Rice Based Irrigated Agriculture Using GIS

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Abstract

A basic understanding of rice physiology is essential to the success of remote sensing applications in rice-based agricultural systems. This knowledge can play a critical role in the planning stages of a remote sensing project (e.g., identifying optimum acquisition dates for the purchase of imagery) as well as in the final stages of analysis .The growing cycle of rice can be separated into two stages with respect to most analyses of remotely sensed data: vegetative and reproductive The vegetative stage includes the part of the growth cycle where the plant develops and grows, starting after sowing and ending when the plants start to reproduce. This stage is characterized by a steady increase in plant height and biomass. The reproductive stage starts when the plant stops growing taller and ends after maturity and includes panicle and grain development. It may be beneficial at times to further split the reproductive stage into two categories: reproductive pre-heading and reproductive post heading. Reproductive pre-heading defines the period from panicle primordial initiation to heading and post-heading refers to the period from heading to maturity.

Kwywords: Rice, Agriculture, Remote sensing, GIS

1.INTRODUCTION

1.1 General

The ‘Green Revolution’ in rice farming of the late 1960’s denotes the beginning of the extensive breeding programs that have led to the many improved rice varieties that are now planted on more than 60% of the world’s riceland (Khush, 1987). This revolution led to increases in yield potential of 2 to 3 times that of traditional varieties (Khush, 1987). Similar trends have also been seen in the Irrigation Areas and Districts of southern New South Wales (NSW) as the local breeding program has produced many improved varieties of rice adapted to local growing conditions since the 1960’s (Brennan et al., 1994). Increases in area of rice planted, rice quality, and paddy yield resulted (Brennan et al., 1994).

Increased rice area, however, has led to the development of high water tables and risk of large tracts of land becoming salt-affected in southern NSW (Humphreys et al., 1994b). These concerns have led to various environmental regulations on rice in the region, culminating in 1994 when restrictions on rice area, soil suitability, and water consumption were fully enacted (Humphreys et al., 1994b). Strict environmental restrictions in combination with large areas of land make the management of this region a difficult task. Land managers require, among other things, a way of regulating water use, assessing or predicting crop area and productivity, and making management decisions in support of environmentally and economically sustainable agriculture. In the search for more time and cost effective methods for attaining these goals, while monitoring complex management situations, many have turned to remote sensing and Geographic Information System (GIS) technologies for assistance.

The spectral information and spatial density of remote sensing data lends itself well to the measurement of large areas. Since the launch of LANDSAT-1 in 1972, this technology has been used extensively in agricultural systems for crop identification and area estimation, crop yield estimation and prediction, and crop damage assessment. The incorporation of remote sensing and GIS can also help integrate management practices and develop effective management plans. However, in order to take advantage of these tools, users must have an understanding of both what remote sensing is and what sensors are now available, and how the technology is being used in applied agricultural research. Accordingly, a description of both follows: first a description of the technology, and then how it is currently being applied. The applications of remote sensing relevant to this discussion can be separated into crop type identification; crop area measurement; crop yield; crop damage; water use/ moisture availability (m_a) mapping; and water use efficiency monitoring/mapping. This study focuses on satellite remote sensing for broad-scale rice-based irrigation agricultural applications. It also discusses related regional GIS analyses that may or may not include remote sensing data, and briefly addresses other sources of finer-scale remote sensing and geospatial data as they relate to agriculture. Since a complete review of the remote sensing research was not provided in the rice literature alone, some generic agricultural issues have been learned from applications not specifically dealing with rice. Remote sensing specialists may wish to skip section 2.

1.2 Background Of Remote Sensing

Remote sensing is the acquisition of digital data in the reflective, thermal or microwave portions of the electromagnetic spectrum (EMS). Measurements of the EMS are made either from satellite, aircraft or ground-based systems, but it is characteristically at a distance (or "remote") from the target. Due to the large spatial extent of the areas considered for the CRC for Sustainable Rice Production Project 1.1.05, this report will focus on data gathered from satellite remote sensing systems.Remotely sensed images are recorded digitally by sensors on board the satellites. An example of a satellite operation is shown in Figure 1. The satellites vary in height above the Earth's surface from approximately 700 km, which orbit the earth, to some 36 000 km, which are geostationary above the equator. The images can be manipulated by computers to highlight features of soils, vegetation and clouds. Each pixel, or picture element, contributing to the image is a measurement of a particular wavelength of electromagnetic radiation at a particular spatial scale for a particular location at a specific time. The most common display of remotely sensed data is a single overpass, which non-remote sensing specialists may think of as a 'satellite photo'.

1.3 Data Collection And Gis Database Development

Many years of reliable climatic data records are required to estimate different parameters for a proper irrigation water management. The Department of Irrigation and Drainage (DID), Department of Agriculture (DOA), Department of Survey .The detailed configuration of the irrigation canals, irrigation head regulator, Constant Head Orifice (CHO) off take structures and specifications, stage and discharge data for the main canal were obtained from the Irrigation and Drainage Authority of the Scheme and also from the DID Headquarters, Malaysia. Database development is the crucial task to bring all the information obtained into a GIS database. All the data were properly registered and assembled in GIS platform.

