characteristics; though the accuracy of NOAA-AVHRR derived result is not ideal. The Landsat ET results in this study match very well with the Eddy system. Considering the lack of high spatial resolution thermal satellite and need of time-series ET dynamics, the MODIS data could be used to provide seasonal actual ET for regional studies. The combination of MODIS and Landsat can be a better choice for future ET study at regional or catchment scale, but further study need to be conducted to integrate to provide both high spatial and temporal ET.

Estimation of actual ET and soil moisture from TERRA MODIS in combination with Landsat imagery indicated relatively good accuracy and potential for use in the water balance and water productivity analysis at the catchment level. In future, the ET will be modeled from high resolution airborne data acquired during NAFE campaign over Yanco area and Kyeamba creek and the results will be compared with the optical satellite imagery results to find out uncertainty in up-down scaling modeling for ET estimation.

# 1. INTRODUCTION

Modelling, mapping and monitoring, of actual evapotranspiration (ET) and soil moisture from farm to catchment scale is vital knowledge for water resources management. ET and soil moisture information could be used in optimizing irrigation water use, irrigation system performance, crop water deficit, drought mitigation strategies and accurate initialisation of climate prediction models especially in arid and semiarid catchments where water shortage is a critical problem. ET and soil moisture are multifaceted functions that depends upon soil properties, climatic conditions, land use, vegetation, and topography which cause these parameters to vary in both space and time. Therefore, it is difficult to estimate or representatively measure these parameters at the regional scale (Parlange et al., 1995).

Traditionally, ET has been estimated by multiplying a weather-based reference ET by crop coefficients ($K_c$), determined according to the crop type and the crop growth stage (Allen et al. 1998). However, surface resistance can vary according to the day, the weather conditions, especially available radiation and vapor pressure deficit (Ortega et al., 2004). The determination of crop coefficients is also debatable due to many factors, such as, whether crops grown compare with the conditions represented by the $K_c$ values, especially in water short areas (Neale et al., 2005). Similarly, measurement approaches for soil moisture content ranges from ground based soil moisture profile measurement to remote sensing based modelling; and land surface models (Walker et al., 2006).

Satellite remote sensing is a powerful means to estimate Actual Evapotranspiration ($ET_a$) and soil moisture measurement over various temporal and spatial scales, which ranges from individual pixels to an entire raster image that may cover a whole river basin. These techniques have become increasing popular since 1990 due to the relatively reported low cost of data collection, $0.03/ha for irrigated lands. Different methods have been developed to estimate evapotranspiration and soil moisture by combining satellite images and ground meteorological data for large areas, from empirical approaches such as the simplified relationship to complex methods based on remote sensing data assimilation along with SVAT models (Dominique et al., 2005). The complexity of these methods depends on the balance between the empirical and physically based modules to solve the energy budget from image overpass time to daily and upto monthly.

The recent drought in Australia and concerns about climate change has highlighted the need to manage water resources more sustainably especially in the Murrumbidgee catchment which utilizes bulk water for food production. It further reinforces the need to accurately measure actual ET and soil moisture in a spatio-temproal format which can be used for sustainable management of limited available water. In 2006, University of Melbourne with several international institutes conducted intensive National Airborne Field Experimentation (NAFE; see http://www.nafe.unimelb.edu.au) campaign, lasted over 3 weeks (October 30 to November 21, 2006) in the Murrumbidgee catchment. Airborne observations was made with a small environmental aircraft equipped with passive microwave, infrared and visible sensors to map the study area, which was supported by ground data collected during the NAFE campaign. The aim of the NAFE campaign is to provide high resolution data for process level understanding of soil moisture retrieval, scaling and data assimilation. While the data collected during NAFE campaign are applicable to a wide range of potential hydrological modelling. However, this paper deals with the modelling of evapotranspiration and soil moisture.

