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Low cost satellite data for monthly irrigation performance monitoring: benchmarks from Nilo Coelho, Brazil

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Abstract. Irrigation performance indicators can help water managers to understand how an irrigation scheme operates under actual circumstances. The new contribution of remote sensing data, is the opportunity to study the crop growing conditions at scales ranging from individual fields to scheme level. Public domain internet satellite data have been used to calculate actual and potential crop evapotranspiration, soil moisture and biomass growth on a monthly basis in the Nilo Coelho irrigation scheme, Pernambuco (Brazil). Satellite interpreted raster maps were merged with vector maps of the irrigation water delivery system. Monthly values of a minimum list of irrigation performance indicators for the various service units in the pressurized Nilo Coelho scheme were determined. Nilo Coelho is a good performing scheme. The performance can be improved further if 25% irrigation water is saved from February to July. The benchmark figures from this modern irrigation system are presented for comparitive analysis with other systems. The acceptable ranges in space and time are presented. On average, 65% of the lateral pumping units on a monthly basis fall within the acceptable limits of irrigation performance. Low cost irrigation performance data based on low resolution satellite images (US$ 1/ha) will help the management team to focus on specific pumping units, and discuss alternative irrigation and farm management strategies with the stakeholders.

Key words: irrigation performance, water management, remote sensing, benchmark figures

Introduction

Irrigation performance indicators have been introduced since the seventies to describe the hydrological behaviour of complex irrigation schemes by means of a few and understandable numbers (e.g. Jensen 1972; Bos & Nugteren 1974). Since then, many case studies have been reported in the international literature to demonstrate how performance indicators can be applied to describe actual irrigation practices. (Bos et al. 1994). Bos (1997) concluded: "the indicators now are sufficiently mature to be recommended for use in irrigation and drainage performance assessment".

Examples of diagnostic studies on irrigation performance conducted in the South-American continent were reported before. In the Rio Tunyan Irrigation scheme in Mendoza, Argentina, Bos et al. (1991) and Morabito et al. (1998) showed that the actual water supply to all lateral units is very uniform. They used the concepts of *overall consumed ratio*, among others. In the Samaca Irrigation project in Columbia, de Fraiture and Garces-Restrepo (1997) included agricultural production in the diagnosis, being essential for return to investment studies. For the Nilo Coelho irrigation scheme in Pernambuco, Brazil, Brito et al. (1998) remarked that the predicted water requirement by crops matched quite well the irrigation water amount delivered. Kloezen (1999) investigated the Lerma-Chapala Basin in Mexico and he concluded that groundwater users consumed more water than canal water users, and that aquifers are unnecessary depleted.

The basic input data for irrigation performance indicators consists of diverted water volumes from the head-works, the flow rates at (lateral) offtakes and information on cropping pattern and agro-meteorological conditions. This explicitly implies that these indicators cannot distinguish spatial scales smaller than that of the area located downstream of a water delivery structure with a discharge measurement function. The agro-meteorological conditions are often assumed to be uniform over the project area. Bastiaanssen & Bos (1999) recently summarized the possibilities of using remote sensing to improve the diagnosis under data scarce conditions. Their reported opportunities to cover two aspects: (i) description of irrigation performance at a multitude of scales and (ii) estimation of the parameters of the soil-vegetation-atmosphere continuum, such as soil moisture, crop evapotranspiration and crop biomass production. They demonstrated that various successful cases were realized in the international research community on using remote sensing data for irrigation analysis, but that this new tool is not well known to water resources managers and irrigation engineers. Some indicators can be computed without needing access to *in situ* measured parameters. This is a major benefit for large irrigation schemes and river basins in circumstances where a proper hydro-informatics infrastructure and database management is absent.

The current paper describes the results of a demonstration study using low-cost and low resolution satellite measurements complemented with field data on water flows and rainfall in a modern and commercialized irrigation scheme in Northeast Brazil. To the authors knowledge, it is the first time that such an analysis with public domain and low-cost satellite data is achieved to evaluate the year-round irrigation processes.

Irrigation performance indicators

The International Commission on Irrigation and Drainage (ICID) published a long list of proposed performance indicators to evaluate irrigation and drainage projects (Bos 1997). From this proposed standard terminology, a ‘short-list’ of indicators was composed following consultation with the irrigation managers, and experts from the Brazilian Agricultural Research Organization, EMBRAPA. This short-list was compiled to support the local water distribution decision making. The proposed ICID terminology was followed whenever possible. Other indicators are proposed also (Table 1). The *Relative Water Supply* relates the total water supply (including precipitation) to the total crop water demand. The *overall consumed ratio* quantifies the fraction of supplied irrigation water which is evapo-transpired by the crops in the water balance of the irrigated area, assuming that crop water stress is irrelevant (Bos & Nugteren 1974). This situation may hold for drip irrigation systems where water is given on a day-to-day basis such as in the Nilo Coelho scheme. The *overall consumed ratio* is less meaningful for protective irrigation systems with consistent under-irrigation practices.

The *depleted fraction* was introduced by Molden (1997) to apply performance in the context of multiple irrigation systems and at river basins level. *Depleted fraction* is the fraction of available water (inflow corrected for storage changes) that is depleted and not longer available for other water consumption processes. The depletion in an irrigation scheme is governed by actual evapotranspiration. Because the actual evapotranspiration can be determined by remote sensing, *depleted fraction* was added to the list in Table 1.

The purpose of irrigation is to enhance crop evapotranspiration. From a soil-physical side, this implies that soil water should be retained in the unsaturated zone at a soil water potential at which plants can uptake water easily. The usual target soil moisture level is field capacity, and the *relative soil wetness* is introduced to evaluate the deviation from this optimum moisture status.

The concepts of productivity of water were introduced to better describe the performance of water scarce systems. Different definitions exist, but they all relate the physical mass of production or the economic value of production measured per unit of water diverted, depleted or consumed (Molden & Sakthivadivel 1999). A crop dependent water management measurement program is deemed necessary to quantify the productivity of water for a particular

Table 1. Formulation of irrigation performance indicators applied in the current study in the Nilo Coelho scheme

Irrigation performance indicator	Mathematical expression	Unit
Relative water supply	$(P_{gross} + V_c)/ET_{pot}$	dimensionless
Overall consumed ratio	$(ET_{pot} - P_e)/V_c$	dimensionless
Depleted fraction	$ET_{act}/(P_{gross} + V_c)$	dimensionless
Crop Water Deficit	$ET_{pot} - ET_{act}$	mm/month
Relative evapotranspiration	ET_{act}/ET_{pot}	dimensionless
Relative soil wetness	θ/θ_{FC}	dimensionless
Biomass yield over irrigation supply	Bio/V_c	kg/m^3

P_{gross}	=	gross precipitation (mm/month)
P_e	=	effective or net precipitation (mm/month)
V_c	=	water delivery from the (river or) reservoir (mm/month)
ET_{act}	=	actual evapotranspiration by irrigated crops (mm/month)
ET_{pot}	=	potential evapotranspiration by irrigated crops (mm/month)
θ	=	Volumetric soil water content in the rootzone (cm^3/cm^3)
θ_{FC}	=	Volumetric soil water content at field capacity (cm^3/cm^3)
Bio	=	crop growth expressed as above ground dry bio-mass growth (kg/ha per month)

crop. Although such detailed effort can be achieved at plot scale, it is hardly possible to realize this at scheme and global level. Because biomass is crop independent, Table 1 uses instead *biomass yield over irrigation supply* as a surrogate for productivity of water. The economic value per unit biomass can be calculated from the annually accumulated biomass and the market price received for the fruits. The harvest index is the ratio of grain or fruit yield over biomass yield, and lies essentially between 0.25 to 0.50. Fruit and biomass yield are linearly related. The relative scales of *biomass yield over irrigation supply* and productivity of water are thus similar.