1.4 Water Demand Estimation

Water demand estimation is the primary considerations for planning, design and evaluating of the irrigation scheduling of a scheme. In Malaysia, the recommended design presaturation and supplementary irrigation requirements for the rice irrigation systems are 2.31 l/s/ha (20 mm/day) and 1.16 l/s/ha (10 mm/day), respectively. The total water requirement for rice production is about 1000–1500 mm depending on characteristics of the schemes. A quantitative estimation of the major components of field water balance provides management decisions on how the scheme ought to be operated to ensure better distribution of irrigation water and the delivery performance.

1.5 Assessment Of The Irrigation Delivery Performance For Rice

Indicators and measures of irrigation water delivery performance are best when those can be used to evaluate the irrigation delivery performance and as management tool to keep track of the water delivery performance as the season progresses. In this regards, the RWS concept is appropriate and can be applied for paddy rice and upland rice or other crops. This discussion however is restricted mainly to paddy rice for characterizing the irrigation delivery performance using the RWS concept.

2. REMOTE SENSING

2.1 Reflective Remote Sensing

The reflective portion of the EMS ranges nominally from 0.4 to 3.75 micro meters (µm). Light of shorter wavelength than this is termed ultraviolet. The reflective portion of the EMS can be further subdivided into the visible 0.4 to 0.7 µm, near infrared (NIR) 0.7 to 1.1 µm, and mid infrared 1.1 to 3.75 µm. It is in the visible portion of the EMS that we sense with our remote sensing device (eyes) which allow us to see. Different surface reflective properties allow us to distinguish colour in the visible region of the EMS. Chlorophyll pigments that are present in leaves absorb red light. In the NIR portion, radiation is scattered by the internal spongy mesophyll leaf structure, which leads to higher values in the NIR channels. This interaction between leaves and the light that strikes them, often determined by their different responses in the red and NIR portions of reflective light, see Figure 4, is how vegetation is detected using remote sensing. The objective of vegetation analysis from spectral measurements, often, is to reduce the spectral data to a single number that is related to physical characteristics of vegetation (e.g. leaf area, biomass, productivity, photosynthetic activity, or percent cover) (Baret and Guyot, 1991, Perry and Lautenschlager, 1984 , Huete, 1988), while minimising the effect of internal (e.g. canopy geometry, and leaf and soil properties) and external factors (e.g. sun-target-sensor angles, and atmospheric conditions at the time of image acquisition) on the spectral data (Baret and Guyot, 1991, Chavez, 1988, Gong et al., 1992, Huete et al., 1985, Huete, 1987, Huete and Warrick, 1990, Huete and Escadafal, 1991, Kimes, 1983, Li et al., 1993, Richardson and Wiegland, 1977, Slater and Jackson, 1982, Singh, 1989).

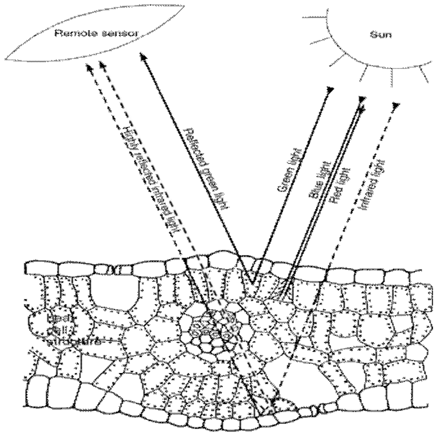

Figure 3. Schematic reflectance of a typical green leaf in cross section

Vegetation Indices (VI's) were developed in an attempt to obtain this objective from remote sensors by taking advantage of the differences in the reflective responses of vegetation in the red and NIR wavelengths. Although VI's are often hampered by limitations in dealing with the complex nature of real-life vegetation canopy interactions (Baret and Guyot, 1991, Huete et al., 1985, Huete, 1987, Huete and Jackson, 1987, Huete, 1988, Huete and Warrick, 1990, Huete and Escadafal, 1991, Huete et al., 1992, Qi et al., 1993), they have gained widespread popularity due to the benefits of remote sensing's high spatial density and extent, and the value added to generic, rather coarse-scale vegetation modelling.

Primarily, the reflective portion of the EMS has been used for:

1. identification of rice;
2. area estimation of rice;
3. estimation and prediction of crop yield; and
4. crop damage assessment

These are discussed more fully in section 3.1, 3.2, 3.3 and 3.4, respectively.

2.2 Microwave Remote Sensing

The microwave portion of the EMS ranges nominally from 0.75 to 100 centimetres. Radio signals have wavelengths that are included in these bands. These systems can either be active (the sensor sends its own signal) or passive (the background signal from the Earth's surface is observed). There are five smaller sections of this range which are used for remote sensing. These are :

P band	100 - 30 cm;
L band	30 - 15 cm;
S band	15 - 7.5 cm;
C band	7.5 - 3.75 cm; and
X band	3.75 - 2.4 cm.

