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Full Length Research Paper

Critical appraisal of an irrigation command and water productivity based on satellite remote sensing

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Irrigation policy makers and managers need information on the irrigation performance and productivity of water at various scales to devise appropriate water management strategies, considering dwindling water availability, further threats due to continually rising population and food demand. It is often difficult to access sufficient water supply and use data to determine crop water consumption and irrigation performance. Energy balance techniques using remote sensing data have been developed by various researchers, and can be used as a tool to directly estimate actual evapotranspiration that is, water consumption. Study demonstrates how remote sensing-based estimates of water consumption and water stress combined with secondary agricultural production data, which provide better estimates of irrigation performance, water productivity. A principle benefit of the approach is that it allows identification of areas where agricultural performance is less than potential, there by providing insights into how irrigation systems can be managed to improve overall performance and increase water productivity in a sustainable manner. To demonstrate the advantages, the approach is planned to be applied in North Gujarat, India based Dharoi Irrigation Scheme. Remote sensing-based indicators reflecting equity, adequacy, reliability and water productivity can be estimated. This paper is purely the extensive research review and conceptualized concept to be used for future research in above said region.

Key words: Actual evapotranspiration, equity, adequacy, reliability, water productivity, surface energy balance, SEBAL.

INTRODUCTION

While irrigation has greatly increased global and regional food security, further rapid increases in agricultural production will be required to meet future food and fiber demands. This goal can be achieved either by bringing more area under irrigation or by increasing the yields of existing cropped area whilst using similar or even reduced water resources. Prospects for finding new water sources in these areas are relatively slim, because most of the surface and groundwater resources have already been exploited. Therefore, further expansion in irrigated area is often limited by water availability. Thus it is important to find ways to increase agricultural production by careful evaluation of existing irrigated lands. This strategy will not only help to meet future food demands but may also ease competition with other sectors and help to ensure water availability for nature. The science of evaluating irrigation systems has undergone major development during the last 30 years, moving from a focus on classical irrigation efficiencies to performance indicators (Bos et al., 1994; Clemmens and Bos, 1990). Public domain internet satellite data and scientific development makes remote sensing an attractive option to assess irrigation performance from individual fields to scheme or river basin scale (Bastiaanssen and Bos, 1999; Bos et al., 2005; Akbari et al., 2007). Such spatial information is increasingly important for large irrigation

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systems and river basins such as the Sabarmati basin irrigation system of North Gujarat, India to help identify suitable water management strategies across different scales. This is particularly important because the means to improve water productivity lie substantially at farm scale in terms of crop management and at system scale in terms of irrigation water distribution and possible allocation.

There are a number of well known and emerging irrigation management objectives and needs in North Gujarat, India. The region being scanty rain fed. Remote sensing, geographic information systems (GIS) and geo-statistics approaches, along with limited field data, can be used to solve distributed water balance and estimate net groundwater use. Government can launch a new pro-gram to maintain a computerized database for irrigation releases to improve irrigation management, reduce rent seeking, increase transparency and demon-strate which users are getting what quantity of water. It is expected that these initiatives will improve data management and availability of surface supplies.

But to work, information on overall water consumption (surface and groundwater) at various scales will be essential for judicious and efficient water resources management in the region. There is a need to study water distribution and consump-tion patterns and the im-pacts of this on productivity. Remotely sensed estimates of actual evapotranspiration take account of factors that reduce water consumption below potential, such as salinity, crop condition and poor irrigation scheduling all of which are important, specifically in region like North Gujarat,India. The objectives of this paper are: appli-cation of the surface energy balance algorithm for land (Dharoi in North Gujarat, India.) to estimate actual evapotranspiration (ET_a), quantification of agricultural water consumption in different irrigation subdivisions of Dharoi scheme; understanding the seasonal and spatial patterns of evapotranspiration in North Gujarat, India and their linkage to groundwater consumption, completion of irrigation and water use performance diagnoses in terms of crop water productivity and water consumption.