Study area

The Nilo Coelho scheme with perennial fruit irrigation lies on the left bank of the San Francisco River in the state of Pernambuco, Brazil (latitude 09°09′S, longitude 40°22′W). The construction of the irrigation scheme was completed in 1990 and since then fruit trees are planted and agricultural business investments are made. Most orchards have a sub-surface drainage system. The San Francisco Valley Development Company (CODEVASF) is the governmental agency responsible for promoting the development of the river valley using irrigation as a propelling approach. The distribution of river water in Nilo Coelho is managed by the Nilo Coelho Irrigation District. The water for the scheme is pumped from the huge Sobradinho reservoir at a maximum discharge capacity of 23.2 m^3/s. The minimum discharge released from the dam into the downstream San Francisco river is 2,070 m^3/s and the average discharge is nearly 3000 m^3/s. Hence, the Nilo Coelho scheme takes only 1% of the total river flow. More water resources could be developed downstream of the reservoir and there is ample room for expanding irrigated agriculture.

The water is pumped from the Sobradinho reservoir into the main canal. At the head of this canal, flow is measured with a Parshall flume and a water level recorder. The irrigation scheme is subdivided into 31 lateral service units or *nucleus* (Figure 1). Irrigation water supply towards the nucleus happens with open primary and secondary canals. These canals are lined and well maintained. Ultrasonic devices measure the water depth in these open canals and adjust the discharges if necessary. Every nucleus has its own pumping station to pressurize water to 3 bar for further distribution to the farmer inlets.

Farmers can take water on demand. Water is applied to perennial fruits by means of micro-sprinklers, hand move sprinklers, drip systems and center pivot systems. The perennial fruits are banana, coconut, mango, grapes and some smaller fruits such as guava and acerola. There are two types of entrepreneurial plots: small areas of 20 ha and medium to large areas of 50 ha or more (Brito et al. 2000). Family plots have an average size of 6 ha. The soils have a sand fraction of more than 70%. These sandy loams are permeable and retain only a limited amount of water. Excess soil moisture will quickly supplement the groundwater system and subsequently drains off. High tech irrigation systems have been installed to make high frequency irrigation water supply to these coarsely structured soils feasible.

The climate of Petrolina is semi-arid. The EMBRAPA experimental farm near the main research center is equipped with a rain gauge and a pyranometer for measuring solar radiation. For the study period between August 1998 and August 1999, an annual precipitation of 585 mm yr^{-1} was registered by a tipping bucket rain gauge. This value is somewhat comparable with an average year (513 mm yr^{-1} for 1989 to 1997), although it is a little more. Figure 2 shows the monthly variations in precipitation in relation to total irrigation water diversions. Most rain falls in the summer season elapsing from February to April. Less irrigation water is supplied during March when the peak rainfall occurs (Figure 2). Some farmers do not irrigate during this period. The lowest irrigated area of 12,450 ha occurs in February. July has the maximum irrigated area of 13,489 ha. The mean irrigated area is 12,849 ha. Due to earth-sun positions, the lowest potential evapotranspiration occurs between

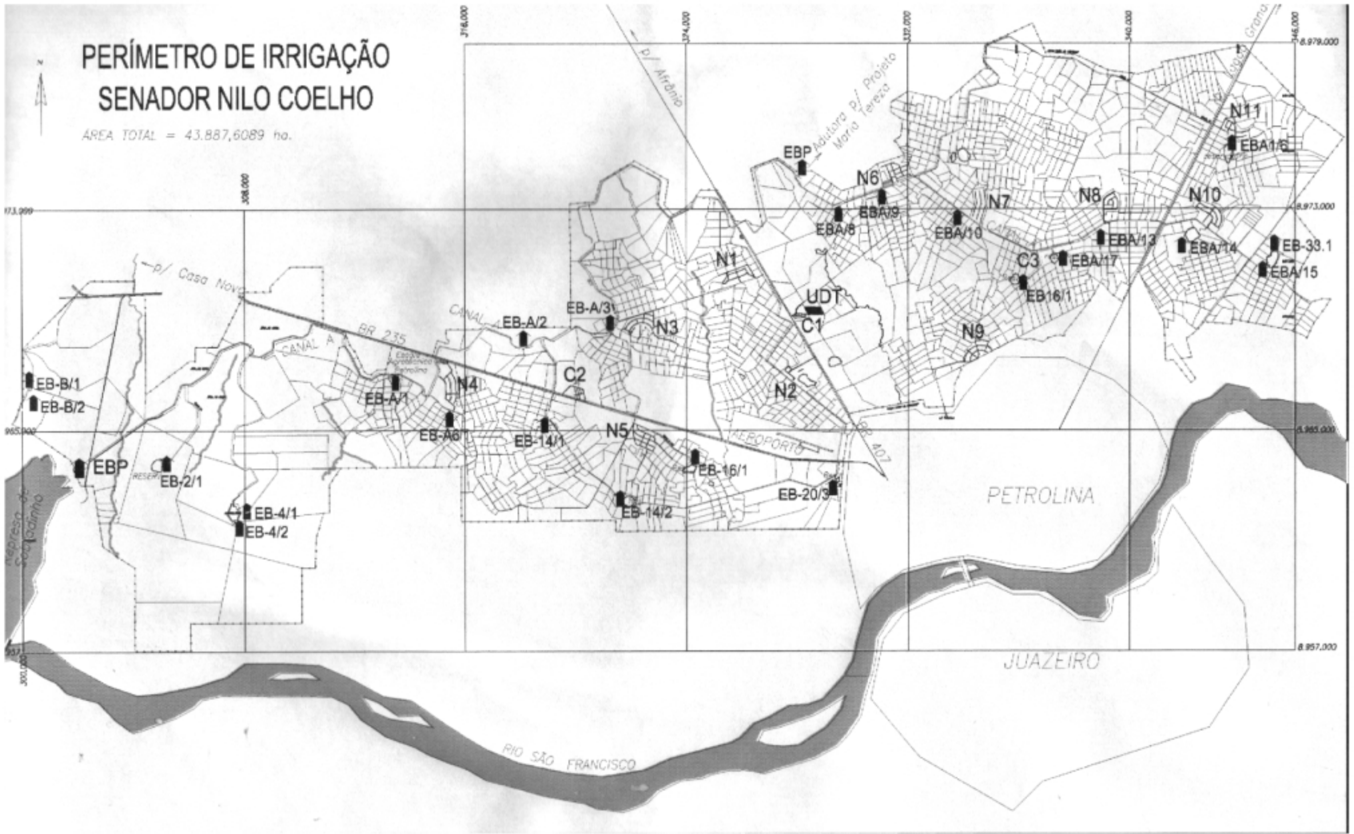

Figure 1. Schematic lay-out of the Nilo Coelho irrigation scheme at the Left Bank San Francisco river near Petrolina in Northeastern Brazil. The EB numbers relate to the location of the pumping stations of the lateral service units.

