

Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)—Applications

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Abstract: Recent satellite image processing developments have provided the means to calculate evapotranspiration (ET) as a residual of the surface energy balance to produce ET “maps.” These ET maps (i.e., images) provide the means to quantify ET on a field by field basis in terms of both the rate and spatial distribution. The ET images show a progression of ET during the year or growing season as well as its spatial distribution. The mapping evapotranspiration at high resolution with internalized calibration (METRIC) is a satellite-based image-processing procedure for calculating ET. METRIC has been applied with high resolution Landsat images in southern Idaho, southern California, and New Mexico to quantify monthly and seasonal ET for water rights accounting, operation of ground water models, and determination of crop coefficient populations and mean curves for common crops. Comparisons between ET by METRIC, ET measured by lysimeter, and ET predicted using traditional methods have been made on a daily and monthly basis for a variety of crop types and land uses. Error in estimated growing season ET was 4% for irrigated meadow in the Bear River basin of Idaho and 1% for an irrigated sugar beet crop near Kimberly, Id. Standard deviation of error for time periods represented by each satellite image averaged about 13 to 20% in both applications. The results indicate that METRIC and similar methods such as SEBAL hold substantial promise as efficient, accurate, and inexpensive procedures to estimate actual evaporation fluxes from irrigated lands throughout growing seasons.

DOI: 10.1061/(ASCE)0733-9437(2007)133:4(395)

CE Database subject headings: Metric systems; Calibration; Evapotranspiration; Satellites; Water rights; Crops.

Introduction

Land surface evapotranspiration (ET) transfers large volumes of water from soil (evaporation, E) and vegetation (transpiration, T) into the atmosphere. Quantifying the consumption of water over large areas and within irrigated projects is important for water rights management, water resources planning, and water regula-

tion, especially in areas of water scarcity. ET refers to the combined E and T fluxes that show substantial spatial, diurnal, and seasonal variation and the operational use of ET over large areas requires nonpoint source data, whereas traditional point measurements are valid only locally. Satellite data are ideally suited for deriving spatially continuous fields of ET using energy balance techniques. Traditionally, ET from agricultural fields has been estimated by multiplying the weather-based reference ET by crop coefficients (K_c) determined according to the crop type and the crop growth stage. However, there is typically some question regarding whether the crops grown compare with the conditions represented by the idealized K_c 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 (Bastiaanssen et al. 2005; Allen et al. 2007) have provided accurate estimates of ET and K_c for large populations of fields and water users (Tasumi et al. 2005a) and quantified net ground-water pumping in areas where water extraction from underground is not measured (Morse et al. 2004).

The background and procedures of mapping evapotranspiration at high resolution with internalized calibration (METRIC) are described in Allen et al. (2007). METRIC has, as its foundation, principles and techniques used by the important model SEBAL, an energy balance model developed in the Netherlands and applied worldwide by Bastiaanssen (2000) and Bastiaanssen and associates (1995, 1998a,b 2005). In particular, METRIC uses the SEBAL technique for estimating the near surface temperature gradient, dT , as an indexed function of radiometric surface temperature, thereby eliminating the need for absolutely accurate sur-

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Note. Discussion open until January 1, 2008. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on November 17, 2005; approved on January 31, 2007. This paper is part of the *Journal of Irrigation and Drainage Engineering*, Vol. 133, No. 4, August 1, 2007. ©ASCE, ISSN 0733-9437/2007/4-395-406/\$25.00.

face temperature or for air temperature measurements.