RADAR (RAdio Detection And Ranging), is an active system based upon sending a pulse of microwave energy and then recording the strength, and sometimes polarisation, of the return pulses. The way the signal is returned provides information to determine characteristics of the landscape. RADAR has been used in the determination of near surface soil moisture, and the identification of rice crops based on the presence of standing water.

2.3 Thermal Remote Sensing

The thermal portion of the EMS ranges nominally from 3.75 to 12.5 micro meters. The radiant energy observed by sensors is emitted by the surface, be it land, ocean or cloud top, and is a function of surface temperature. Models have been developed to allow surface temperature to be extracted from thermal remote sensing. Prata et al. (1995) review the algorithms and issues involved in the calculation of land surface temperatures, denoted T_s.Thermal remote sensing is an instantaneous observation of the status of the surface energy balance (SEB). The SEB is driven by the net radiation at the surface. During the daytime this is usually dominated by incoming shortwave radiation from the sun, the amount reflected depending on the albedo of the surface. There are also up and down welling longwave components. At the ground surface, the net allwave radiation is balanced between the sensible, latent and ground heat fluxes. Over long periods of time the ground heat flux averages out, and the SEB represents the balance with the sensible and latent heat fluxes. During the day the measured surface temperature at the Earth's surface is, in part, dependent on the relative magnitude of the sensible and latent heat fluxes.

The thermal portion of the EMS has been used to determine:

1. surface temperature estimation (including water temperature); and
2. moisture availability (m_a) mapping.

2.4 Integrating Remote Sensing With Other Data Types In A Geographic Information System (GIS)

Remotely sensed data (visible, thermal, microwave), GIS data layers (soils, geology), point based measurements (rainfall, soil moisture, biomass) or model outputs (biomass, soil moisture) all have spatial and temporal attributes associated with the data attribute, and can be integrated. Economic situations and social indicators will have a time and may have a space associated with the data attribute and can also be integrated. The integration of several data types will allow factors such as crop types, yield estimates, and water use to be determined more objectively.

Many GIS data layers cover entire regions. However, these are often produced from the spatial interpolation of point samples; this is especially the case for some meteorological surfaces. Some physical parameters, such as soil water holding capacity, which are assumed to be time in-variant, only need to be mapped once. Remote sensing provides repeated measurements, at a particular spatial scale and electromagnetic wavelength, which allows dynamic environmental conditions, such as soil moisture and vegetation cover, to be monitored. Data of varying degrees of spatial and temporal density can be incorporated into a GIS. Spatial and temporal resolutions of the data will vary, depending on, among other things, the issues being addressed. See Langran (1992), Peuquet (1994), Peuquet (1995) and Mitasova et al. (1995), for detailed discussions of both the theoretical and the technical aspects of data integration arising from the inclusion of time in GIS.

3.REMOTE SENSING IN RICE BASED AGRICULTURE

A basic understanding of rice physiology is essential to the success of remote sensing applications in rice-based agricultural systems. This knowledge can play a critical role in the planning stages of a remote sensing project (e.g., identifying optimum acquisition dates for the purchase of imagery) as well as in the final stages of analysis (e.g., aiding in the delineation of rice paddies or the estimation of growth stages) (Ribbes and Toan, 1999, Le Toan et al., 1997). The growing cycle of rice can be separated into two stages with respect to most analyses of remotely sensed data: vegetative and reproductive (Casanova, 1998, Ribbes and Toan, 1999).

The vegetative stage includes the part of the growth cycle where the plant develops and grows, starting after sowing and ending when the plants start to reproduce. This stage is characterised by a steady increase in plant height and biomass. The reproductive stage starts when the plant stops growing taller and ends after maturity and includes panicle and grain development (Ribbes and Toan, 1999). It may be beneficial at times to further split the reproductive stage into two categories: reproductive pre-heading and reproductive postheading. Reproductive pre-heading defines the period from panicle primordia initiation to heading and post-heading refers to the period from heading to maturity (Casanova, 1998).

The length of the growth cycle of rice can vary from 3 to 6 months for different varieties (Casanova, 1998), and can also be categorised into two main groups for many remote sensing applications: tropical and temperate. Growth cycles for tropical rice varieties last about 110120 days, while those of temperate varieties usually last around 140-150 days (Le Toan et al., 1997) . However, this duration can vary based on cultivar. For example, short duration varieties have been bred with growth cycles less than 90 days (Senanayake et al., 1994). These differences in growth cycle length are due to differences in vegetative stage duration: the vegetative stage can be anywhere from 40 to 120 days in length (Senanayake et al., 1994).