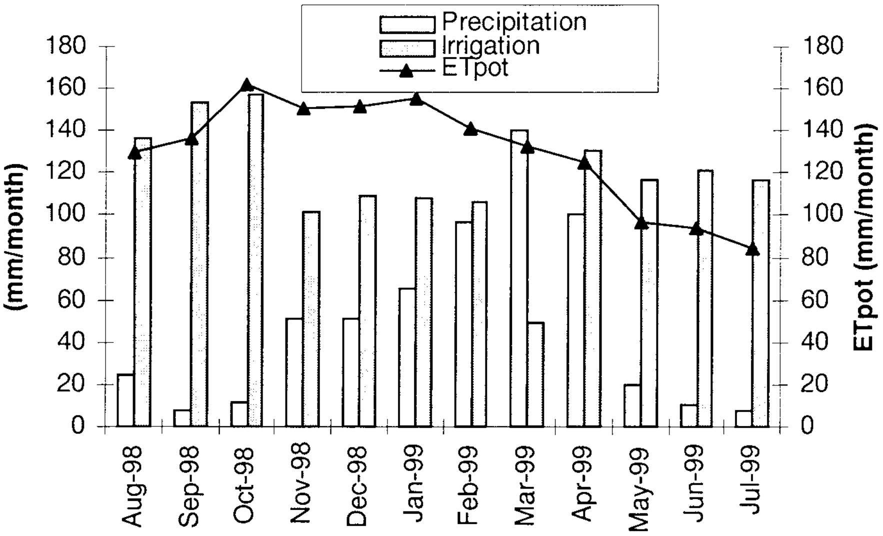

Figure 2. Inter-annual variation of precipitation, irrigation and potential evapotranspiration. The data relates to the period August 1998 to August 1999

May and July, which is the dry period. The peak potential evapotranspiration appears in October, due to fewer clouds.

The total water supply (precipitation plus irrigation) is approximately 165 mm/month during January to April. During the winter period between July and October, the total water supply averages at around 150 mm/month. This reasonably temporal constancy of total water supply shows that rainfall effects are strategically incorporated in the irrigation planning. But the potential evapotranspiration shows more variability than the total water supply, and this is not effectuated in the irrigation planning.

Material and methods

The National Oceanic and Atmospheric Administration (NOAA) satellite has an Advanced Very High Resolution Radiometer (AVHRR) which measures red, near-infrared and thermal infrared radiation. NOAA14 passes over in the mid-afternoon when the surface temperature is approximately at its maximum. Most national meteorological organizations have a NOAA receiver, which retrieves images in real time. This has the advantage that multiple images can be stored and that the qualitative best satellite images in a period of, say, one week or 10 days (a typical period for irrigation scheduling), can be selected for further analysis. If such meteorological infrastructure is not operationally available, raw AVHRR data can be downloaded free of charge

Table 2. Selected NOAA-14 afternoon overpass days used for diagnosing irrigation performance in the Nilo Coelho irrigation scheme

August 20, 1998	November 9, 1998	February 12, 1998	May 15, 1999
September 16, 1998	December 24, 1997	March not available	June 11, 1999
October 13, 1998	January 15, 1999	April 27, 1999	July 16, 1999

from http://www.saa.noaa.gov. The latter option was also utilized for the current Nilo Coelho study. An area of 200 by 300 km was selected for every month. Table 2 shows the NOAA overpass days selected for the monthly irrigation performance assessment study. The NOAA images are processed once a month, and images with favourable clear sky conditions were selected. Elongated cloud cover during March 1998 made it impossible to find a cloud free image. Also December 1998 appeared to be cloud covered for most days and an image from the preceding year was selected. The raw AVHRR spectral radiance data were converted to spectral reflectance and temperatures using the calibration software program NPR1A (Gieske 1999).

The NOAA satellite data were used to determine monthly values for actual evapotranspiration using the Surface Energy Balance Algortihm for Land (SEBAL) developed by Bastiaanssen et al. (1998) and Bastiaanssen (2000). This method is based on the thermo-dynamic exchange processes occurring at the soil-atmosphere interface. The potential evapotranspiration was estimated according to the Priestley and Taylor equation (Priestly & Taylor 1972) using 24-hour net radiation values derived from the NOAA data. The use of net radiation data of a particular crop under actual field conditions determined by satellites avoids the need to use tabular and generic crop coefficient data (Mekonnen & Bastiaanssen 2000). Volumetric soil water content has been estimated empirically from the evaporative fraction, i.e. latent heat flux / net available energy fraction, where available energy is the difference of net radiation and soil heat flux. This soil moisture value describes the average soil wetness in the root zone. If roots are absent, it describes the moisture conditions in the upper 5 cm soil. A biomass growth routine after concepts of Asrar et al. (1985) has been applied to estimate the above ground growth of the fruit trees. The temporal integration of above ground biomass growth is a good indicator of crop yield, provided that the ratio between physical harvestable yield and total biomass is known or can be established (e.g. Donald & Hamblin 1976; Gallaghar & Biscoe 1978)

The spatial resolution of NOAA-AVHRR is 1.1 km, and this implies that every pixel covers a mixture of land use. Fields with and without irrigation are comprised by a single AVHRR pixel, and if the interest goes to the irrigated fields in isolation, high resolution satellite images need to be collected (Bastiaanssen & Bos 1999). The vegetation cover was selected to convert gross evapotranspiration and moisture values at 1.1 km to values applicable for the areas under irrigation. The vegetation cover can be determined from the spectral vegetation index (e.g. Carlson & Ripley 1997; Choudhury & DiGirolamo 1998). In an arid environment, green vegetation cover can be associated to irrigation practices. It is however a limitation of low-resolution data, and lowers the accuracy, which needs to be recognized. Appendix 1 provides the physical-mathematical procedures applied to convert gross pixel values to irrigated area values.

The NOAA satellite data have been complemented with field data. CODEVASF has an extensive flow-measuring network. Every pumping station or nucleus is equipped with a modern ultrasonic flow meter and the outlets at the farms are equipped with impeller type flow meters. Flow data are collected and made available on a monthly basis. The availability of discharge measurements at all important off-take points is a unique situation which invites to thoroughly diagnose the pathways of irrigation water from the reservoir to the fruit crops. The boundaries of all 31 lateral pumping units have been digitized from an irrigation map and described as vectors. The resulting vector map has been superimposed on the raster map, and all NOAA pixels falling within a certain polygon have been identified. Average raster values for every vector, as well as the spatial variation occurring within a vector, were extracted.

Results

Soil water balance

Because of topography (hills) and soil conditions (rocks), only part of the *gross* area encompassed by the external irrigation boundaries is supplied by water. The *gross area* is defined as the area enclosed by the outer boundaries of areas under service by the pumping stations. Some parts of the *gross area* are vegetated by natural bush-land, rainfed crops or fallow land and are thus not irrigated. The *gross area,* therefore, is larger than the *irrigable area*, which in turn is larger than the *irrigated* area. The gross area is 33,813 ha. The average irrigated area (12,849 ha) is 38% of the gross area. The annual water balance of the *gross area* of the scheme was first calculated. Note that all satellite data from pixels contain per definition gross area, i.e. all forms of land use are included in the satellite measurements. The values of precipitation and irrigation are drawn from field measurements. The total runoff is taken as 30% of the gross precipitation (Poifo 2000). Most of the

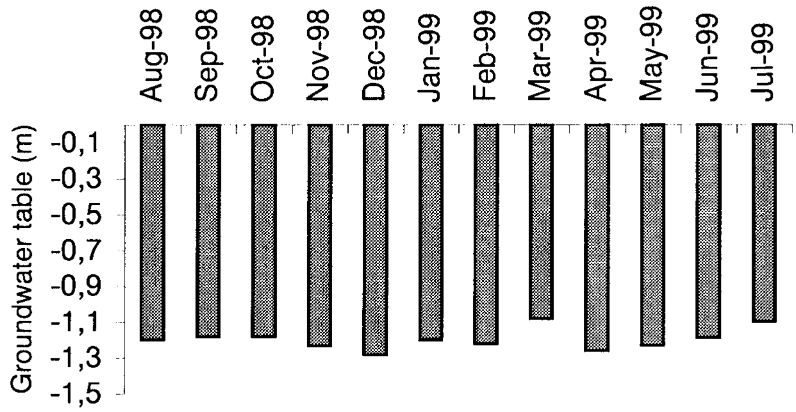

Figure 3. Groundwater table fluctuations in an irrigated mango orchard in the Nilo Coelho scheme (after Cordeiro 2000)

runoff is likely to origin from erratic rainstorms. The groundwater table is according to field information rather steady and the annual storage chances may, therefore, be neglected (see Figure 3). The flat water table behaviour reveals that the drains are working properly. Non-consumed irrigation water is drained away back into the San Francisco River (see Table 3).