In this study, Surface energy balance algorithm for land (SEBAL) was applied for an estimation of actual evapotranspiration and soil moisture over two key study areas i.e. the 3600 km$^2$ Yanco area including Coleambally Irrigation Area (CIA) and the 600 km$^2$ Kyeamba catchment in the Murrumibdgee Catchment. SEBAL is an intermediate approach using both empirical relationships and physical parameterizations which was developed in Spain (Bastiaanssen 1995). SEBAL is a thermodynamically based model, which partitions sensible heat flux and latent heat of vaporization flux. Semi-empirical relationships are used to estimate emissivity, roughness length from *NDVI*. Water consumption of large irrigation systems has been addressed also with NOAA-AVHRR in Pakistan. Combinations of Landsat 7 ETM+ and NOAA are found in Chemin and Alexandridis (2001). Later on, Hafeez (2003) applied SEBAL for the estimation of seasonal actual evapotranspiration using ASTER, MODIS and Landsat sensors in UPRIIS, Philippines.

The primary aim of this study is to calculate the daily actual evapotranspiration and soil moisture in Yanco area including CIA area and Kyeamba creek, using the SEBAL model applied to a remote sensing TERRA/MODIS, NOAA-AVHRR 18 and Landsat 5 TM sensor during different satellite over pass days in NAFE campaign. The second objective is to compare modelled actual ET from remote sensing and Eddy Covariance System installed in Kyeamba creek.

## 2. The Study Regions

The 84,000 km² Murrumbidgee catchment, located in central New South Wales (NSW), ranges from semi-arid to alpine and covers a range of soil and vegetation types typical of much of Australia. NAFE campaign was carried out in two well instrumented sites i.e. the 3600 km² Yanco area including Coleambally Irrigation Area (CIA) and the 600 km² Kyeamba catchment in the Murrumibdgee Catchment as shown in Figure 1. The Lower Murrumbidgee Catchment has a 948 km reach and it starts downstream of Burrinjuck Dam, north of Wagga Wagga and finishes at the confluence with the Lachlan River at Redbank Weir, near Balranald in South-Western NSW. Its annual rainfall varies from more than 1500 mm in the high country to less than 400 mm on the western plains. The annual evaporation averages about 1000 mm to 1800 mm. Landuse in the catchment is predominantly agricultural with exception of steeper parts of the catchment with native forests.
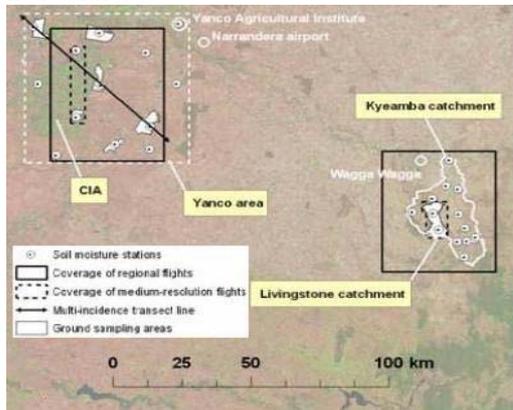


**Figure 1**: Location of NAFE study area (picture taken from NAFE website)

## Yanco Area

The Yanco area is a 60 × 60 km area located in the broad western plains of the Murrumbidgee where the topography is flat with very few geological outcroppings (Walker et al., 2006). Approximately, one third of area is irrigated area under the Coleambally Irrigation Area (CIA), while rest of the area is either dryland cropping (typically wheat and fallow) or grazing (perennial pasture vegetation). During the 1960's 333 farms were allocated 79,000 ha of land and irrigation began in the CIA with irrigation water diverted from Gogeldrie Weir 25 km east of Darlington Point. The total average rainfall in the CIA lies between 400–450 mm/year. The shallow watertables fluctuates every year due to changes in climatic conditions and land management practices within the CIA. There are also a number of piezometers wells, climate and streamflow recording stations installed in CIA. In addition, there are around 13 soil moisture monitoring sites

in the Yanco area are located in a grid-based pattern (Figure 1).

**Kyeamba Creek**

The Kyeamba creek catchment covers an area of 600 km² to the south east of Wagga Wagga in central NSW and major drainage features are Kyeamba and Livingstone Creeks. Long term average annual rainfall is around 650 mm, with a gradient decreasing from the highlands in the south to the confluence with the Murrumbidgee in the north. Land use is dominated by cattle grazing, limited sheep grazing, some irrigation of crops and vegetables in the higher country (Walker et al., 2006). More than 14 sites have been used for monitoring of soil moisture in the catchment. In addition, University of Melbourne has also installed a 3D Eddy correlation flux tower for monitoring of actual evapotranspiration over the pasture area in the catchment.