Irrespective of cultivar, reproductive pre-heading duration is about 23-25 days, while reproductive post-heading duration lasts 30-35 days (Senanayake et al., 1994). During the reproductive stage, plant height and biomass typically remain stable at around 100 cm and 2000 gm^{-2}, respectively (Ribbes and Toan, 1999). The vertical characteristics of the rice plant also change as the plants grow, with stem inclination decreasing and the leaf angle increasing (Ribbes and Toan, 1999).

For different locations, the timing of the growth cycle of rice varies depending on local climate, management, and cultivar planted. Consequently, the timing of rice for a particular site of interest should be known. Australian rice varieties have changed over the past 40 years with Caloro dominating the 1960's, Calrose in the 1970's to mid 1980's and Amaroo from the mid 1980's into the 1990's (Brennan et al., 1994). This has been associated with development of long-grain, fragrant and Spanish varieties to meet higher priced markets (Brennan et al., 1994). Short duration varieties are generally desirable because they can be competitive with weeds, require less pesticides and herbicides, utilise less irrigation water, and allow for double cropping in tropical environments (Khush, 1987). In a temperate environment like southern NSW, short duration varieties are also desirable because they can allow more leeway for sowing and harvesting between the limitations of cold springs and autumns (Reinke et al., 1994). Timing of rice in southern NSW is summarised as:

1. placed under permanent flood and aerially sown in late September/early November;
2. canopies emerging during late October/late November;
3. flowering by late January/early February;
4. de-watered in late February/March; and
5. harvested in March/May.

Other summer crops in NSW include corn, sorghum, and soybeans, while winter crops include wheat, barely, oats, and canola. Pasture is grown in both seasons. Citrus, stone fruits, and grapes are also grown in the area. Some of these crops may use remnant soil moisture after a flooded rice crop, whereas others are furrow or drip irrigated. There is an interest in monitoring other crops than rice within the irrigation areas of southern NSW from remote sensing. Of these other crops, there is a good potential for remote monitoring of corn and soybeans. The spectral reflectance characteristics of corn and soybeans along the EMS are slightly different in shape and amplitude (Thenkabail et al., 2000) allowing for differentiation between these two crops (Badhwar et al., 1982). Multitemporal remote sensing data has been used to estimate soybean and corn crop characteristics such as yield, LAI, biomass, plant height (Thenkabail et al., 1994a, Thenkabail et al., 1994b), development stage (Badhwar and Henderson, 1985), and crop proportion (Badhwar, 1984b, Badhwar, 1984a). For single date imagery, however, the timing of image acquisition can greatly influence classification results since confusion between spectral signatures can occur due to differences in crop growth stages. That is, on the day of image acquisition, the two crops could look spectrally similar.

Moderately high correlations (from 0.7 to 0.85) have been reported between several soybean and corn crop characteristics when related to VI's. Soybean was correlated to standard NIR and red-based VI's , whereas corn crop characteristics were more highly correlated with VI's that include at least one MIR band (Thenkabail et al., 1994b, Thenkabail et al., 1994a). Mature soybean crops have higher reflectance in the NIR and lower reflectance in the red portions of the EMS than corn, resulting in detectably higher standard VI values for soybeans (Tucker et al., 1979). This means that three of the main summer crops (rice, corn, and soybeans) can potentially be discriminated from each other using remote sensing. However, to do this, more than one image throughout the growing season might be needed in order to take advantage of spectral differences due to the phenology of these crops. Remote sensing based applications, then, will not only take advantage of both the characteristics and timing of growth cycle, but will also consider the spectral reflectance of different crops. Since rice is the focus of this report, the basic spectral patterns of rice must be understood. The reflectance from rice, like all green vegetation, can be summarized by a generalised vegetation response as seen in Figure 3. It is the differences in this basic vegetation response that allow discrimination between vegetation types. However, these vegetative-type responses are harder to differentiate between each other than a non-vegetative-type response like soil or water. This is true since non vegetative-type features usually reveal drastically different response curves when compared to vegetation (Figure 3).

As irrigated rice fields are flooded, the spectral characteristics of water can be used to distinguish potential rice paddocks and provide an early estimate of rice area (Barrs and Prathapar, 1996, McCloy et al., 1987). Inaccuracies result, however, when this early estimate is not adjusted by a later image, which can aid in elimination of permanent water bodies and other irrigated crops from the classification (Barrs and Prathapar, 1996, McCloy et al., 1987). The visible and near infrared wavelength response of rice, once the vegetation starts to cover the water in flooded paddocks, is much the same as other crops (Martin and Heilman, 1986). However, rice was found to be more distinguishable from other crops due to its water absorption characteristics by including middle infrared (MIR) wavelengths in the crop discrimination(Martin and Heilman, 1986, Thenkabail et al., 1994b).

The applications of remote sensing relevant to this discussion can be separated into 6 main categories as determined by the bulk of the current rice-based remote sensing literature.

These are:

1. crop type identification;
2. crop area measurement;
3. crop yield;
4. crop damage;
5. water use/ moisture availability (m_a) mapping; and
6. water use efficiency.