The actual evapotranspiration from the irrigated plots calculated by SEBAL results to 1200 mm yr^{-1}. The average daily evapotranspiration for the local mixture of agricultural crops is 1200/365 = 3.3 mm d^{-1}. This number also includes the evapotranspiration originating from young plantations. The potential evapotranspiration estimated by the Priestley and Taylor method using remotely sensed data, is 1560 mm/year. The advantage of directly using ET_{pot} is that use of the crop coefficient, which for fruit crops with different heights is not exactly known, can be avoided. A *relative evapotranspiration* of 1200/1560*100% = 77% indicates an overall sufficient evaporative behaviour and shows – indirect through the crop yield response to evapotranspiration theory – that the fruit production is satisfactory (Doorenbos & Pruitt 1977).

EMBRAPA conducts field experiments to quantify the actual evapotranspiration of mango's and banana using the Bowen ratio surface energy balance technique (e.g. Todd et al. 2000 for more information on technical aspects). The evaporative fraction is an energy partitioning factor defined as the fraction of latent heat flux and the net available energy. The net available energy is the net radiation minus soil heat flux. The measured seasonal averaged evaporative fraction for mangos is 0.83. The *in situ* measurements of evaporative fraction of grapes (variety *Italia*) varied between 0.40 to 0.60 and is thus significantly lower than the taller mango trees. Field measurements of banana showed an evaporative fraction of 0.95 to 1.0 which can be attributed

Table 3. Annual water balance of the Nilo Coelho irrigation scheme. The gross area contains also non-irrigated crops and fallow land enclosed by the scheme boundaries. For clarification, the irrigation and drainage volumes (m^3/year) are similar for both systems, but differ when they are expressed per unit of land (mm). The potential evapotranspiration is 1560 mm/year

Term	Unit	Gross area	Irrigated area
Area	ha	33,813	12,849
Precipitation	mm/year	586	586
Irrigation	mm/year	529	1,339
Actual evapotranspiration	mm/year	888	1,200
Surface runoff	mm/year	176	176
Drainage	mm/year	51	549
Storage change	mm/year	0	0

to the high leaf area index (LAI). These *in situ* energy balance measurements reveal that the evapotranspiration of bananas consume all net available energy and by doing that little to no energy is left for heating the atmosphere. Grapes on the opposite consume approximately 50% of the energy available to evapotranspiration and warm the air through the development of sensible heat transfer. At similar net radiation values, this implies a double evapotranspiration in bananas as compared to grapes. The controlling factors for the evapotranspiration of irrigated land in Nilo Coelho are thus, besides day-to-day cloud variation, the distribution of banana's and grapes and the age of the plantations.

The field measurements of actuale evapotranspiration obtained during individual days reveal significant variability due to cloud cover variations. The actual evapotranspiration of mango's varied between as low as 1.4 mm d^{-1} to 6.5 mm d^{-1} during July 1999. The average evapotranspiration for adult mango trees between 25 August and 23 December 1998 was 4.4 mm d^{-1} (Silva 2000). The same author reports for the period between 10 June 1999 and 15 November 1999 an average actual evapotranspiration of 4.2 mm d^{-1}. Castro et al. (1999) measured the actual evapotranspiration of grapes, yielding to 503 mm for the entire growing period of 117 days (on average 4.3 mm d^{-1}). The average actual evapotranspiration for a mixture of fruit crops computed with SEBAL between Augustus to January (5 months) was 3.8 mm d^{-1}. Although this comparison may not be regarded as a strict validation – the areas and crop types are not identical – it reveals that the evapotranspiration results from the SEBAL model are with 12% deviation not in conflict with *in situ* measurements.

Maintaining soil wetness in a sandy loam at field capacity for ideal crop growth cannot be achieved without loosing soil moisture from the root zone to the groundwater table. As groundwater table fluctuations are flat, irrigation water excess must be evacuated through drainage. An annual amount of 549 mm/year (see Table 3) is estimated to be drained away from the irrigated farms. The drainage has been calculated as a water balance residual, thus by taking precipitation from meteo stations, the water diversion from discharge measurement devices and actual evapotranspiration together with soil moisture storage from NOAA imagery. An annual drainage of 549 mm/year in irrigated areas is equivalent to 1.5 mm/day. This value is not uncommon for irrigated agriculture in semi-arid regions (e.g. Sarwar et al. 2000). Figure 4 shows the peak drainage to occur during the rainy season followed by a gradual decline from August to November when drainage becomes nihil. Figure 3 shows the water table to be at 1.2 m during this period. The drainage patterns match the water table fluctuations presented in Figure 3 remarkably well, with deepest water tables coinciding with lowest drainage rates in October through December and the opposite in April to June. Hence, the regional scale water balance seems plausible.

Irrigation performance indicators

A substantial part of precipitation water is not consumed. This also appears from the low *depleted fraction* (∼0.60), revealing that not all water from precipitation and irrigation is consumed. The depleted fraction is the lowest in April (∼0.40) when the drainage rate reaches the peak (100 mm/month). April has both a high precipitation and irrigation water supply. Due to proper drainage systems and an adequate dosage of irrigation water, the volumetric soil water content is temporally conserved and the water table is under control. A significant amount of electricity can be saved if irrigation supply is reduced in the rainy season. A new law has been approved by the Brazilian Congress to charge for water. This law provides an economic incentive for water saving.

The evaporative demand of the atmosphere varies between 80 to 150 mm/month (Figure 2). The irrigation water supply should therefore correct for seasonal changes of the potential evapotranspiration. This is the rationale behind using the *relative water supply* as a performance indicator. Figure 5 shows a distinct variation of *relative water supply* with time. Three aspects need more attention:

– From Feburary till July, the *relative water supply* averages around 1.4 (exceeding 1.7 in April), whereas October through January is characterized by a *relative water supply* around 1.0. This implies that

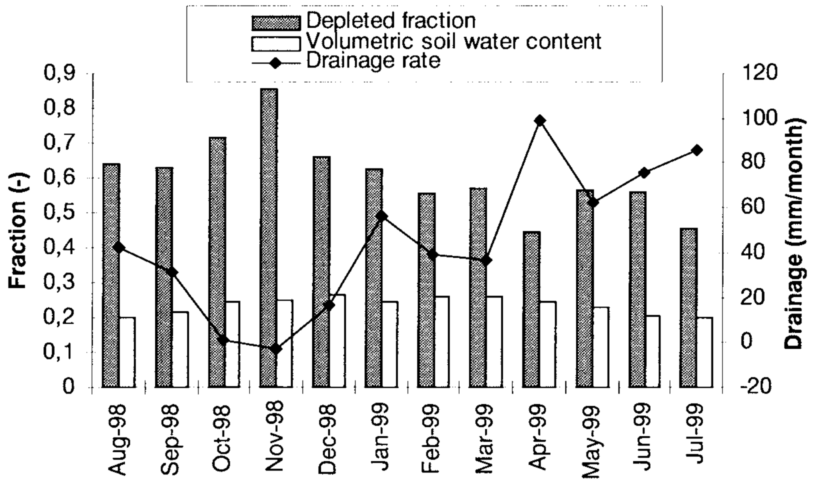

Figure 4. Soil moisture process of the irrigated plots in the Nilo Coelho scheme.

over-irrigation occurs between February through July. Irrigation water can be saved in this period and eventually supplied to the crops in other parts of the year.