MATERIALS AND METHODS

This study is proposed on for the upper Sabarmati river basin irrigation system in North Gujarat, India with particular focus on and around Mehasana District, a land unit lying between the Unjha, Visnagar, Vijapur, Sidhpur and Kheralu villages. The gross area of the right bank irrigation is about 142321 ha. Summers are long and hot, lasting from April through September with maximum daytime temperatures ranging from 40 to 45°C. The winter season lasts from December through February with maximum temperatures ranging between 25 and 27°C. Mean annual precipitation is about 850 mm (Dharoi irrigation department). SEBAL can be used for actual evapotranspiration calculations, which is a well-tested and widely used method to compute ET_a (Bastiaanssen et al., 1999). SEBAL results have been validated in a number of countries using field instruments including weighing lysimeter, scintillometer, Bowen ratio and Eddy-correlation towers, indicating daily ET estimates have errors on the order of 16% or lower at 90% probability (www.waterwatch.nl). At longer time scales, such as a crop season, E_T errors cancel out to 5% (Bastiaanssen et al., 2005). SEBAL is an image-processing model, which computes a complete radiation and energy balance along with resistances for momentum, heat and water vapor transport for each pixel (Bastiaanssen et al., 1999; Bastiaanssen, 2000). From the reflectance and radiance measure-ments of the bands, first land surface parameters such as surface albedo vegetation index, emissivity and surface temperature. The key input data for SEBAL consists of spectral radiance in the visible, near-infrared and thermal infrared part of the spectrum. In addition to satellite images, the SEBAL model requires routine weather data parameters (wind speed, humidity, solar radiation and air temperature). With this data, evapotranspiration is then calcu-lated from the latent heat flux, and the daily averaged net radiation, Rn_{24}.The latent heat flux is computed from the instantaneous surface energy balance at satellite overpass on a pixel-by-pixel basis.

$$\lambda E = R_n - (G_0 + H) \tag{1}$$

Where λE = (W/m^2) is the latent heat flux (λ is the latent heat of vaporization and E is the actual evaporation), Rn (W/m^2) is the net radiation, G_0 (W/m^2) is the soil heat flux and H (W/m^2) is the sensible heat flux.

The latent heat flux describes the amount of energy consumed to maintain a certain evapotranspiration rate. The energy balance Equation (1) can be decomposed further into its constituent para-meters. Rn is computed as the sum of incoming and outgoing short wave and long-wave radiant fluxes. G_0 is empirically calculated as a G_0/R_n fraction using vegetation indices, surface temperature and surface albedo. Sensible heat flux is computed using wind speed observations, estimated surface roughness, and surface to air temperature differences that are obtained through a self-calibration between dry (see=0) and wet (H =0) pixels. The dry and wet pixels are manually selected, based on vegetation index, surface temper-ature, albedo and some basic knowledge of the study area. The need for this technique makes SEBAL somewhat subjective and difficult to automate. SEBAL uses an iterative process to correct for atmospheric instability caused by buoyancy effects of surface heating. More details and recent references/literature on SEBAL is available at www.waterwatch.nl. Then instantaneous latent heat flux, λE, is the instantaneous evaporative fraction (Bastianssan et al., 2000).

$$\lambda = (\lambda E / \lambda E + H) = \lambda E / (R_n - G_0) \tag{2}$$

λ expresses the ratio of the actual to the crop evaporative demand when the atmospheric moisture conditions are in equilibrium with the soil moisture conditions. The instantaneous value can be used to calculate the daily value, because the evaporative fraction tends to be constant during daytime hours, although the H and λE fluxes vary considerably. The difference between the instantaneous evaporative fraction at satellite overpass and the evaporative fraction derived from the 24 h integrated energy balance is often marginal and in many cases be neglected for time scales of 1 day, G_0 is relatively small and can be ignored and net available energy / (Rn-G_0) reduces to net radiation (Rn). At daily timescales actual evapotranspiration, ET_{24} (mm/day) can be computed as:

$$ET_{24} = (86{,}400 \times 10^3 / \lambda \rho w) \times \lambda R_{n24} \tag{3}$$