3.1 Crop Type Identification

The most commonly practiced application in remote sensing of agriculture is mapping land cover to identify crop types. This process primarily uses the spectral information provided in the remotely sensed data to discriminate between perceived groupings of vegetative cover on the ground. The spatial (Atkinson and Lewis, 2000) and temporal information included in single date and time series data, respectively, usually play a secondary role, but can also aid in the classification procedure. Discrimination of crops is usually performed with 'supervised' or 'unsupervised' classifiers. The basic difference between these types of classification is the process by which the spectral characteristics of the different groupings are defined. Common clustering algorithms include maximum likelihood, minimum distance to mean, and parallel piped (Jensen, 1986).

3.2 Crop Area Measurement

Crop area measurement is a very common practice in agriculture. Remote sensing is often used for this purpose because of its strengths in regard to spatial extent, temporal density, relative low costs, and potential for rapid assessment of spatial features. Many of the same issues concerning crop type identification also affect crop area measurement from remotely sensed data. This is because crop type identification is a necessary first step to area estimation. In many cases, though, crop type identification is more concerned with classifying all crop types from each other, where area estimation often is concerned with only a few target crops. In either case, these two applications are frequently performed in sequence: first crop identification and then area estimation. There are a few issues that are not exclusively related, but tend to more specifically pertain to crop area estimation, including positional accuracy, mixed pixels and pixel size, and a mismatch between individual and overall accuracies of the results.

Positional accuracy, here, can be defined as the difference in the position of a feature on a map compared to the feature's real world or 'true' position. As such, the position of boundary lines on the map, for instance, are most likely not where they are in the real world, but are more accurately represented as a belt or swath around that boundary line on the map. This swath contains the 'true boundary line' and has a width that is inversely related to the scale of the source (Van Niel and McVicar, 2000)

3.3 Crop Yield

Crop yield forecasts can greatly influence farm-level management decisions, such as fertiliser applications and water delivery, as well as provide a means for farm income assessment. Consequently, individual farmers and district-level land managers show great interest in producing rapid and accurate estimates of crop yield, both locally and regionally. In the past, the standard yield estimation procedure included the analysis of crop cuttings at randomly sampled ground plots during harvest (Murthy et al., 1996), or meteorological regression models using rainfall and past yield data (Karimi and Siddique, 1992). These methods often produce results that are either not timely nor spatially explicit. Though still used, these methods are being replaced by estimation of crop yields using remote sensing because of its ability to produce results quickly and spatially. Using this technology, it was found that spatially meaningful estimates of yield can be made as early as 1 to 3 months prior to harvest (Quarmby et al., 1993b, Rasmussen, 1997), thus impacting management reaction time to yield forecasts.

3.4 Water Use And M_a Mapping

Knowing crop water use, both temporally and spatially, in irrigated areas allows water delivery to match agricultural demands. Crop water use can be determined either by crop specific empirical models or use of process based models. Both of these approaches require access to ground based meteorological data, usually with a daily time step. To perform either modelling approach over large irrigation areas will require access to a network of meteorological stations with a suitable spatial density and extent to characterise the spatial variation in observed meteorological variables. A commonly used method to estimate crop water use is application of the Food and Agriculture Organisation (FAO) Guidelines for prediction of crop water use (Smith et al., 1991 , Doorenbos and Pruitt, 1977, Frere and Popov, 1979). Class A Pan evaporation can be measured if such facilities exist and are properly maintained, or can be estimated from commonly observed meteorological data. The FAO method requires modification of crop coefficients; it does not require remotely sensed data. However, knowledge of different land uses are required to extend this approach spatially. Remote sensing is seen to be a timely and cost effective way to provide these maps to GIS models annually. A derivate of this method have been used by Kirk et al. (1999) to provide estimates of crop water use for farm-level irrigation water use efficiency for irrigation areas in South Australia. The location of paddocks was obtained from a GIS data base of paddock level cropping.

3.5 Water Use Efficiency

With population growth comes a decrease in living space (or global land area per capita) and thus, increased competition for land and water resources (Lund and Iremonger, 2000). These higher demands on water and land, among other things, result in a need for more efficient use of the resources. Assessing and improving Water Use Efficiency (WUE) in agricultural systems, then, will become exceedingly important as the demand for food production on these limited resources continues to increase. Water savings from these systems, in particular, could affect the regional and global water balances as the area of land placed under agriculture is expected to increase considerably in the near future (Lund and Iremonger, 2000). WUE of the irrigated agricultural lands of southern NSW has become increasingly relevant, as the Snowy Water Inquiry into the environmental issues associated with the corporatisation of the Snowy Mountains Hydro-electric Scheme was initiated in 1998. Ninety-nine percent of the runoff from the Snowy Mountains is diverted inland to generate hydroelectric power, and irrigation water for agriculture (Gale, 1999). The Scheme provides an average of 1200 Gl per year to the Murray River and 1210 Gl per year to the Murrumbidgee (Gale, 1999). This water is used in the production of approximately A$1.5 billion per year worth of irrigated agricultural products (Gale, 1999).