- Re-allocation is however not necessary because *overall consumed ratio* and *relative water supply* are both adequate during August to January (Figure 5). The *relative water supply* and *overall consumed ratio* have an inversely proportional relationship, and proper irrigation management will tend them both towards one. During October to December a tendency to close the gap between *relative water supply* and *overall consumed ratio* can be witnessed. Most water is than effectively consumed by the fruit crops and the losses are less, whereas the soil is little above field capacity. October and November are school examples of how irrigation water should be managed and used without losses.
- The average irrigation supply of 1339 mm exceeds together with a rainfall of 586 mm far the actual crop evapotranspiration. An *overall consumed ratio* of 0.7 can be met if irrigation supply is reduced to 1000 mm/yr. A reduction from 1339 to 1000 is equivalent to 25% savings in the irrigation water diversions.
- The period February to April shows that maximum crop water use is less than half of the pumped irrigation water; a serious over-irrigation occurs. The result is that the soil water content is high and excess water is drained away.
- Numerical model simulations with the Richard's equation has shown that a field capacity soil water content of 0.20 cm^3 cm^{-3} is typical for the sandy loam soils of Petrolina. The inter-annual fluctuations are minor,

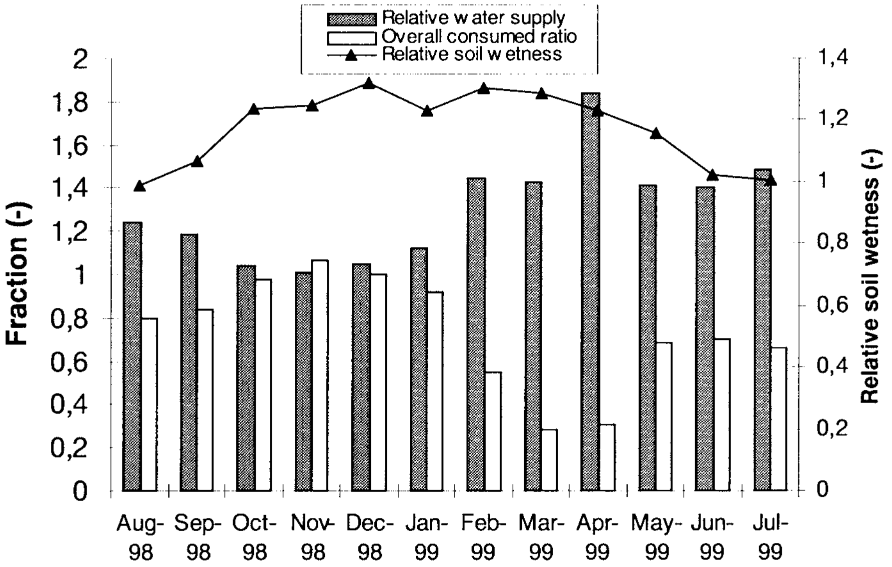

Figure 5. Supply related indicators and the soil moisture response of the entire Nilo Coelho irrigation scheme in the period August 98 to July 99.

and the *relative soil wetness* is the whole year round 1 or more. This implies that the soil moisture remains at or a little above field capacity and that the expensive high precision irrigation and sub-surface techniques keep water in the root zone at adequate levels. This information is very important and implies that soil moisture management is optimal.

As shown in Table 3, the crop evapotranspiration demand of 1560 mm/year is with 77% rather satisfactorily met (ET_{act} = 1200 mm/year), although a dip is apparent in July with *relative evapotranspiration* values of 70%, and again in December and January (Figure 6). In the latter case, an absolute deficit of almost 50 mm/month can be noticed, being more serious than the deficit of 28 mm/month in July. The irrigation managers seem to provide enough water during December and January (*relative water supply* = 1.0). Despite ideal soil water content levels at field capacity, the actual evapotranspiration in December and January is lagging behind. This seems to be more related to a plant physiological effect, rather than to soil physical processes. Most reductions of crop evapotranspiration in absolute terms occur in the hot summer season from October to January. It is likely that the high temperature in summer (maximum air temperature of 40°C) induces crop stomatal closure through bio-physical mechanisms which behave independent of water uptake by roots (Jarvis 1976). Allen et al. (1996) mentioned that the upper limit for stomatal activity is 35 to 40°C and that the optimum conductance through the

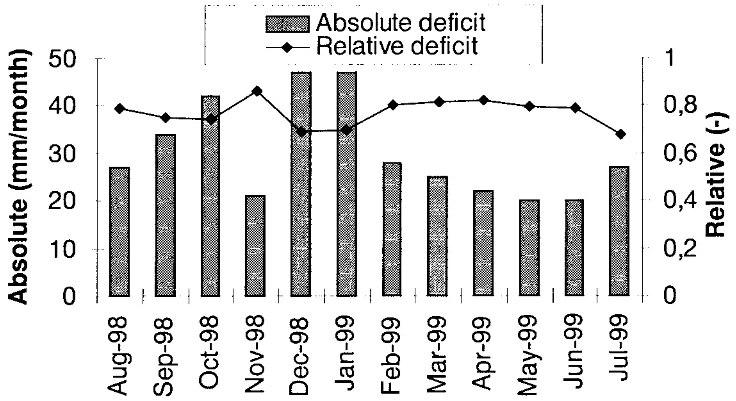

Figure 6. Crop water stress expressed by combinations of actual and potential evapotranspiration in the period August 98 to August 99. The absolute deficit is the difference and the relative deficit is the ratio.

stomatal aperture for agricultural crops lies between 25 to 35°C. This implies that the fruit crops in Nilo Coelho have thermal stress, which is a climatic fact that cannot be prevented by any management action. Another plausible reason is the harvesting period. Farmers keep the field drier for the fruit pickers and trucks to transport away the bananas, grapes and mango's to the market.

The biomass development due to crop evapotranspiration is presented in Figure 7. The fastest plant growth occurs from February to April when the rain starts, soil moisture is above field capacity, air humidity is high and air temperature is ideal for stomata. Farmers chemically manipulate the vegetative and fruit harvest phases and most leaf development coincides with the period having maximum Photosynthetically Active Radiation (PAR). The maximum biomass production of 3500 kg/ha/month, which is equivalent to 116 kg/ha/d, is controlled by the high cloud cover in this period. The extra-terrestrial sunshine reaches its maximum in November and shortly again during February. February had a total solar radiation at ground level of 54.4 MJ/m^2 , which coincides with an average atmospheric transmissivity of 49% only. February has a higher total water supply from rain and irrigation than in November, and this is reflected in moist growing conditions. The fast biomass growth in February and March is therefore the result of both water supply and solar radiation. The crop evapotranspiration deficit during this period is with 25 mm/month, very low.