METRIC is autocalibrated for each satellite image using ground-based calculation of alfalfa reference ET (ET_r) (based on hourly weather data). Accuracy and dependability of the ET_r estimate has been established by lysimetric and other studies in which we have high confidence (ASCE-EWRI 2005). Internal calibration of the sensible heat computation within SEBAL and METRIC and the use of the indexed temperature gradient eliminate the need for refined atmospheric correction of surface temperature (T_s) or reflectance (albedo) measurements using radiative transfer models (Tasumi et al. 2005b). The internal calibration also reduces impact of bias in estimation of aerodynamic stability correction or surface roughness. In fact, sensitivity analyses conducted by Tasumi (2003) showed that one can double or halve surface roughness and even eliminate atmospheric correction with generally less than 5% impact on any pixel. This seemingly lack of sensitivity to roughness and stability correction bias occurs only if *all* pixels are treated similarly, so that biases caused by this treatment (doubling or halving roughness or elimination of stability correction) are imbedded into the sensible heat calibration at the hot and cold pixels and then brought back out during application to all image pixels. The attributes of the internal calibration and substantial compensation for component estimation biases enhance the operational applicability of METRIC for important ET applications related to water rights management, water rights and water transfers, and hydrologic water balances.

The Idaho Department of Water Resources and the University of Idaho have developed a variety of METRIC applications. METRIC has been used to monitor water rights compliance and aquifer depletion, as a tool for water resource planning, and in hydrologic modeling (Morse et al. 2004). In the Rio Grande Valley of New Mexico, METRIC has been used to map ET from riparian vegetation and in the Imperial Valley of California, METRIC ET maps have been used to assess irrigation and salinity management. This paper describes the applications of METRIC in Idaho, New Mexico, and California, including comparisons with lysimeters using data from the Bear River Basin and from the USDA-ARS Research Laboratory near Kimberly, Id.

Comparisons against Lysimeter Measurements

Evapotranspiration lysimeters, which are usually constructed as large underground tanks filled with soil and vegetation, represent an excellent standard against which ET estimates can be compared. Lysimeters can, however, provide biased ET measurements if the vegetation inside and immediately outside the tanks does not have the same height, density, and moisture conditions as the vegetation of the surroundings (Pruitt and Lourence 1985; Pruitt 1991; Allen et al. 1991b,a). Therefore, lysimeters and corresponding data sets must be carefully scrutinized to ensure that the data are representative of general ET conditions. This has been done with the weighing lysimeter data sets collected by Dr. J. L. Wright, USDA-ARS, Kimberly, which constitute exceptionally high quality ET measurement data (Wright 1982, 1996) and with drainage lysimeter data sets from Dr. R. W. Hill, Utah State University near Montpellier, Id. (Hill et al. 1989; Morse et al. 2000). ET data from these two lysimeter data sets have been used to compare against ET estimated by METRIC applications in the two regions.

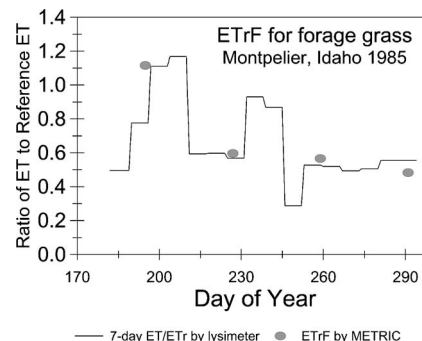


Fig. 1. Comparison of ET_r fractions (i.e., K_c) derived from 7 day lysimeter measurements near Montpellier, Id. during 1985 and values from METRIC for four Landsat dates (ET =crop ET and ET_r =alfalfa reference ET_r)

Lysimeters at Montpellier, Id.

In Phase I (R. G. Allen et al., unpublished report, 2003) of our study, ET maps were generated monthly for a 300 km $\times$ 150 km area (comprised of two Landsat image scenes) encompassing much of the Bear River basin of Idaho, Utah, and Wyoming. Images were processed for 1985, coinciding with an ET study using lysimeters (Hill et al. 1989) that allowed for comparison with ET by METRIC. Lysimeters near Montpellier, Id., just north of Bear Lake, had been near the corner of a large irrigated field planted to an irrigated native sedge forage crop characteristic of the area and local surroundings. The lysimeters had approximately 1 m² surface area and were about 1.2 m deep. ET was derived from weekly measurements of water table depth in the lysimeters and neutron meter readings of the soil profiles (Hill et al. 1989). ET from the three lysimeters was averaged to reduce random error and uncertainty in the ET measurements.