Single-leaf WUE is commonly defined as the net CO_2 uptake per unit of transpiration. On a continuous basis – that is, at any instant within a day – it is expressed as the ratio of leaf net photosynthetic rate to leaf transpiration rate, or at the daily time-step it is expressed as the ratio of daytime CO_2 uptake to daytime transpiration. Canopy (or community) WUE is commonly defined as the ratio of the net CO_2 assimilation of crop canopy to crop canopy transpiration – that is, the ratio of the canopy CO_2 flux to the H_2O flux for canopy transpiration. Canopy WUE can be expressed continuously and at a daily time-scale, as above, and can also be calculated for specific growth stages. Field WUE can be defined as the ratio of grain yield per unit of water, hence the units would be kg/ha.mm; however the ‘plant growth’ and ‘water’ terms need to be explicitly defined. Regional WUE has similar definitions to field WUE except it applies to a larger area.

There are three main approaches available to assessing WUE regionally:

1. Remote sensing, which can estimate both evapotranspiration and CO2 exchange of large areas at specific times of day, can be used to present regional WUE estimates at specific times (Schuepp et al., 1987). This requires access to much ancillary ground based meteorological data and presents difficulties in extending this from the field sites to regions. There are also difficulties in temporally extending the data from specific times to entire growing seasons;
2. Using remotely sensed based estimates of yield and of λ**E**. However, as has been discussed previously there is difficulty in estimating yield in irrigated

environments where LAI is high. Methods exist for providing daily λ**E** maps from specific time-of-day T_s observations, however, reliable estimates of λ**E** are difficult to obtain in highly advective irrigated agricultural environments. Taking isolated daily observations to estimate growing season λ**E** would again require access to ground based meteorological data; and

3. Regional databases of yield, precipitation, irrigation and initial soil water can be developed allowing an 'input-output' (Zoebl, 2000) definition of regional WUE (McVicar et al., 2000). 'Input' is the water available over the crop growing season and 'output' is the yield. This approach is well suited to spatial assessment of regional WUE. Coupling this approach with canopy and field-scale process understanding will allow identification of the regional data bases that are required to develop` a more process constrained regional WUE estimation.

For many of the variables that influence WUE, data are usually not regionally available, and hence they cannot be included in the development of regional WUE estimates. Factors varying both spatially and temporally include:

1. crop varieties, which includes plant breeding (Khush, 1987, Brennan et al., 1994, Brennan et al., 1997) and genetic modifications;
2. soil conditions (Christen and Skehan, 1999, So and Ringrose-Voase, 2000), including soil erosion, sodicity, salinisation, and waterlogging;
3. climate change (Loaiciga et al., 1996), including precipitation patterns and CO_2 concentration (Hunsaker et al., 2000);
4. agricultural practices, including the use of fertilisers (Anbumozhi et al., 1998), irrigation management (Pereira, 1999), crop rotation (So and Ringrose-Voase, 2000), planting density, and the use of mulch (Tolk et al., 1999) to reduce soil evaporation.

These interactions are complex, and largely unknown at the regional scale of southern NSW, making absolute measures of WUE difficult. The 'input-output' GIS definition of regional WUE, however, is most suited to the analysis of relative trends, both spatially and temporally. Such a GIS would rely on access to data recorded by irrigation companies and the Rice Grower's Cooperative, all who are industry participants in the CRC for sustainable rice production.

4. LIMITATIONS OF REMOTE SENSING IN RICE-BASED AGRICULTURE

Remote sensing is a valuable source of data in rice-based agriculture, especially when regional-scale issues are the concern. However, there are some limitations of remote sensing regarding agricultural applications including:

1. Data availability;
2. Length of recording period;
3. Limited mapping capability;
4. Requirement of expertise and computer facilities; and
5. Cost

A very brief discussion of these topics follows.

4.1 Data Availability

Non-availability of remotely sensed data may be due, among other things, to rocket launch, satellite operational problems or political issues. Events such as these will continue to occur and operational systems must pre-determine the influence of any data stream becoming nonavailable. Satellites have different repeat cycles (Table 1). This means that certain satellites will provide only 2 images per month, for example, whereas others can produce an image everyday. This can have considerable impact on agricultural applications since repeat cycle characteristics of satellites are one of the determinants for forecasting yield with the ∫NDVI approach, for example. Also, these high repeat cycle platforms usually have lower spatial resolution, impacting the appropriateness of its data to fine-scale applications. Another major cause of optical data unavailability is cloud coverage.
This could be problematic when timing of image acquisition is critical as in crop identification. This may be avoided by using either microwave or airborne remote sensing. However, processing of these data can be a problem due to the scientific expertise needed for analysis of microwave data and the data management associated with large area airborne acquisitions.