There is a signal in Figure 7 that tells us that the period May to July is less contributive to crop growth. Figure 7 suggests that the delayed fruit growth coincides with lower evapotranspiration rates and lower solar radiation (see Figure 2). This is typical for the winter conditions in Brazil. The evapo-

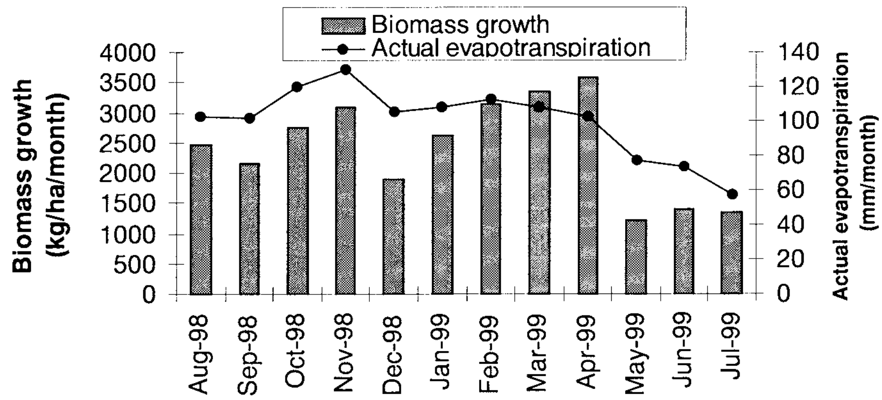

Figure 7. Crop growth parameters of the Nilo Coelho irrigation scheme in the period August 98 to August 99.

transpiration deficit is not apparent from May to July. Hence, the reduction in biomass growth is radiation driven, although effects from harvesting and pruning cannot be *a priori* excluded as explanatory variables. It has to be verified whether purposely management strategy plays a role.

Figures 4 to 7 demonstrate the monthly variability of the irrigation performance indicators, and the lesson learned is that none of these indicators is constant in time. This fact needs to be recognized with more attention in the strategic planning of irrigation water resources. The ranges of performance indicators can be fruitfully explored to compute the time and space variability to derive the benchmark figures. The average size of a nucleus (unit) is approximately 400 ha. There are 31 pumping units and 12 months, hence there are a total number of 372 observations. The total variability appears from the histogram such as for instance is provided in Figure 8.

The *relative water supply* ranges from as low as 0.4 to a high value of 3.1. The optimum values for *relative water supply* are indicated in bold. This indicates that using average values for an irrigation scheme can induce wrong conclusions and recommendations to the management because real values may significantly deviate from the average values. On average the *relative water supply* is with 1.26 little at the higher side, but as discussed earlier, there are periods in which several nucleus are under-irrigated.

A similar conclusion is drawn for *crop water deficit*. The range from 0 to 90 mm/month is extremely high and the average value does not provide information on that wide range. If an average evapotranspiration deficit of 1 mm/d is accepted, i.e. 30 mm/month, than only parts of the nucleus (units) are in the proper range. The availability of statistics of these indicators, allows the computation of the standard deviations, the coefficients of variation

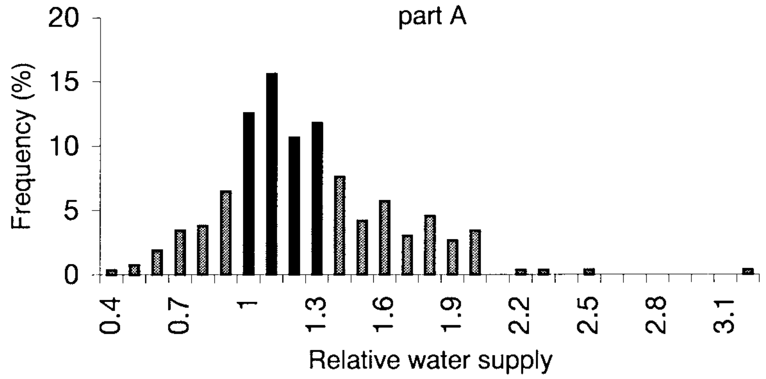

Figure 8a. Frequency distribution of monthly irrigation performance indicators for the period August 1998 to August 1999. The ranges for relative water supply (part A) and crop water deficit (part B) are given. The ideal ranges are marked in bold.

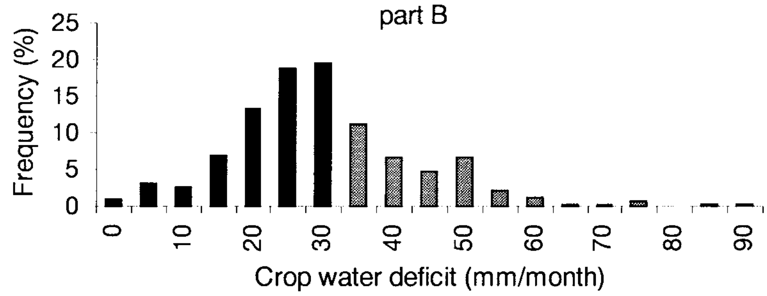

Figure 8b. Continued.

and the percentage of cases encompassed by the acceptable range of the performance indicator. Such type of data analyses has been performed and the results are presented in Table 4. An analysis on the variability can help defining benchmark levels for irrigation performance. In this case stuy, the remote sensing data were the vehicle to obtain the spatio-temporal information of the irrigation performance that is relevant for addressing the acceptable deviations from the mean.

Pumping unit conditions

The performance indicators are calculated for all 31 lateral units served by a pumping station on a month-to-month basis. This performance statistics allow diagnosing the differences among the lateral units. One example is provided in Figure 9. The largest variation of RWS among the units occurs during May 1999. Pumping stations EB10.04, EB11.04 and EB15.09 under-irrigate with $0.75 < RWS < 1.0$ as compared to intended RWS values between 1.0 and 1.3.

Pumping station EB30.07 shows the opposite performance with RWS > 3.0 revealing a waste of water and energy.

Pumping station EB23.04 consistently pumps less water per unit crop water demand as compared to the other pumping stations. The temporal variability of RWS is very small and it can from this perspective be an example for the other pumping stations. The reasons for this stable performance are not clear and there is no clue on whether performance is good by intention or is related to deviating discharge measurement accuracies, peculiar crop combinations or usage of wrong field data on the irrigation planning process. It is recommended that the irrigation manager pays attention to this and discuss with the stakeholders the situation. The lower supply of EB23.04 can also be noticed from the *crop water deficit* (CWD), with CWD-values exceeding 30 mm/month in August and October to March (not shown). Figure 9B shows that January 1999 has a variability between CWD=25 to 60 mm/month, sometimes even for neighbouring lateral units (e.g. EB 29.05 and EB 28.06).

The *biomass yield over irrigation water supply* ratio is a surrogate of the productivity of water. The productivity of water is presented in Figure 9c for February 1999. The northeastern edge of the Nilo Coelho irrigation scheme shows a higher 'productivity per unit of water' (e.g. lateral units EB 21.09, 22.06, 23.04, 25.06). On the contrary, the lateral units EB9.05 and EB12.06 are the least productive. The average harvest index for mango, banana and grape was found to be 0.42, which implies that the productivity varies between 0.6 to 2.3 kg/m^3 physical yield per unit of water diverted. These numbers reveal a high water productivity, but the associated variability is also high. The highest *biomass yield over irrigation supply* ratio occurs in April. The higher productivity cannot be explained by fruit types or the age of the fruit trees. If fruit market prices and water delivery costs are known, the economic return per unit of water can be calculated.

A general observation is that the spatial variability in the *crop water deficit* is more distinct than the variability of the *relative water supply*. This indicates that the spatial variation in crop growth and the *relative soil wetness* is not caused by irrigation management of the Nilo Coelho Irrigation District, but merely is a consequence of (i) different crop mixtures, (ii) water distribution within a lateral unit, (iii) irrigation distribution techniques and (iv) non-water management practices.