Daily ET on satellite image dates was calculated in this early METRIC application using an extrapolation of EF from image time to the surrounding 24 h period, rather than using ET_rF , where EF=evaporation fraction, defined as the ratio of ET to ($R_n - G$), all expressed in energy units, where R_n =radiation and G =soil heat flux density. ET_rF =fraction of reference ET, defined as the ratio of calculated ET to ET from the alfalfa reference (ET_r), both expressed as depths of evaporated water (Allen et al. 2007). Following the use of EF to extrapolate from instantaneous ET at satellite image time to ET for the day, a value for ET_rF was generated from the daily ET, using 24 h time steps, and was used to interpolate ET_rF between satellite images. ET_r is used for interpolation between image days because it accounts for changes in ET caused by weather variation between satellite image dates, including cloudiness. In more recent METRIC applications, ET_rF is used for extrapolation from instantaneous to daily ET, in place of EF, as well as for estimating ET for days in between image dates (Allen et al. 2007). In the Bear River application, the weather data were collected from a single weather station located within a few kilometers of the lysimeters. However, the “cold” pixel used to calibrate METRIC was located about 30 km west of the lysimeter and the “hot” pixel was located about 30 km to the NE.

Results for the four satellite images processed during the 1985 growing season (July 14, Aug. 15, Sept. 16, Oct. 18) are summarized in Fig. 1 and Table 1, where METRIC-based ET was sampled from 9 pixels in a large field of forage adjacent to the lysimeter having similar characteristics. The average standard de-

Table 1. Summary of METRIC- and Lysimeter-Derived ET for Weekly and Monthly Periods and the Associated Error for Bear River, 1985

	7 day Lys. ET ave. surrounding image date (mm day ⁻¹)	METRIC ET _F on image date	7 day METRIC ET surrounding image date (mm day ⁻¹)	Diff. in 7 day ET (METRIC-Lys) (%)	Monthly ET _r (mm)	METRIC monthly ET (mm)	Lys. monthly ET (mm)	Diff. in monthly ET (METRIC-Lys.) (%)
July	5.3	1.12	6.8	28	202	198	167	19
Aug	3.5	0.59	3.7	6	201	119	145	-18
Sept	1.9	0.57	2.1	10	115	66	54	22
Oct	0.7	0.49	0.6	-14	45	22	23	-5
July-Oct.	2.9	0.73	3.3	15	563	405	388	4

violation among the three lysimeters that were averaged was 0.18 in terms of K_c for the periods of comparison to METRIC. The results from this early METRIC application (made in 2000) compared well to lysimeter data for the last three image dates. The earliest date, July 14, compares well when examined in context of the impact of precipitation preceding the image date and rapidly growing vegetation during that period (Morse et al. 2000). The predicted monthly ET derived from the processed images averaged $\pm 16\%$ relative to the lysimeter at Montpelier (Table 1). However, the seasonal difference between METRIC and lysimeters, calculated by summing the ET over the 4 month period, was only 4% due to impacts of reduction in the random error components present in each estimate, such as random incidences of surface wetting by irrigation and in calculation of R_n , G , the near-surface temperature difference, and aerodynamic resistance. In addition, there may have been a random error in the lysimeter measurements.

Lysimeters at Kimberly, Id.

The comparisons of METRIC with measurements on the Snake River Plain have centered on the use of two precision-weighing lysimeter systems in place near Kimberly, Id., from 1968 to 1991. The lysimeter system was installed and operated by Dr. James Wright of the USDA-ARS (Wright 1982, 1996) and measured ET fluxes continuously for a wide range of weather conditions, surface covers, and crop types. Measurements of net radiation, soil heat flux, and plant canopy parameters were periodically made near the lysimeter site. The lysimeter data sets provided valuable information to verify METRIC over various time scales and for various conditions of ground cover. The hourly weather data were measured at the lysimeter site over the grassed field containing the USDA lysimeter 1. Weather measurements used to calculate ET_r were solar radiation, wind speed, air temperature, and vapor pressure measured by a chilled mirror system.