# 3    MATERIALS AND METHODS

## 3.1    Satellite Data

This study deals with four TERRA/MODIS, four NOAA-AVHRR 18 and 1 Landsat 5 TM images, covering the both study sites, acquired on different overpass dates (see details in Table 1) to estimate an actual evapotranspiration and soil moisture during NAFE campaign in 2006.

Table 1: Optical satellite images used in this study

| Sensors | Image Acquisition Dates |
|---|---|
| TERRA/MODIS | November 5, 2006 |
| | November 7, 2006 |
| | November 14, 2006 |
| | November 19, 2006 |
| NOAA AVHRR 18 | November 5, 2006 |
| | November 7, 2006 |
| | November 17, 2006 |
| | November 19, 2006 |
| Landsat 5 TM | November 23, 2006 |

TERRA/MODIS view the entire earth surface every 1 to 2 days, acquiring data in 36 spectral bands (different wavelengths of electromagnetic radiation) with 250 to 1000 m spatial resolution. NOAA AVHRR imagery, having a spatial resolution (1.1 × 1.1 Km), is one of the most stable sources of information available publicly from Internet. Landsat 5 TM image is a high spatial resolution (120 m) satellite, which is most widely used for environmental monitoring worldwide.

## 3.2    *Specificity of Porting SEBAL*

The pre-processing parameters required for SEBAL include the Normalized Difference Vegetation Index (NDVI), surface emissivity,

broadband surface albedo, leaf area index and surface temperature. MODIS Level 3 product was downloaded from NASA website including so called Quality Assessment Science Data Sets (QA-SDS). The software application "Time Series Generator" TiSeG was used to exclude invalid data by analyzing the MODIS QA-SDS. Similarly, NOAA AVHRR 18 image was downloaded from NASA website and radiometric and geometric corrections was applied in ERDAS imagine. All pre-processing parameters were estimated using standard NOAA relationship (see more detail in Hafeez and Khan, 2006). Landsat 5 TM image was orthorectified for the study area. All pre-processing parameters were estimated using empirical relationship mentioned in Hafeez 2003. The subset of image covering Yanco Area and Kyeamba creek was created for the modelling purpose. All ground truth data for calibration of SEBAL model was collected during the field campaign.

## 3.3 Running SEBAL

Calculation of the net incoming radiation and the soil heat flux were done after Bastiaanssen (1995), while the later development of Tasumi et al. (2000) were incorporated to determine the sensible heat flux. However, to calculate the first temperature difference between air and soil for the "hot" pixel (i.e., where the latent heat flux is assumed null), a first estimation of the air density was required. This was achieved by generalizing meteorological data of relative humidity and maximum air temperature from meteorological station at the time of satellite overpass. Iterations of sensible heat flux were conducted five times. Operational observation showed that this method does not stabilize the air-soil temperature

difference as fast as the earlier method found in Bastiaanssen (1995). In SEBAL, manual sampling of hot pixel values of the previous iterations output image files are required before the next iteration can be done which is a practical constraint in the operationalization of this technique. This constraint can be resolved by automation (after hot pixel identification) in the data collection of the results. The sensible heat flux can be improved by repeating the iteration 10 times, but this process is time and space consuming. The daily ET is calculated in SEBAL (Hafeez, 2003) from the instantaneous evaporative fraction, $\Lambda$, and the daily averaged net radiation, $R_{n24}$. More detail can be found in (Hafeez and Khan, 2006).