Where Rn_{24} (W/m^2) is the 24 h averaged net radiation, λ (J/kg) is the latent heat of vaporization, and ρw(kg/m^3) is the density of water. For timescales longer than 1 day, actual evapotranspiration can be estimated using the relation proposed by Bastiaanssen et al. (2002). The main assumption is that specified in Equation (3) remains constant over the entire time interval between capture of each remote sensing image so that:

$$ET_{int} = dt\ (86,400 \times 10^3 / \lambda\rho w) \times \lambda\ Rn_{24t} \qquad (4)$$

Where ET_{int} (mm/interval) is the time integrated actual evapotranspiration, and Rn_{24t} (W/m^2) is the average Rn_{24} for the time interval dt measured in days. Rn_{24t} is usually lower than Rn_{24}, because Rn_{24t} also includes cloudy days.

Remote sensing-based irrigation performance indicators quantify the efficiency of the project. A wide range of irrigation and water use performance indicators are available (Rao, 1993; Bastiaanssen and Bos, 1999; Bos et al., 2005) to assist in achieving efficient and effective use of water by providing quantification aid in such study, indicators representing equity, adequacy, reliability, and water productivity can be used to evaluate the performance of irrigated agriculture in the North Gujarat, India based Sabarmati basin. Irrigation policy makers and managers need information on the irrigation performance and productivity of water at various scales to devise appropriate water management strategies, considering dwindling water availability, further threats due to continually rising population and food demand. It is often difficult to access sufficient water supply and use data to determine crop water consumption and irrigation performance.

Energy balance techniques using remote sensing data have been developed by various researchers, and can be used as a tool to directly estimate actual evapotranspiration that is, water consumption. Study demonstrates how remote sensing-based estimates of water consumption and water stress combined with secondary agricultural production data, which provide better estimates of irrigation performance, water productivity. A principle benefit of the approach is that it allows identification of areas where agricultural performance is less than potential, there by providing insights into how irrigation systems can be managed to improve overall performance and increase water productivity in a sustainable manner. To demonstrate the advantages, the approach is planned to be applied in North Gujarat, India based Dharoi Irrigation Scheme. Remote sensing-based indicators reflecting equity, adequacy, reliability and water productivity can be estimated. This paper is purely the extensive research review and conceptualized concept to be used for future research in the above said region Reservoir project. Traditionally, equity is calculated from the supply side.

But in water scarce system, like in the North Gujarat, equity in water consumption is more relevant from the farmer's perspective and can be computed from remote sensing-based ET_a maps of an irrigation system. Adequacy is the quantitative component, and is defined as the sufficiency of water use in an irrigation system. In contrast, reliability is the time component and defined as the correspondence of water supply upon request. Both, adequacy and reliability of water supplies to cropped area can be assessed using the evaporative fraction maps as they directly reveal the crop supply. In this study, adequacy is defined as the average seasonal evaporative fraction and reliability as the temporal variability, that is temporal coefficient of variation of evaporative fraction in a season. Evaporative fraction values of 0.8 or higher indicate no stress (Bastiaanssen and Bos, 1999), and below 0.8 reflect increases in moisture shortage to meet crop water requirements as a result of inadequate water supplies. Similarly, the lower values of coefficient of variation represent the more reliable water supplies throughout the cropping season. The term water productivity is defined as the physical mass of production or the economic value of production measured against gross inflows, net inflow, depleted water, process depleted water, or available water (Molden, 1997; Molden and Sakthivadivel, 1999). For systems comprised of multiple agricultural enterprises, the water productivity is often computed in monetary terms.

Remote sensing data to evaluate the irrigation performances (Findings from case studies)

Remote sensing data to determine actual evapotranspiration and crop water stress for managing irrigation systems was suggested by several authors. However, it was also showed, how high resolution landsat images could be used to map crops and crop phenology stages in two Italian irrigation districts, and to detect crop-specific effects such as water stress. Menenti et al. (1989) made a list of indicators that could be quantified with remotely sensed data. They looked at equity by evaluating actual flow per irrigated area at different spatial scales. The irrigated area was taken from satellite images, supplemented with records of flow from the field. They also used the interesting marginal benefit indicator as defined by being the difference between actual evapotranspiration in situations with and without irrigation divided by the volume of water that is supplied to that unit. This shows the portion of irrigation water used to enhance actual evapotranspiration.In a way, data on flow and actual evapotranspiration reveals also valuable information on system losses between the off-take and the root zone.