4.2 Length Of Recording Period

The period over which remotely sensed data are available has little impact on agricultural applications. Most agricultural research and management is interested in current or future concerns. However, for the few agricultural projects dealing with historical context, the recording period could be restricting. Remote sensing, unlike meteorological data, has not been recorded for a century. The longest time series currently available of free to ground remotely sensed data covering Australia at monthly time steps is AVHRR at 15 years. LANDSAT data has been recorded since 1972, but can be quite expensive when acquiring a long time series

4.3 Limited Mapping Capability

The limited capability of remote sensing to map certain agricultural variables has been discussed in detail in section 3. Specifically, remote sensing is limited to mapping single crops to slightly higher than 90% accuracy when multi-date, multi-sensor, or GIS data is also used. Remote sensing alone, however, is more limited at discrimination of multiple crops to this level of accuracy. Yield predictions are also limited from remotely sensed data because of the saturation problem discussed in section 3.3. Remote sensing is also often unable to detect direct sources of crop damage (section 3.4). These limitations may decrease in the future as spatial and spectral resolutions, and repeat cycles increase. However, the resolutions needed for this type of detection will probably not be available for some time. Finally, although remote sensing from satellites has high potential for providing spatially variable data needed for precision agriculture, the limitations of fixed spectral bands, too coarse spatial resolutions, inadequate repeat cycles, and long delivery times (Moran et al., 1997) make it non operational at this time.

4.4 Requirement Of Expertise And Computer Facilities

Agricultural research with remote sensing requires a moderate level of expertise and computing support. The processing of remotely sensed data requires an investment in training of personnel as well as adequate computers and data storage. Computer hardware and software are important, but perhaps more important is mindware to ensure the correct use of remote sensing to assist in the decision making process.

4.5 Cost

Cost of remote sensing projects can be prohibitive, especially when fine detail is needed over large areas. However, this depends on the application and the appropriate remote sensing platform. Much agricultural research has been accomplished with free NOAA AVHRR data. Yet, AVHRR data is not appropriate for many applications. With the launch of the TERRA satellite in 1999, came a new era in remote sensing: no cost moderate to fine resolution data. The spatial resolution of the ASTER and MODIS sensors is appropriate for many different agricultural applications. However, some remote sensing data is currently expensive for large areas of land (e.g., 1,000 km^2) , including very high spatial resolution data (e.g., IKONOS or airborne systems), and hyperspectral data. The cost estimates for specified common commercially available remotely sensed data is summarized in Table 2 by each irrigation area in southern NSW. These estimates are intended to give potential users of remotely sensed data a general idea of the costs involved, and by no means are meant as a precise cost. Values in this table are most useful when viewed in the relative context of prices by sensor and by irrigation area. Figure 5 provides the spatial context of the extent of two popular sensors ((E)TM and SPOT) for the study site.

5. WATER SAVING PRACTICES

5.1 Strategies For Water Saving

Water saving practices, which require greater water control is associated with improving agronomic practices and the use efficiency of other inputs. Available strategies include developing improved varieties, improving agronomic management, changing the crop planting date, reducing water use for land preparation, changing rice planting practices with wet or dry seeding, reducing water use during crop growth through intermittent flooding, maintaining the soil in sub-saturated condition, alternate drying and wetting, optimum use of rainfall, supplementary irrigation of rain-fed low-land rice, water distribution strategies, water reuse or recycling and conjunctive use and alternative methods to flooding for growing irrigated rice under aerobic conditions.

High rice yield are obtained with good on-farm water management. Many researchers reported that continuous submergence with 5 to 7 cm of water is probably best for irrigated rice considering all factors. Submergence allows better weed control, higher efficiency of fertilizer use, and better insect and weed control with granular chemicals. Research has shown no difference in yield of rice grown at saturated soil condition with minimum water use but weed control is expected to be more costly. Other researchers found optimum rice growth and production at 9 cm of ponded water depth. High values of water productivity were also found at this depth under different water regimes and fertigation levels. High water levels are required after transplanting for recovery and rooting stage and booting stage up to flowering stage. Low depths are required for tillering, panicle development and milk stage.

Higher yielding areas are associated with mid-range ECad, medium ECas, low Db, high clay and low sand. Low yielding areas are associated with low ECad, low ECas, high Db, medium clay, medium sand vigorous tillering. Mid-season drainage is important to cut-off the supply of ammonia-N to secure desirable plant characteristics, viz. short and erect upper 3 leaves, including flag leaf, and short lower inter-node to prevent lodging, to induce favourable ear (panicle) formation conditions, and to supply soils with oxygen to ensure healthy root growth. Mid-season drainage removes hydrogen sulphide and other harmful substances, which are produced by microbial action under reductive conditions of submergence. Water (5 cm) is needed at milk stage for translocation of nutrients stored in plant body to ear or panicle for healthy development of developing grain or spikelet.