Soil moisture conditions in the root zone were estimated from the evaporative fraction using the empirical relationship developed by Ahmad and Bastiaanssen (2003).
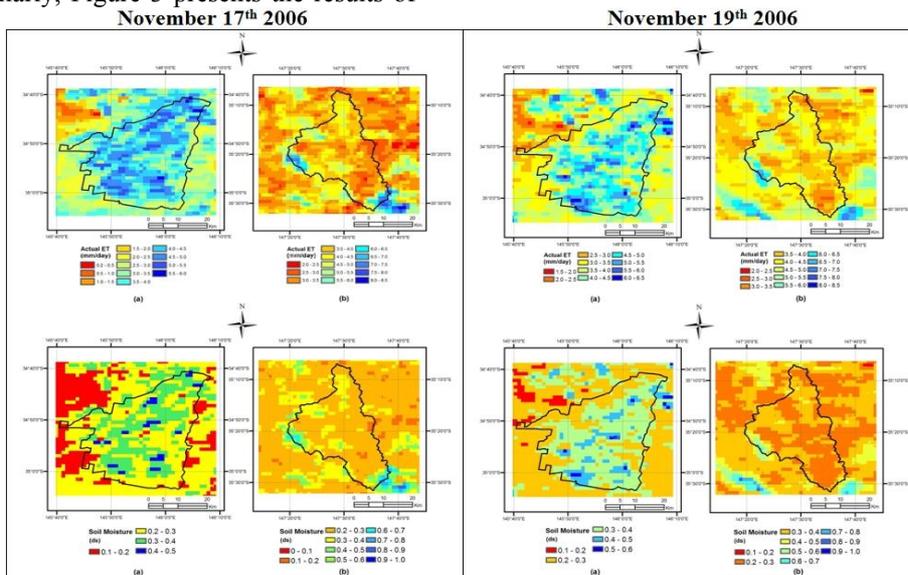
## 4 Results and Discussion

Figure 2 shows the maps of actual ET and root zone soil moisture (degree of saturation) using NOAA AVHRR 18 for (a) Yanco area and (b) Kyeamba creek on November 5th and November 7th, 2006. For Yanco area, the actual ET ranges from 0.6-5.9 mm/day (mean 3.01 mm/day) on November 5th and 0.2-8.1 mm/day (mean 2.379) on November 7th, 2006. There was a rain of 6.4 mm on November 6th in Yanco area which has effect on ET, clearly shown in the image (gradual decrease of many light blue colour pixels on Nov. 5th to few light blue colour pixels on Nov. 7th) The root zone soil moisture is low for both days with majority of area having 0.2-0.4 degree of
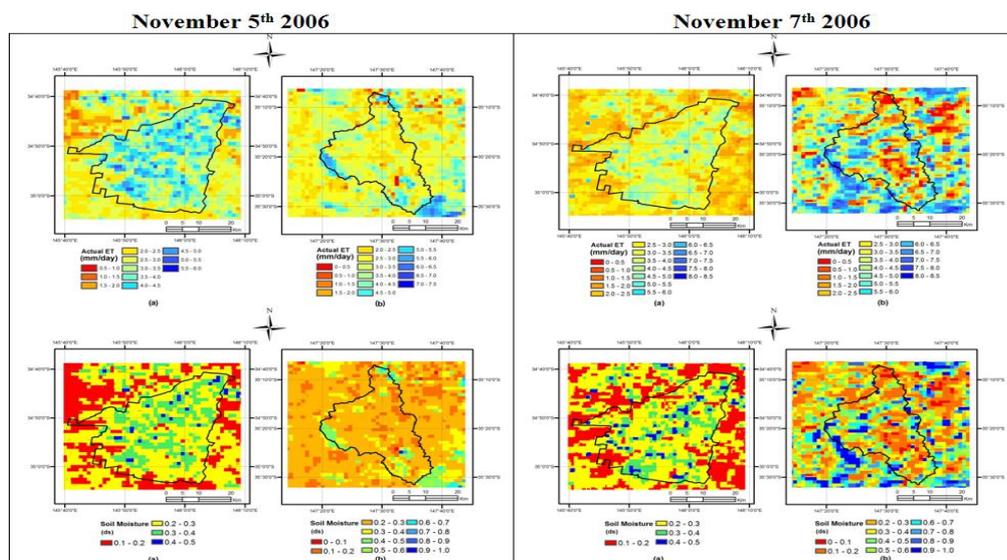


**Figure 2:** Actual evapotranspiration and soil moisture for; (a)Yanco area including CIA; and (b) Kyeamba Creek using NOAA-AVHRR 18 During NAFE Campaign.