If evapotranspiration under rain-fed conditions is negligible, or the crop selection in the irrigated areas is entirely different from the neighboring rain-fed agricultural practices, the benefit indicator can be re-defined as actual evapotranspiration over actual flow delivered. Menenti et al. (1989) have used remote sensing data to generate maps of irrigated area and potential crop water requirements based on remote sensing derived k_c factors. Operational algorithms to compute actual evapotranspiration were not yet available at that time. Instead, a hydrological simulation model was suggested to compute actual evapotranspiration. Moran (1994) described the results of a farm irrigation management study in Arizona where the maximum possible cloud-free SPOT and Landsat images were used in conjunction with airborne remote sensing data from an altitude of 100 m above ground level. Alfalfa and cotton were continuously monitored in terms of vegetation index (SAVI) and surface temperature to deduce the water deficit index (WDI) for adequacy evaluations. It became obvious that satellite data could not always be obtained due to technical shortcomings in the satellite receiving systems in that case aircraft data was found more reliable and faster available.

Data collection and preprocessing

This study can be conducted for the period representing fall and spring cropping seasons. Daily meteorological data on temperature, humidity, wind speed and sunshine hours for and regional can be collected from the North Gujarat Meteorological department for prescribed period. Rainfall data can be collected from number of gauging stations in and around North Gujarat and be interpolated to obtain gridded values of seasonal and annual rainfall. Considering the type of vegetation and bunds around field, interception and runoff losses from cropped areas are minimal and therefore ignored in this analysis (Ahmad et al., 2006). Data describing surface flow diversions at the heads of the main irrigation canals can be collected for the same time period from the irrigation and power department for the main canal systems of North Gujarat. For the gross value of production esti-mation, data on crop area, production and output prices can be collected from secondary sources including the Economic Wing of the Ministry of Food, Agriculture and Livestock. Data on cropped area and production are available at district level with for all fall and spring crops. District level GVP can be transformed to the scale of irrigation subdivisions based on the fraction of district area falling in a specific irrigation subdivision using over-lay analysis in GIS. This was mainly done to overcome the limitation of district boundaries, which do not match those of the irrigation subdivisions. GVP can be computed on real prices and wholesale price index (WPI) can be used to convert the current/nominal prices into constant/real prices with a base year considered.

Framework for remote sensing and irrigation performance indicators

Summary of definitions

This section is not intended to standardize performance indicators that can be quantified by use of satellite data, but merely a summary of technically possible and workable indicators. There is not enough experience worldwide to arrive at a consensus. More awareness and case studies are needed to demonstrate the advantages of remote sensing-based indicators as compared to the data collection based on classical field surveys. From the literature review, it is concluded that a larger set of indicators exists for adequacy and equity than for reliability and productivity. This is a mere consequence of the surface energy balance and the partitioning of energy, being direct indicators for adequacy and equity. Note that all surface energy balance studies rely on thermal infrared measurements. Productivity has basically two components: one for the physical biomass or yield per unit of water and a second which describes the use of the water resources through the comparison of water consumed by crop evapotranspiration versus the volume of irrigation water supplied. The latter ‘overall consumed ratio’ is bio-physically related to the former due to the strong relationships between actual evapotranspiration and crop yield. More research is recommended to comply with a remote sensing deter-minant of reliability in the irrigation service. The indicators against which the performance of irrigation can be assessed vary widely with legal aspects, related regula-tions and with traditions of local irrigation communities. All groups of performance indicators has its own require-ments for frequency of images and time constraints between image acquisition and availability at the door of the irrigation manager. For example, in rigid water distribution systems, preseason planning can be based on interpretations of remotely sensed water distribution data from the proceeding season combined with the recorded deviations between actual and intended water supply. The protective rotational water supply systems aim at equity and some of these systems have an increasingly severe problem of sustainability (salinity). The water distribution with pressurized irrigation systems with sprinklers and drip systems demand high invest-ments, productivity evaluations are more important than issues such as equity or reliability.