5.2 Water-Efficient Irrigation Regimes To Increase Water Productivity

The shortage of water resources became an important problem and many
water efficient irrigation regimes for rice have been tested, advanced, applied

Based on the results of experiment and the experience of spread of these new irrigation regimes, the following conclusions were drawn by the author:

- Three essential water efficient irrigation regimes (WEI) for rice which include the regimes of combining shallow water depth with wetting and drying (SWD), alternate wetting and drying (AWD) and semi—dry cultivation (SDC), have

- been adopted in the different rice growing
- In comparison to the traditional irrigation regime (TRI), rice yield can be increased slightly, water consumption and irrigation water use of paddy field can be decreased greatly and the water productivity of paddy field can be increased remarkably underthe WEI.
- The main causes of decrease of water consumption and irrigation water use are the decrease of the percolation rate in paddy field and increase in the utilization of rainfall.
- A positive environmental impact is obtained by adopting WEI, the main cause of getting bumper yields were that the ecological environment under WEI is more favourable for the growth and development of rice than that under TRI.
- For avoiding the decrease of yield under WEI, some measures, as timely irrigation, coordinating irrigation with fertilization and weed control must be used since shortage of water resources.

5.3 Distribution Variability Of Effective Rainfall

With global warming and climate change, greater competition is expected among water users, and paddy irrigation may be sacrificed during water shortage in dry months favouring domestic and industrial users. However, rice granaries practicing multiple cropping have yet to improve on the use of "effective rainfall". Currently, the measurement of rain falling in a rice growing area is based solely on the available rain gauge network. These gauges are located at convenient locations which may not be representative of the whole rice growing area. Hence, under- or over-estimation of rainfall distribution and runoff occurs and consequently affects the management of floods during rainy seasons or base flow for irrigation during dry seasons. Therefore, better estimates of mean areal rainfall are needed as contribution of effective rainfall in the water balance during the irrigation season.

5.4 Dynamic Linkage Between Model And GIS

The GIS of the Patna canal system and the rice water balance model were dynamically linked for real time application in any season. This linkage allows:

(i) Selection of the distributary of interest on screen to identify the corresponding weather station and soil data files.
(ii) Running the rice field water balance model for each transplanting date in real time up to current date in any year, after entering the current date in response to screen queries.
(iii) Preparing a report of the current water status in rice fields in the command area of the distributary transplanted on different dates.
(iv) Preparing a water indent for the irrigation requirements at the head of the distributary for the next irrigation cycle, after accounting for weather forecasts and conveyance losses.
(v) Proceed to next distributary.

Steps (i) to (v) are carried out sequentially and on-line within the GIS environment. The user need not at any stage come out of the GIS environment. For steps (i) to (iv), the complete sequence is run for each distributary with actual rainfall data up to the current date and withthe forecast data of daily rainfall for the next 14 days of the irrigation cycle. At the end of this cycle, which is also the beginning of the next cycle, the actual rainfall data for this period would be available. Before the irrigation indents are prepared for the next cycle, the actual rainfall data of the previous cycle are used to assess the water status at the beginning of the cycle, and the entire sequence is repeated. For this reason, the model needs to be run twice for any irrigation cycle – first with forecast rainfall for the current cycle and then with the actual rainfall in this cycle, when the irrigation cycle advances to the next.

6. CONCLUSION

Remote sensing is a valuable source of data that can provide a synoptic perspective critical for understanding biophysical relationships at a regional scale. Because of this, remote sensing has been a popular tool readily accepted into agricultural research and management. Since the launch of LANDSAT-1 in 1972, scientists and managers have been using remote sensing for crop identification, area measurements, yield prediction, and crop damage assessment. More recently, remote sensing has been seen as a source of spatial data for precision agriculture, although currently these systems are not widely operational. Remote sensing along with climate data and GIS technology can also be used for modelling **E** and m_a for regional analyses of water use efficiency. As fine to moderate remotely sensed data is now available free of cost, the use of remote sensing in agricultural management is more appealing than ever. The current availability of very fine spatial resolution data as well as the anticipation of hyperspectral data also broadens the scope of remote sensing and its usefulness regarding agricultural management. Water savings can be obtained by practicing precision farming of rice in lowland paddy fields. However a rapid assessment of the paddy soil variability needs to be determined, for example through mapping of the bulk electrical conductivity (ECa) of the paddy fields, so that variable treatments of the management zones can be adopted to save the precious resources. ET monitoring is necessary to determine the required amount of water at each crop growth stage, and the rainfall distribution pattern in the irrigation scheme should be considered to make better use of effective rainfall with respect to the stage of crop development.

Area measurement of crops from remote sensing is largely straightforward. However, positional accuracy and pixel size can both affect the results attained in this procedure. The scale of the remote sensing data, therefore, should be appropriate for the level of accuracy desired. This means that clear management objectives should be outlined prior to areal measurements. Individual areal measurements may vary more widely and be less accurate than summed (overall) measurements because errors of underestimation are offset by errors of overestimation when a number of areas are added together.

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