Enhancing Water Management Decision Support Systems with High Spatio-temporal Resolution Mapping of Actual Evapotranspiration

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Quantifying water consumption over large areas and within irrigated projects is important for water demand forecasting, water rights management, water resources planning and water regulation. Due to the difficulty of capturing this information, however, it is often one of the most poorly understood and thus weakly represented components of water decision support systems supporting these management activities. Currently, agricultural water consumptive use is generally computed based on estimates of evapotranspiration (ET) for individual crops. Crop ET is estimated as a fraction (i.e., crop coefficient) of computed ET for a reference crop. Reference ET is a standardized estimate of potential ET calculated at an appropriately sited weather station and for a specific vegetation condition (0.5 m height and full ground cover). In practice, crop ET is estimated by selecting derived crop coefficients corresponding to the crop growth stage and multiplying by the reference ET value. Aggregated ET over a large area is then calculated by summing across all fields within the area, if specific field-crop information is available. This aggregation thus requires the creation and regular update of GIS crop-type maps, which are costly to maintain. There is typically some question regarding whether the crops grown compare with the conditions represented by the Kc values, especially in water short areas. In addition, it is difficult to predict the correct crop growth stage dates for large populations of crops and fields. Recent developments in satellite remote sensing ET models have enabled us to accurately estimate ET and Kc for large populations of fields and water users and to quantify net groundwater pumpage in areas where groundwater extraction is not measured. Improvements in the accuracy of ET estimates or in the processing efficiency of consumptive use demand for large irrigated lands and associated verification can greatly benefit water DSS modeling efforts to better understand the temporal and spatial relationships between water demand and water availability, ultimately leading to better water planning decisions and water management. Better information on ET is essential for better understanding of consumptive use and soil moisture availability.

This workshop presentation focuses on a three-year NASA supported project, currently in its second year, that uses NASA research results to enhance two water decision support tools (SPDSS and RiverWare) serving issues related to water availability. Maps (images) of physically-based actual ET are modeled using thermal wavelength Earth-Sun System results from two sensors (MODIS and Landsat) for the calculation of earth surface temperature. The MODIS satellite has a high temporal resolution (one overpass per day) that is more than adequate for mapping ET, but a relatively coarse spatial resolution of 1000 m which makes the identification of water consumption from individual fields and for individual crops impossible. The 60m spatial resolution of thermal bands onboard the Landsat 7 satellite and 120 m spatial resolution onboard the Landsat 5 satellite is nearly ideal for the computation and mapping of evapotranspiration from individual irrigated fields (water rights regulation and administration are critically tied to identification and quantification of water consumption on a field by field basis). Also important, Landsat satellite images have near continuous coverage and a long image archive, which is important for tracking the changes in water consumption over time and space for individual fields, irrigation projects, river basins, and regions. The return time (16 days), while not optimal, is workable for ET mapping. Because neither of these sensors combines the optimal requirements for multi-purpose ET mapping into one satellite, our approach leverages the capabilities of the thermal bands of all these sensors to take advantage of their particular strengths and to minimize their weaknesses for a variety of ET mapping applications.

The model we are using to develop the ET maps (i.e. images) is a NASA supported model called METRIC (Mapping Evapotranspiration at high Resolution with Internalized Calibration). METRIC is an image-processing model comprised of multiple submodels for calculating evapotranspiration (ET) as a residual of the surface energy balance. METRIC is a variant of SEBAL, developed in the Netherlands by Bastiaanssen (2002). METRIC was extended by Dr. Rick Allen at the University of Idaho to provide tighter integration with ground-based reference evapotranspiration and to increase repeatability and accuracy. ET images provide the means to quantify, in terms of both the amount and spatial distribution, ET on monthly and seasonal basis, field by field. Using an energy balance at the surface, energy consumed by the ET process is calculated as a residual of the surface energy equation:

$$LE = R_n - G - H \qquad (1)$$

where LE is the latent energy consumed by ET, R_n is net radiation (sum of all incoming and outgoing shortwave and longwave radiation at the surface), G is sensible heat flux conducted into the ground, and H is sensible heat flux convected into the air. The utility of using energy balance is that *actual* ET rather than *potential* ET (based on amount of vegetation) is computed so that reductions in ET caused by shortage of soil moisture and agronomic management variables are captured. Rn is computed from Earth-Sun-System research results, specifically broad-band reflectances and surface temperature; G is estimated from Rn, surface temperature, and vegetation indices; and H is estimated from surface temperature ranges, surface roughness, and wind speed using buoyancy corrections, thus weather information is important. METRIC differs from SEBAL principally in how the “H function” is calibrated for each specific satellite image. In both METRIC and SEBAL, H is predicted from an aerodynamic function where:

$$H = \rho C_p \frac{dT}{r_{ah}} \qquad (2)$$

where ρ is air density, Cp is specific heat of air at constant pressure, and r_{ah} is aerodynamic resistance between two near surface heights (generally 0.1 and 2 m) computed as a function of estimated aerodynamic roughness of the particular pixel and using wind speed extrapolated from a blending height above the ground surface (typically 100 to 200 m), with an iterative stability correction scheme based on the Monin-Obhukov functions (Allen et al.,1996). The dT parameter represents the near surface temperature difference between the two near surface heights. The dT parameter is used because of the possibility of difficulties in estimating surface temperature (Ts) accurately from satellite information. In addition, T_s, as measured by satellite (i.e., radiometric temperature) can be several degrees different from “aerodynamic” temperature that drives the heat transfer process. dT is designed to “float” above the surface, beyond the height for sensible heat roughness (z_{oh}) and zero plane displacement, and can be approximated as a relatively simple linear function of T_s:

$$dT = a + bT_s \qquad (3)$$

The relatively simple approach to calibrate heat and ET fluxes for satellite images used in the METRIC approach has been proven successful, with high accuracy demonstrated across images and application areas (Tasumi et al., 2005; Allen et al., 2005). During calibration, parameters a and b in (3) are computed by setting dT = (H r_{ah})/(ρ C_p) at T_s of a “hot” pixel that is dry enough so that one can assume that LE = 0 and therefore, from (1) and (2), dT = ((Rn-G) r_{ah})/(ρ Cp). A daily surface soil water balance is run for the hot pixel to confirm that ET = 0 or to supply a nonzero value for ET for the hot pixel for calibration of (3). For the lower calibration point of dT in METRIC, a well vegetated pixel having relatively cool temperature is selected and dT at that pixel is calculated as:

$$dT = \frac{(R_n - G - k\ ET_r)\ r_{ah}}{\rho C_p} \qquad (4)$$

where k is an empirical factor set to 1.05 to describe evaporative behavior of the cooler, wetter pixels relative to the ET_r reference that represents ET from 0.5 m tall, dense vegetation. With Landsat images, fields of alfalfa or other high leaf area vegetation can generally be identified that are close to or at full cover, so that the ET from these fields can be expected to be near the value of “reference ET” (ET_r) computed for an alfalfa reference. In the METRIC model, the standardized ASCE Penman-Monteith equation is used for alfalfa reference (ASCE-EWRI 2004). Generally, METRIC can be applied without crop classification, since specific crop type is not required, reducing the need for costly crop-mapping on a regular basis. The theoretical and computational approaches of this approach are described further in Bastiaanssen et al., (1998a and b), and Tasumi et al. (2005b).

ET maps are being used to develop multi-temporal and spatial scale ET application prototypes to augment the decision support capabilities and increase operational efficiencies of the selected water management decision support systems, SPDSS and RiverWare. Applications have been developed in Colorado (SPDSS), and later will be developed for Washington State (RiverWare). Benchmarking evaluation tests have been developed and implemented to identify, measure and report the degree of enhancement afforded to the respective NCWCD and USBR application of SPDSS and RiverWare to specific water management issues. In Colorado, benchmark evaluations are focusing primarily on enhancements to SPDSS with regard to the following operations and decision making: forecasts of ET demands for storage releases and irrigation scheduling, planning for well augmentation, and development of water balances to increase water management efficiency. In Washington state, evaluations will later focus primarily on enhancements to the USBR ET-Toolbox by calibrating this approach with METRIC estimates of ET to increase current accuracy and usability, and by benchmarking the enhanced ability of RiverWare to predict return flows more accurately with inputs of spatially distributed, physically-based METRIC estimates of ET against the more general estimates of ET-Toolbox.