Nineteen Landsat 5 satellite image dates were processed for Kimberly, Id., covering the period between 1986 and 1991. These dates had quality lysimeter and cloud-free micrometeorological data and represent a combination of crop growth stages and times of the year. Eight images from 1989 are discussed here.

Constancy of the fraction of ET_r during a day. The success of METRIC is predicated on the assumption that ET_F for a 24 h period can be predicted from the ET_F from the instantaneous satellite image. This constancy is demonstrated here using Kimberly lysimeter data for both clear sky and cloudy conditions. The denominator ET_r in the ET_F calculation (Allen et al. 2007) serves as an index representing the maximum energy available for evaporation. The lysimeter data for intervening periods between image dates were used to assess the impact of various methods for extending ET maps from a single satellite image date to longer

periods. They were also used to assess the variability or constancy in ET_F over a day, where constancy of ET_F is a critical assumption made within the METRIC process (Allen et al. 2007). ET_r was calculated at Kimberly for hourly periods and summed to 24 h using the ASCE standardized Penman-Monteith method for an alfalfa reference (ASCE-EWRI 2005), representing the ET from a well-watered, fully vegetated crop, in this case, full-cover alfalfa 0.5 m in height. Weather data were measured near the lysimeter and included solar radiation, wind speed, air temperature, and vapor pressure.

An illustration of ET_F for a day in 1989 is given in Fig. 2 for cool season clipped fescue grass and sugar beets. The hourly ET_F observed for the grass showed some continuing decline during the afternoon, but ET_{F1100} was still similar to the daily average ET_F . Hourly ET_F for many days was more constant than that shown in the figures. Other examples are presented in Allen et al. (2007). In nearly all cases, the ET_F for the 24 h period is within 5% of the ET_F at around 1,100 h, which is close to Landsat overpass time. Lysimeter data analyses showed $ET_F = ET/ET_r$ to be preferable to the EF parameter used in some applications of SEBAL (Bastiaanssen et al. 1998b; Bastiaanssen 2000). The better performance by ET_F was due to its consistency during daytime and the general agreement between ET_F at satellite overpass time and daily ET_F . Figs. 3(a and b) show side-by-side comparisons of ET by the METRIC ET_F procedure versus lysimeter and ET by the EF method versus lysimeter for satellite image dates, where the SEBAL application was of 2000 vintage and where 24 h EF was assumed to equal EF at satellite overpass time. The daily ET estimates by METRIC on May 4th, June 24th, August 21st, and September 25th were particularly closer to measured ET than were daily estimates based on EF. During May 4th and June 24th, the air was dry (dewpoint during afternoon was 0°C on May 4th and 5°C on June 24th) and wind speeds were moderate to high ($> 5 \text{ m s}^{-1}$ between 0800 and 1700 h on May 4th and between 2.5 and 4 m s^{-1} on June 24th). The combination of low humidity and moderate to high wind speeds produced substantial advection during afternoon periods of these two days that was captured better by the ET_F extrapolation than by the EF extrapolation. Both of these days were clear. The afternoon of August 21st was clouded with relatively calm wind (1 to 2 m s^{-1}) and 10°C dewpoint. Therefore, no significant advection occurred on this day, but the change in solar radiation conditions between satellite time (clear) and afternoon (clouded) was again better captured by the ET_F extrapolation than by EF. Hourly weather data were missing for September 25th due to an afternoon storm having very high wind speeds and had to be estimated. The writers note that current versions of SEBAL ap-