saturation over Yanco area (pixels flooded with water for rice production has 0.4-0.5). Similarly, ET ranges from 0.2-7.2 mm/day (mean 3.10 mm/day) on November 5th, 2006 and 0.2-8.0 mm/day (mean 4.0 mm/day) on November 7th, 2006 for Kyeamba creek. There was a rain (2 mm) on November 6th over the study area which resulted in high ET and soil moisture, shown for November 7th map over Kyeamba creek. For Kyeamba creek, the root zone soil moisture is very low on Nov. 5th with the majority of area having 0.1-0.3 degree of saturation. However, the soil moisture was bit higher on Nov. 7th for few pixels. Similarly, Figure 3 presents the results of

ET and soil moisture modelling in a spatio-temporal distributed format for (a) Yanco area and (b) Kyeamba creek from November 17th and November 19th, 2006. Actual ET ranges from 0.4-5.8 mm/day on November 17th and 1.8-6.4 mm/day on November 19th, 2006 over yanco area. There was rain on November 12th and 16th over Yanco area which is clearly shown in image of Nov. 17 with lot of pixels having higher values to Nov. 19th with decreasing ET values over majority of pixels. Majority of Kyeamba creek area have very low ET values and soil moisture showing the dry conditions in the area.

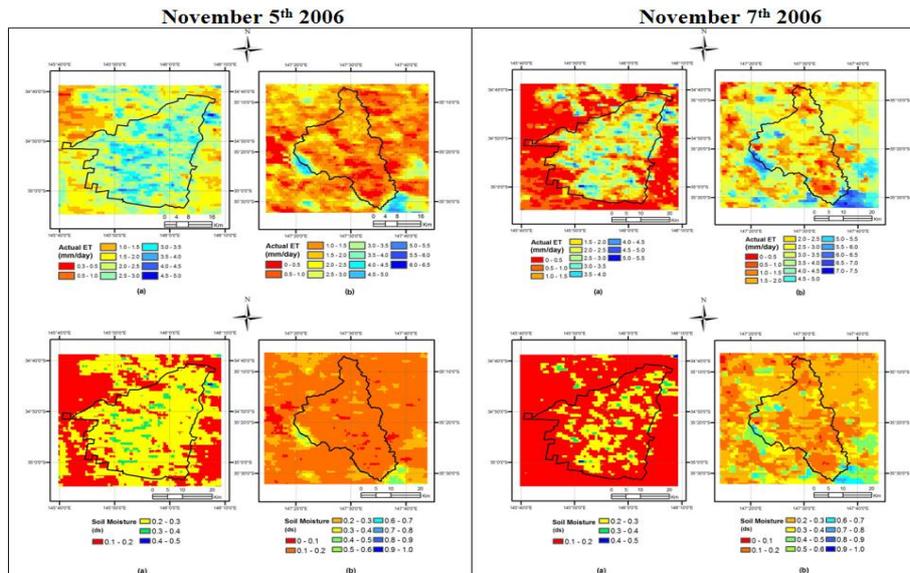**November 17th 2006**          **November 19th 2006**



**Figure 3:** Actual evapotranspiration and soil moisture for; (a)Yanco area including CIA; and (b) Kyeamba Creek using NOAA-AVHRR 18 During NAFE Campaign.

Figure 4 shows the maps of actual ET and root zone soil moisture (degree of saturation) using TERRA MODIS for (a) Yanco area and (b) Kyeamba creek on November 5th and November 7th, 2006. For Yanco area, the actual ET ranges from 0.3-4.9 mm/day (mean 2.3 mm/day) on November 5th and 0.2-5.3 mm/day (mean 1.2) on November 7th, 2006. There was a rain of 6.4 mm on November 6th in Yanco area which has effect on ET, clearly shown in the image (gradual decrease of many light blue colour pixels on Nov. 5th to few light blue colour pixels showing dry conditions on Nov. 7th). The root zone soil moisture is low with majority of area having 0.2-0.4 degree of saturation on Nov. 5th, and 0.1-0.3 on Nov. 7th over Yanco area. For Kyeamba creek, the ET ranges from 0.1-6.4 mm/day (mean 1.4 mm/day) and soil moisture is very low 0.0-0.1, showing the dry condition on Nov. 5th. Similar trend was observed for November 7th, 2006.
Figure 5 presents the results of actual ET and soil moisture using TERRA MODIS on November 14th and November 19, 2006 for the study areas.