An internet map serving and GIS analysis capability has been developed by RTi to streamline the flow of data into the SPDSS at NCWCD (CO), and to the USBR RiverWare model in Yakima (WA). The ability to visualize the METRIC ET information as a temporal sequence (with the ability to create videos of ET over the duration of a growing season) in combination with other spatial information is providing previously unavailable analytical opportunities, including identification of stressed crops or water logged soils, groundwater recharge zones, un-permitted water use, and changes in ET as a function of land use change. RTi will later work with CADSWES to develop extensions to Riverware to facilitate the import of spatial information into the Yakima RiverWare model.

Numerous activities throughout the project are aimed at systematically building a project exit strategy that guarantees water DSS advances have life beyond NASA support, and that the project results are extended to other areas. Some of these strategies will be discussed.

Key advantages of the ET mapping approach described in this presentation are:

- It calculates *actual* ET rather than *potential* ET and does not require knowledge of crop type (no satellite-based crop classification is needed). Thus, these can be applied in near real-time ET forecasting;
- It relies heavily on theoretical and physical relationships, but provides for the introduction and automated calibration of empirical coefficients and relationships to make the process operational and accurate;
- The use of ET_r in calibration of METRIC and the use of ET_rF in extrapolation to 24-h ET provides general equivalency and congruency with ET as estimated using the traditional K_c ET_r approach, where ET_r is alfalfa reference ET calculated using the ASCE-EWRI standardized Penman-Monteith equation (ASCE-EWRI, 2004). This congruency is valuable for using ET maps generated by METRIC in water rights management where water rights are based on previous K_c ET_r calculations;
- The model is auto-calibrated for each image using ground-based calculations of ET_r (made using weather data) where accuracy of the ET_r estimate has been established by lysimetric and other studies in which we have high confidence;
- Physical crop ET estimates from satellite imagery are calculated on a pixel basis and thus provide site-specific ET suitable for spatial analysis and correlation with other geospatial data and as a input parameter to spatially distributed models (e.g. MODFLOW);

Runoff from Colorado watersheds supplies water to 18 other states, and numerous interstate compacts and Federal decrees control the supply to those states, thus water management in Colorado has considerable national importance. In WA, the record of crop production on the USBR Yakima Project is outstanding, with nearly one-half million acres of sage-covered lands transformed into one of the richest agricultural areas in the Nation. Yakima County ranks first among all counties of the United States in the production of apples, mint, and hops. Informed water management in CO, WA and across the arid western U.S. is clearly critical for sustainable development, agriculture, recreation, environmental habitat, and homeland security. Methods developed to use water more efficiently now will result in urban and rural communities more resilient to drought and other natural or anthropogenic disturbances, ultimately enhancing the ability of the whole country to sustain a burgeoning population. All tools and operational DSS enhancements based on NASA satellite products developed in this work can be readily extrapolated to irrigated regions throughout the west that are experiencing the same host of problems, constraints and uncertainties being experienced along the South Platte River and Yakima River systems.

The following table describes technical characteristics of the remote sensing-based METRIC products:

Source instrument	Landsat TM	Landsat ETM	Aster	MODIS
Spatial resolution (Determined by the thermal band)	120 m	60 m	90 m	1 km
Frequency of product availability	16 days	16 days	Inconsistent	4 days
Delay between observation and product availability	Approx. 1 week after image acquisition			
Geographic projection and file format	UTM or other common geographic projections and data formats			
Compatibility with GIS software	Most common GIS and image processing software			

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