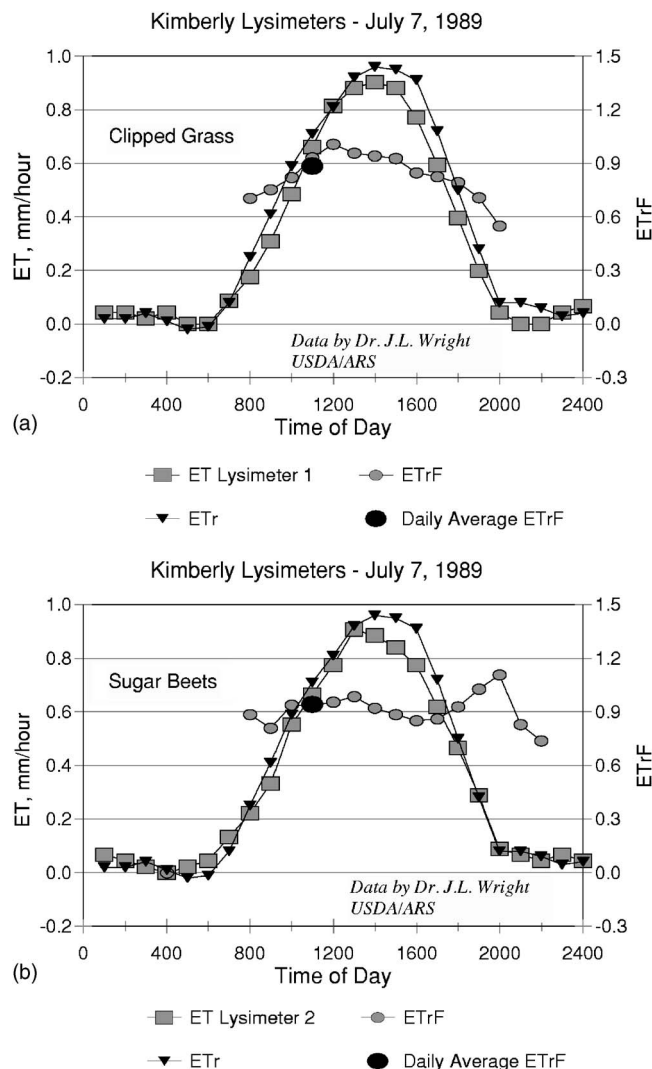


Fig. 2. Hourly measurements of ET, ET_r , ET_rF , and 24 h ET_rF for: (a) clipped grass; (b) sugar beets at Kimberly Id. on July 7, 1989 showing relative constancy of ET_rF during daylight periods

plied by WaterWatch (i.e., SEBAL2004) utilize procedures to adjust daily ET estimates for advection effects based on hourly weather data (WaterWatch 2006).

ET_rF from METRIC versus lysimeter. Fig. 4 shows ET_rF estimated by METRIC compared with ET_rF measured by lysimeter as a function of time during the sugar beet growing season for 1989, a year when a significant number (eight) of both lysimeter measurements of ET and Landsat images were available. Small round symbols represent daily ET_rF (i.e., K_c) derived from all lysimeter measurements with shading according to whether the day was clear, cloudy, or partly cloudy. The relative consistency among measured daily K_c shown in Fig. 4 among clear, partly cloudy, and cloudy days, especially during midseason when vegetation and soil wetness conditions were more consistent, suggests that ET_rF should be expected to be relatively constant between clear and cloudy portions of a day and between clear and cloudy days.

The triangles in Fig. 4 represent ET_rF derived from lysimeter on the image date and large square symbols represent ET_rF by METRIC for the image date. The METRIC ET_rF was extracted from processed Landsat images for the lysimeter field by sampling and averaging four 30 m pixels from near the center of the