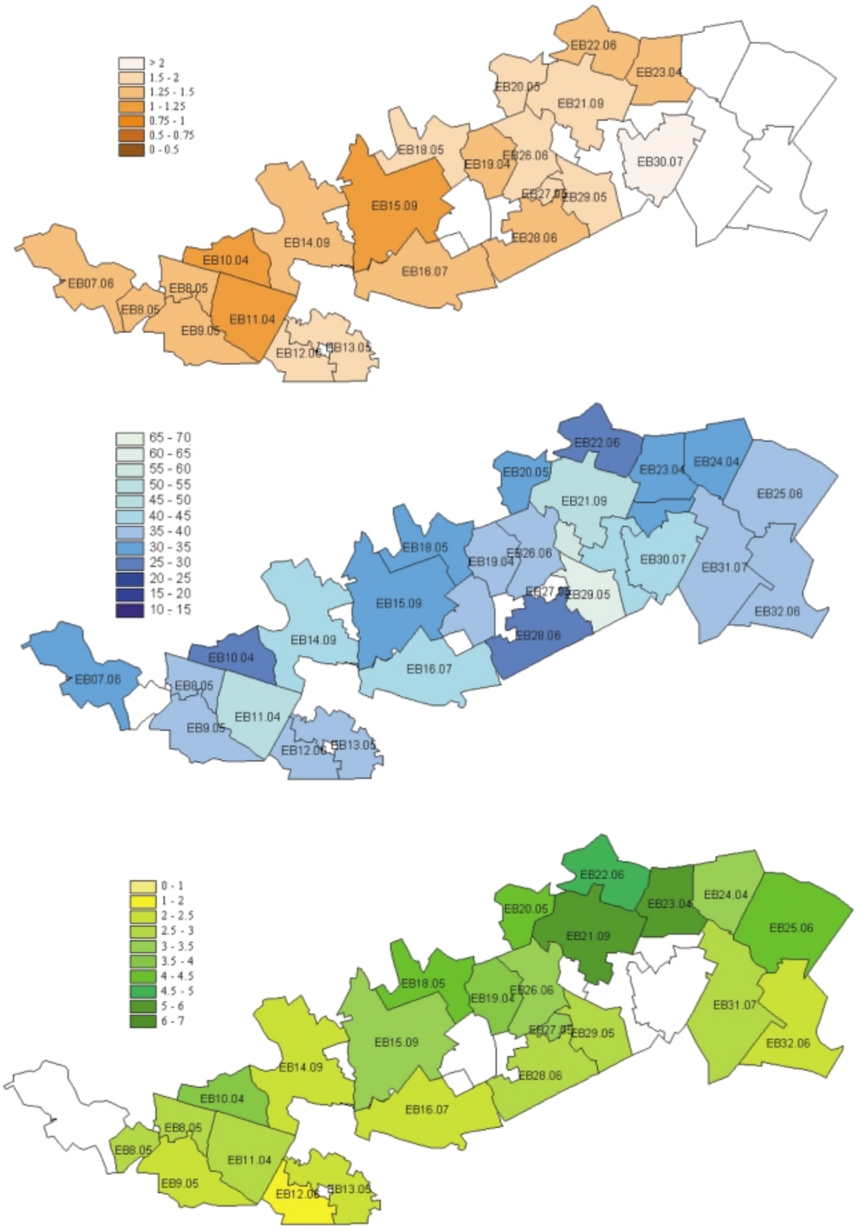

Figure 9. Part A: relative water supply for May 1999 (dimensionless), part B: crop water deficit for January 1999 (mm/month) and part C: Biomass yield over irrigation supply for February 1998 (kg/m^3) in the Nilo Coelho scheme.

Table 4. Lateral units with below-target irrigation performance for the conditions in the Nilo Coelho scheme requiring special attention. Three indicators are selected for the sake of simplicity.

Performance indicator	Target level of indicator	Allowable range of indicator	Poor performing units	Period of the year with low performance
Relative water supply	1.0	0.8 to 1.3	EB10.04, 11.04, 15.09, 21.09, 23.04, 24.04, 30.07	January, May, September, October
Overall consumed ratio	0.9	0.6 to 1.0	All	February, March, April, May, June, July
Crop water deficit	0 mm/mo	$<$30 mm/mo	EB29.05, 21.09, 16.07, 15.09, 26.06, 24.04, 25.06, 12.06, 11.04, 10.04	January, October, December

Recommendations to the Nilo Coelho Irrigation District and agricultural producers

- The Nilo Coelho irrigation scheme is an example of a satisfactory performing irrigation system. Further improvement can, however, be realized if performance is assessed for each month.
- The *relative water supply* is a suitable indicator to inform the irrigation manager whether they supply sufficient water to a larger area of cropped land in order to meet the total crop water demand. It is appropriate to reduce the water supply from February to July. Besides saving energy, this will reduce drainage effluents and reduce the leaching of nutrients and chemicals from the root zone. In general, the temporal variability of *relative water supply* is higher than its spatial variability and the irrigation manager should work on tempering the temporal variability.
- A significant amount of water resources can be saved. The average irrigation supply of 1339 mm exceeds, together with a rainfall of 586 mm, far the actual crop evapotranspiration. An *overall consumed ratio* of 0.7 can be met if 1000 mm irrigation is supplied. A reduction from 1339 to 1000 is equivalent to 25% in the irrigation water diversions.

- With irrigation water prices to be introduced, an economical incentive will spur farmers to save water. More focus should be on the distribution of water among the lateral units in May (see Figure 9A). Units EB 30.07 should get less water and more water should go to EB 10.04, 11.04 and 15.09.
- Special attention should be given to pumping station EB 23.04. The *relative water supply* is at the lower side, but it is the only unit which behaves remarkably constant with time, and it has the highest *biomass yield over irrigation supply*. This shows that a reliable supply increases the productivity of water.
- The *overall consumed ratio* is rather low from February to July. During this period and especially during March and April, precipitation water is being lost to drainage.
- The spatial variation of *crop water deficit* is larger than *relative water supply* and *relative soil wetness*, which reveals that the crop and variety selection and other farm management decisions has significant impact on evapotranspiration. Farm management procedures are apparently the direction in which further improvement of the irrigation performance has to be sought.
- The *crop water deficit* is related to the *relative water supply*, the pressurized distribution of irrigation water to the farm inlet and the farmer's decision to irrigate. The *crop water deficit* shows explainable deficits during December and January when the soil water content is above field capacity. It is interesting to investigate if unavoidable plant physiological factors reduce the actual evapotranspiration during these hot periods or reduction can be explained by harvest and pruning cycli. This thermal stress can be checked out from *in situ* canopy conductance and soil moisture measurements.
- Productive units with the highest return to water are located in the lateral units EB 12.09, 22.06, 23.04 and 25.06. On the contrary, the lowest productivities are witnessed in EB 12.06 and 28.06.