Overall consumed ratio (e_p)

Overall consumed ratio quantifies the degree to which crop irrigation requirements are met by irrigation water in the irrigated area. The ratio is defined as follows:

e_p ¼ = $(ET_p\text{-}P_e)/ V_c$

Where “ET_p is potential evapotranspiration, in mm, “P_e is effective precipitation, in mm” and “V_c is volume of irrigation water diverted” from resource and/or groundwater in mm. Overall consumed ratio should be set within an existing irrigated area and compared to the actual ratio on a monthly and seasonal basis .

Relative water supply (RWS)

The relative water supply used as an indicator of adequacy of irrigation water delivery compares supplied water with that demanded. It is calculated as follows:

RWS ¼ = $(V_c *P_g)/ ETp$

Where, “P_g is gross precipitation, in mm”. The target value of the RWS indicator was considered as 2.0 (Molden et al., 1998).

Depleted fraction (DF)

Depleted fraction shows changes in actual water use by crops and quantifies differences in the water balance of the areas under study. The depletion in an irrigation scheme is governed by ETa. This indicator is defined by (Molden, 1997):

DF ¼ = $ET_a/ (V_c * P_g)$

Where “ET_a is actual evapotranspiration, in mm”. DF should be considered as a function of time. For semi-arid and arid regions the critical value of the depleted fraction averages about 0.6 (Bos et al., 2005). The acceptable range of DF was considered as 0.6 to 1.1(Bastiaanssen et al., 2001).

Crop water deficit (CWD)

Crop water deficit over a period is defined as the difference between ETp and ETa of the cropping pattern within an area. A common period is 1 month, and an average CWD of 30 mm month is acceptable (Bastiaanssen et al., 2001). Crop water deficit is defined as follows:

$$CWD^{1/4} = ET_p - ET_a$$

Relative evapotranspiration (RE_T)

Relative evapotranspiration quantifies reduction in evapotranspiration and detects water-short areas. To evaluate the adequacy of irrigation water delivery to a selected command area as a function of time, the dimensionless ratio of ET_a over ET_p gives valuable information to the water manager.

Conclusions

There is only a small group of researchers working on remote sensing interpretations for irrigation performance assessment. Their work is summarized in this paper to make a larger audience aware of their progress. The accuracy of measuring individual parameter from remote sensing data ranges between 80 to 90%. Performance indicators are usually based on several parameters combined together, and the accuracy is therefore approximately 75 to 85%. It is apparent that scientific progress has been ahead of implementation because the images and processing equipment were a financial burden in the eighties. The current reduction in costs of raw satellite images, direct availability of National Oceanic and Atmospheric Administration (NOAA) satellite images through commercial ground receiving stations, cheaper PC based processing software, and the availability of more robust interpretation algorithms, make applications nowadays more attractive. Irrigation managers, consultants and policy makers are usually not aware of the opportunities remote sensing can offer. This is partially due to the overselling of the possibilities satellites could offer at the onset of the remote sensing era in the seventies. Some of the case studies shown in this paper reveal, however, that irrigation performance indicators can be calculated for

1. Diagnosing water management practices at small unit areas up to farm plot level.
2. Monitoring irrigation events at scales > 500 ha in a regular fashion.
3. Revealing the overall water resources utilization.

This is an appropriate extension of using flow rates in the conveyance network. Aspects of adequacy, productivity, equity, reliability and sustainability in irrigation management can be computed from remotely sensed data. Standardization of irrigation performance indicators is an important issue for the International Committee on Irrigation and Drainage (ICID), and satellite measurements can help in surveying the conditions of irrigated land in a consistent and objective manner. It will allow comparing conditions within and between different irrigation schemes in a normalized manner. Most of the reviewed literature needs a thermal-infrared band to infer surface temperature for crop water stress and surface energy balance modeling.

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