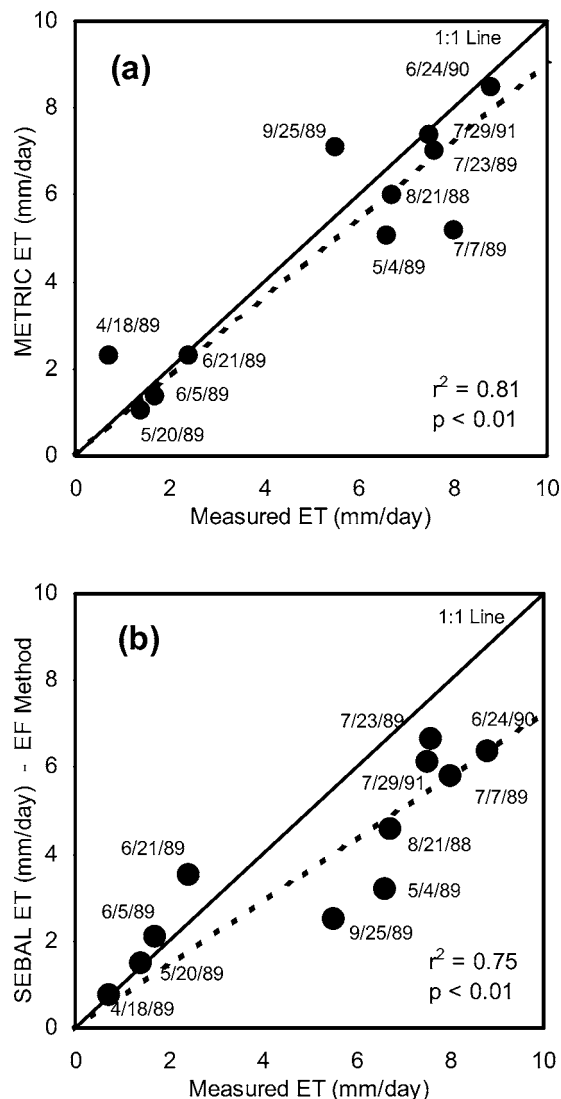


Fig. 3. Comparison of daily ET from METRIC using ET_rF (a); from SEBAL (version 2000) using EF (b) on satellite image dates for sugar beets (1989), potatoes (1988), peas (1990), and alfalfa (1991) compared against lysimeter measurements at Kimberly, Id. (measurement data from Dr. J. L. Wright, USDA-ARS) (graphed data from Trezza 2002)

lysimeter field which was planted to the same crop of sugar beets as the lysimeter. In Landsat 5 images, the six short-wave radiation bands have 30 m resolution, however, the single thermal band has only 120 m resolution. The small size of the lysimeter field (110 × 120 m) prevented procurement of Landsat-based samples from the field for all image scenes that were free of any influence, in the 120 m thermal band of Landsat 5, from areas outside the fields. This “thermal contamination” of some sampled pixels from the small lysimeter field created some degree of bias in METRIC estimated ET that were not present in the lysimeter ET measurements, and would not occur for large fields, which are commonly on the order of 800 × 800 m in southern Idaho. These occasions are noted in Fig. 4, where large dark squares indicate image dates where the METRIC ET_rF image was sampled over the lysimeter field with little thermal contamination from outside the field, and open squares indicate image dates when there was some thermal contamination of sampled pixels.

Table 2 summarizes the differences between METRIC and

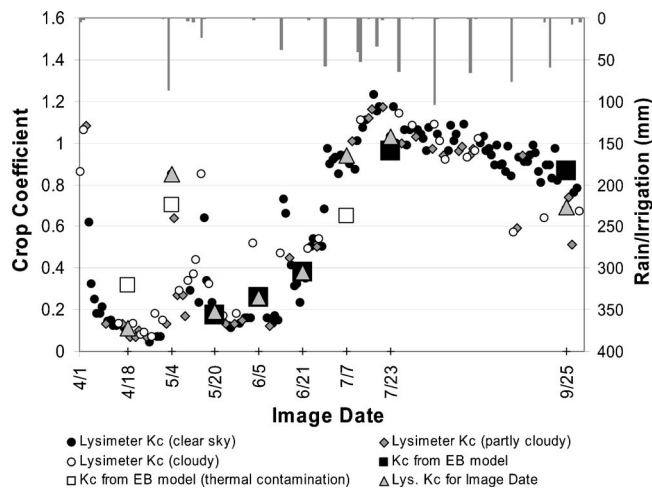


Fig. 4. Comparison of $ET_r F (K_c)$ by METRIC (EB model) and by lysimeter for sugar beets near Kimberly, Id. during 1989 (unpublished lysimeter data from Wright 2000, USDA-ARS, Kimberly, Id.) (adapted from Tasumi et al. 2005a)