General remarks for irrigation performance evolvement

The spatio-temporal patterns of the irrigation performance indicators gave information on the functioning of the Nilo Coelho scheme. Although the scheme is well managed, this information was not available before. Remote sensing provides opportunities to retrieve new performance indicators such as *depleted fraction*, *crop water deficit*, *relative evapotranspiration*, *relative soil wetness* and *biomass yield over irrigation supply*. Another advantage is that potential evapotranspiration can be retrieved directly without the use of crop coefficients. This evades the need to use standardized K_c tables such as provided by Doorenbos & Pruitt (1977). The proposed indicators give key information on the moisture status in the root zone and actual crop water use. The conservation of the water balance allows computing outflow from the root zone, i.e. drainage, as a residual term. This gives a more comprehensive description of the total system as compared to classical indicators describing water delivery and service levels (e.g. Malano & van Hofwegen 1999). In general, it is confirmed that one single performance indicator can neither describe deficiencies in the system management, nor ways to improve them. A combination of indicators enhances the diagnostic opportunities, especially when the entire flow path form the reservoir upto the stomatal cavity an be quantified. There are also limitations of the remote sensing technique which needs further attention and improvement to make the technology more profitable. These limitations of using remote sensing techniques are:

- Remotely sensed information does not explain the causes, it only measures net effects of land surface processes
- High resolution images can, due to cloud cover, not be frequently obtained
- High resolution images are delivered more than a month after acquisition date and cost US$ 600 per scene
- Low resolutions images can be obtained daily and images are instantly available, but the resolution is 1.1 km. This is too coarse for direct interpretations to plot scale or a single crop type. A set of conversion equations such as provided in Appendix 1 can be applied to overcome this problem, but it goes at the costs of accuracy
- Remote sensing provides a regional scale overview and validation of spatially distributed parameters derived from satellite measurements is difficult. Validation is limited to local field studies and consistency checks. General validation efforts have to rely on large-scale (international) field campaigns which are not straightforward to realize.

The modern Nilo Coelho irrigation scheme can be used to assess the benchmark values related to irrigation performance and productivity of water and the deviation of these indicator values. The target values and deviations are summarized in Table 4. If the indicator value remains within the "operational range", crop yield will deviate less than 10% from the target value. If the indicator moves out of the "acceptable range" yield reductions of over 20% occur. The data reveals that it is not possible to manage a modern and small irrigation scheme such as Nilo Coelho in such a way that all indicators are

Table 5. Benchmark values for performance indicators for pressurized systems in irrigated fruit crops in Nilo Coelho (Brazil). CV is the coefficient of variation (standard deviation/mean)

Indicator	Measured mean	CV	Operational range (%)	Acceptable range (%)
Relative water supply	1.26	0.30	1.0 to 1.3 (41)	0.9 to 1.4 (58)
Overall consumed ratio	0.78	0.34	0.7 to 1.0 (43)	0.6 to 1.1 (64)
Depleted fraction	0.61	0.28	0.7 to 1.0 (22)	0.6 to 1.1 (50)
Crop water deficit	30.3 mm/mth	0.45	0 to 30 (58) mm/mth	0 to 40 (80) mm/mth
Relative evapotranspiration	0.76	0.13	0.8 to 1.0 (35)	0.7 to 1.0 (73)
Relative evapotranspiration	0.76	0.13	0.8 to 1.0 (35)	0.7 to 1.0 (73)
Relative soil wetness	1.16	0.28	0.8 to 1.2 (51)	0.6 to 1.2 (63)
Biomass yield over irrigation supply	2.01 kg/m^3	0.53	>1.8 (58) kg/m^3	> 1.5 (58) kg/m^3
Average		0.33	44%	64%

on target value. Too many practical factors, such as erratic rainfall and farm management, affect the overall performance, and the general lesson here is that an average coefficient of variation for all indicators of CV=0.33 is almost unavoidable.

The productivity of water shows the highest variability due to the annual growing cycle of biomass. On the average, 64% of the lateral pumping units – on a monthly basis – fall within the acceptable limits of irrigation performance. This might be a good benchmark figure for comparative studies with other irrigation projects.

NOAA provides a regional perspective being measured in a consistent manner from 1985 to present. It is the largest available satellite database in earth sciences. It is feasible with these technologies to cover the entire valley of the Rio San Francisco by one single overpass. The cost of computing actual and potential evapotranspiration, soil moisture and biomass production from satellite images is about US$ 1000 per image of 10 million hectare. That amount is sufficient to cover specialist labour and computational costs. With twelve images per year, this results to a cost of US$ 0.80/ha for a scheme of the size of Nilo Coelho (15,000 ha). For the further GIS processing needed to convert the satellite data together with the discharge measurement and meteorological data into the performance indicators such as provided in Figure 9 and Table 3, an additional $ 0.20/ha costs have to be added. This is about 4% of the current project operational and maintenance cost of US$ 23.85/ha (Brito et al. 2000). Hence, this technology becomes feasible for these size schemes. The costs per hectare will be lower in the river basin context because the same labour and GIS effort can cover a larger area.

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Appendix 1: Conversion equations for correcting heterogeneous NOAA-AVHRR pixel values into values applicable for irrigated fields

The potential evapotranspiration is computed with the standard equation of Priestley and Taylor (1972) where the net radiation (R_n) is taken from the satellite image considering the actual field conditions being expressed into leaf area index, thermal infrared emissivity and surface albedo:

$$ET_{pot}^{NOAA} = 1.26 R_n s_a/(s_a + \gamma)$$

Where s_a (mbar/K) is the slope of the saturated vapour pressure curve and γ (mbar/K) is the psychrometric constant. $ET_{pot}{}^{NOAA}$ represents the potential evapotranspiration of the entire NOAA pixel encompassing fruit crops, bare soil and natural vegetation. The slope s_a is a temperature dependent function and the areal patterns of temperature are withdrawn from the thermal infrared band. Potential evapotranspiration of the irrigated crops is subsequently computed from the NOAA estimates using the fractional vegetation cover. The potential crop evapotranspiration ET_{pot}^{irr} is obtained from its NOAA counterparts as:

$$ET_{pot}^{NOAA} = v_c ET_{pot}^{irr} + (1 - v_c) ET_{pot}^{nonirr}$$

where

$$ET_{pot}^{nonirr} = 0.8 ET_{pot}^{irr}$$

The fractional vegetation cover v_c is computed from the NDVI following the concepts of Carlson and Ripley (1997). The actual evapotranspiration for every NOAA pixel is computed with the iterative SEBAL algorith and will not be explained here further. The conversion from the mean actual evapotranspration to the evapotranspiration of irrigated crops ET_{act}^{irr} was obtained as:

$$ET_{act}^{NOAA} = v_c ET_{act}^{irr} + (1 - v_c) ET_{act}^{nonirr}$$

where

$$ET_{act}^{nonirr} = \theta^{NOAA}/0.31^* ET_{pot}^{NOAA}$$

The relative soil water content (i.e. fraction of the pores filled with water) is determined from the evaporative fraction of the surface energy balance Λ:

$$\theta^{NOAA}/\theta_{sat} = (1/0.51) exp\{(\Lambda^{NOAA} - 1.28)/0.42\}$$

where θ (cm^3 cm^{-3}) is the volumetric soil water content in the root zone, θ_{sat} (cm^3 cm^{-3}) is the saturated soil water content and Λ (–) is the evaporative fraction. After EMBRAPA's soil physical laboratory data, a porosity of, $\theta_{sat} = 0.38\ cm^3\ cm^{-3}$ is taken. A correction term was introduced to account for the irrigation process:

$$\theta^{irr} = \theta^{NOAA} ET_{act}^{irr} / ET_{act}^{NOAA}$$

The *Relative Soil Wetness* (RSW) then becomes:

$$RSW = \theta^{irr}/\theta^{FC}$$

Moisture storage changes from the root zone were computed for a depth of 1000 mm:

$$\Delta W = \{\theta(t+1) - \theta(t)\}1000$$

The biomass production is computed from the Absorbed Photosynthetical Active Radiation (APAR) and the evaporative fraction Λ:

$$Bio^{NOAA} = APAR^* 2.5^* \Lambda^{NOAA}$$

from where the biomass production for irrigated crops Bio^{irr} can be computed as:

$$Bio^{NOAA} = v_c Bio^{irr} + (1 - v_c) Bio^{nonirr}$$