There was heavy rain on Nov. 12th in Yanco area and Kyeamba creek which is clearly shown on the modelling results of actual ET (most of pixels having higher ET values) and soil moisture (ranges from 0.3-0.7 degree of saturation for Yanco area and 0.3-0.5 for Kyeamba creek) on November 14. After that there was a light rain on November 16th in both study areas which is again captured in ET and soil moisture results of November 19th showing few pixels still have high water contents.

The modelling results of actual ET and root zone soil moisture for both study areas using high spatial resolution of Landsat 5 TM (120 m) image on November 23rd, 2006 is shown in Figure 6. Spatial variation of ET at farm scale is easily captured from Landsat where ET results varies from 0.5-9.8 mm/day (mean 2.69 mm/day) over Yanco area and 1.0-9.2 mm/day (mean 3.6 mm/day) over Kyeamba creek. Similarly, the root zone soil moisture varies 0.3-0.7 degree of saturation over Yanco area and 0.3-0.5 over Kyeamba creek.

**Figure 4**: Actual evapotranspiration and soil moisture for; (a)Yanco area including CIA; and (b) Kyeamba Creek using TERRA MODIS During NAFE Campaign.
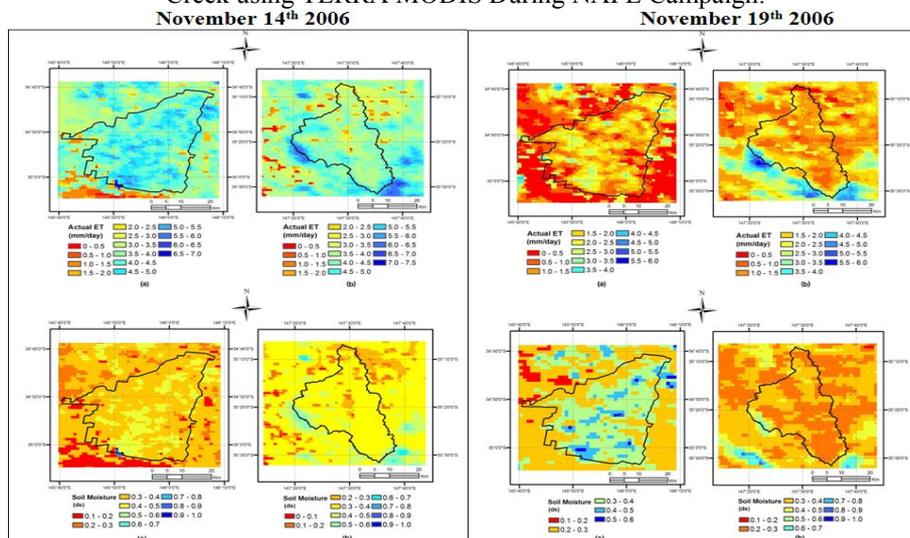


**Figure 5**: Actual evapotranspiration and soil moisture for; (a)Yanco area including CIA; and (b) Kyeamba Creek using TERRA MODIS During NAFE Campaign.
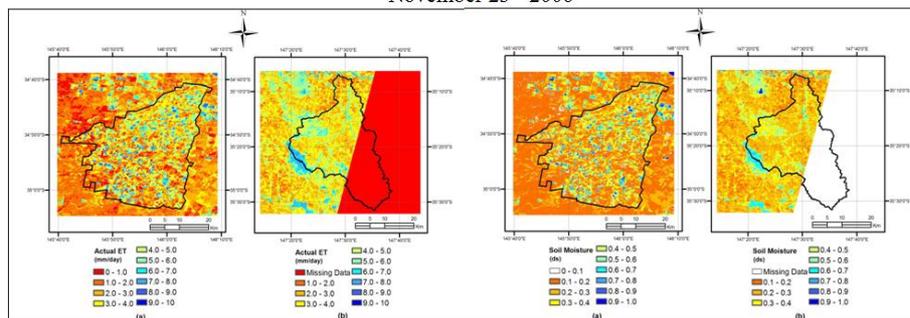


**Figure 6:** Actual evapotranspiration and soil moisture for; (a)Yanco area including CIA; and (b) Kyeamba Creek using Landsat 5 TM During NAFE Campaign.