lysimeter measurements during 1989. Absolute differences averaged 30% for the eight image days. When April 18th was omitted, the average absolute difference was only 14%. April 18th was before planting of the sugar beets and represented a period of drying bare soil following precipitation. The field at this time was nonuniform in wetness due to differential drying, and differences between lysimeter and METRIC computation were only 1 mm. However, the mean measured evaporation of less than 1 mm day^{-1} caused the percentage difference to exceed 100% for this low evaporative condition. The standard deviation of differences between METRIC and lysimeter over the time periods represented by each satellite image averaged about 20%. The standard deviation of differences from May to September was 13%. In comparison, a commonly quoted standard error for ET

prediction equations that are based on weather data, for example, Penman or Penman-Monteith-types of equations, is about 10% for daily estimates (Wright and Jensen 1978).

On the May 4th, 1989 date, the essentially bare soil inside the lysimeter was irrigated for 1 day following the irrigation of the surrounding field. Therefore, METRIC detected a somewhat drier condition and lower evaporation than did the lysimeter, as shown in Fig. 3. The agreement between METRIC and lysimeter was quite good for the mid-May through June period when the sugar beet crop was in the development stage and rapidly growing. This agreement shows good strength in METRIC calculations for estimating ET for partial cover conditions. The “hot” and “cold” pixels of METRIC (Allen et al. 2007) were selected from areas that were 5–30 km from the Kimberly lysimeter site and were therefore completely independent of the lysimeter field and conditions.

The difference between METRIC (714 mm) and the lysimeter measurement (718 mm) was less than 1% for the growing season ET of the sugar beet crop. It appears that many of the differences occurring on individual dates were randomly distributed, and tended to cancel. The random components and reasons for canceling are described in Allen et al. (2005, 2007).

Applications for Water Resources

Idaho Applications

Nine separate applications and usage of the METRIC ET model and data have been made in Idaho by the Idaho Department of Water Resources (IDWR) and University of Idaho. These applications have been made to: (1) estimate water budgets for hydrologic modeling; (2) monitor compliance with water rights; (3) support water resources planning; (4) estimate aquifer depletion; (5) support ground-water model calibration and operation; (6) estimate water use by irrigated agriculture; (7) estimate historical water use for water rights transfers; (8) develop populations of K_c

Table 2. Summary and Computation of ET during Periods Represented by Each Satellite Image and Sums for April 1–September 30, 1989, for Lysimeter 2 (Sugar Beets) at Kimberly, Id. (Lysimeter and Weather Data by Dr. J. L. Wright)

Image Date	Lys. ET on date (mm day^{-1})	METRIC ET on date (mm day^{-1})	Error on Image Date (%)	ET_r on date (mm day^{-1})	ET_r for period (mm)	Lys. ET summed daily for period (mm)	Lys. ET for period based on image date only (mm)	METRIC ET for period (mm)
April 18, 1989	0.73	1.74	139	6.78	147	28	16	38
May 4, 1989	6.61	5.09	−23	7.76	94	30	80	62
May 20, 1989	1.37	1.34	−2	7.27	90	22	17	17
June 5, 1989	1.73	1.78	3	6.68	118	24	30	31
June 21, 1989	2.39	2.54	6	6.33	127	62	48	51
July 7, 1989	7.96	5.89	−26	8.44	120	116	113	84
July 23, 1989	7.64	7.17	−6	7.38	253	266	262	246
September 25, 1989	5.51	7.40	34	8.00	201	171	138	186
April 1–September 30, 1989						718 ^a	705 ^b	714 ^c
Percent	Error					—	−1.8%	−0.6%

^aThe sum of daily measurements computed as the sum over all days between Apr. 1 and Sept. 30.