As shown in Figure 7, NOAA-AVHRR overestimated the actual ET from Eddy Covariane system to about 36.83% on Nov. 5th, where as for the same day TERRA/MODIS modelled actual ET was matching very well (10% lower) to Eddy system ET. Overall, $ET_a$ estimated from NOAA was always overestimating (range from 11.45% to 59.25%) as comparison to Eddy system (on average 37%) during the image acquisition dates. The major reason of high deviation was the
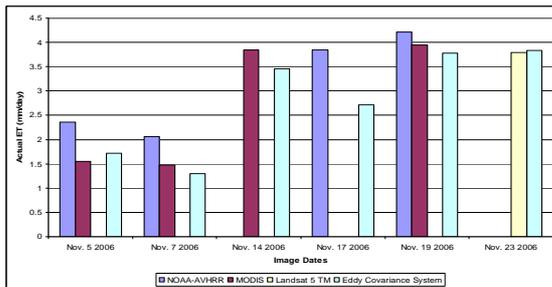
**Figure 7:** Comparison of actual ET over Kyeamba creek.

NOAA-AVHRR bands have much wider spectrum wavelength, spectral mix signatures of roads, agriculture fields and settlements and also due to the off-nadir occurrence of the study region which introduced some BRDF related errors in results. However, for the same image acquisition dates, TERRA/MODIS ET ranges from 9.81% lower to 14.25% higher than the Eddy system. As for Landsat 5 TM, the results were comparable to the Eddy Covariance system having a minor error of -1.21%. This result consisted with the modelling results of Hafeez (2003) in Philippines. It was proven possible to simultaneously use SEBAL for different sensors with the combination of high spatial and temporal resolution to estimate ET spatial distribution characteristics; though the accuracy of NOAA-AVHRR derived result is not ideal. The Landsat ET results in this study match very well with the Eddy system. Considering the lack of high spatial resolution thermal satellite and need of time-series ET dynamics, the MODIS data could be used to provide seasonal actual ET for regional studies. The combination of MODIS and Landsat can be a better choice for future ET study at regional or catchment scale, but further study need to be conducted to integrate to provide both high spatial and temporal ET.

## 5    CONCLUSIONS

This study focused on estimation of daily actual evapotranspiration and soil moisture in Yanco area including CIA area and Kyeamba creek, using the SEBAL model applied to a remote sensing TERRA/MODIS, NOAA AVHRR 18 and Landsat 5 TM sensor during different satellite over pass days in NAFE campaign. All ground truth data for calibration of model was collected during the field campaign. Results showed that $ET_a$ estimated from NOAA AVHRR 18 was always overestimating (range from 11.45% to 59.25%) as comparison to Eddy system (on average 37%) during the image acquisition dates. However, for the same image acquisition dates, TERRA/MODIS ET ranges from 9.81% lower to 14.25% higher than the Eddy system. Landsat 5 TM modeled ET results were comparable to the

Eddy Covariance system having a minor error of -1.21%. Similarly, root zone soil moisture modeled results showed that soil moisture ranges from 0.3-0.7 degree of saturation for Yanco area and 0.3-0.5 degree of saturation for Kyeamba creek on November 14. The effect of rainfall on Nov. 12 was captured in soil moisture results because most of the pixels showing high degree of saturation.

Estimation of actual ET and soil moisture from TERRA MODIS in combination with Landsat imagery indicated relatively good accuracy and potential for use in the water balance and water productivity analysis at the catchment level. In future, the ET will be modeled from high resolution airborne data acquired during NAFE campaign over Yanco area and Kyeamba creek and the results will be compared with the optical satellite imagery results to find out uncertainty in up-down scaling modeling for ET estimation.

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