^bThe sum of ET for each lysimeter period, computed by multiplying summed ET_r during the period by the $ET_r F$ for the image date.

^cThe sum of ET by METRIC for the lysimeter field, computed by multiplying the summed ET_r during the period by the $ET_r F$ computed on the image date by METRIC.

curves and to establish mean K_c curves for south-central Idaho; and (9) evaluate relative performance of an irrigation canal company by comparing ET with diversions.

1. *Water budgets.* Water budgets have been made for large portions of the lower Boise Valley in Idaho and the eastern Snake Plain Aquifer in Idaho to improve accuracy of hydrologic models and projections of effects of system management. The U.S. Bureau of Reclamation and IDWR have improved quantification of irrigation diversions from the Boise River and irrigation return flow into the river. The third main component of the water balance, ET, has been quantified using monthly and annual ET maps derived from METRIC to better calibrate remaining components. The Boise Valley has experienced rapid population growth and changing water consumption and the improved water balance is important for current management and for future planning (Petrich, 2004a,b; Interim Legislative Committee on Natural Resources 2004).

2. *Water rights.* IDWR has tested and implemented a methodology to identify diversions that do not have a water right by using water right place-of-use polygons and Landsat TM false-color composite data in GIS. However, the technical means to identify someone using water “in excess of the elements or conditions of a water right” is more problematic. IDWR has tested METRIC as an operational regulatory tool for administering water rights to identify those fields onto which water was applied in violation of some aspect of the water right, in this case the maximum rate of diversion. The 2002 test covered part of the Eastern Snake River Plain, an area in Landsat path-row 39/30. The test was a comparison of permitted groundwater pumping rates with ET for water-right places-of-use (POU) during the period of peak water demand in July. The comparison was done for 426 water rights in the study area and required comparing the theoretical depth of water applied to each area associated with a POU for the time frame with the depth of ET as determined by METRIC. The test utilized METRIC ET from two Landsat images taken 16 days apart, where ET results were made available to water rights analysts within 14 days of the second overpass. Eighteen potential violations were identified, of which fifteen turned out to be false due to problems with the IDWR water rights file. The enforcement process using METRIC was demonstrated to offer a significant improvement over the present method that uses electrical power records. METRIC data can be processed for analysis during the same irrigation season, which allows enforcement actions to be brought in a timely manner. Analysis of power meter records generally cannot be accomplished during the irrigation season due to the reporting protocols and restrictions on personnel time (T. Morse, personal communication, 2004).

3. *Water Planning.* IDWR is responsible for comprehensive river basin planning in Idaho. One of the important issues that planners must contend with involves changes in water availability in river basins that are rapidly changing from agricultural land use to more urban land uses. Water planners at IDWR need to understand how the demand for water will be affected during the next 50 years by the transition of land from irrigated agriculture to residential, commercial, and industry. The U.S. Bureau of Reclamation and IDWR have previously cooperated to generate a land-use/land-cover (LULC) classification of the Boise River Valley for the year 2000 from 1:24,000-scale aerial photographs. The classification consists of 24 LULC classes in a vector format. The availability of detailed LULC classes has enabled IDWR to combine the LULC classification with METRIC ET data to generate ET by land cover class. Values for ET from METRIC by LULC

Table 3. Ranked Mean Seasonal ET (March 15–October 15) by Land Use/Land Cover Class in the Boise Valley during 2000

Class name	Seasonal ET (mm)	Standard deviation (mm)	Coef. variation	Area (ha)
Wetlands	1,030	290	0.28	5,900
Open water	920	170	0.18	5,300
Recreation	830	250	0.31	2,100
Perennial vegetation	820	210	0.26	2,700
Irrigated crops	810	190	0.23	141,100
Canal rights of way	730	200	0.28	2,700
Urban residential	680	160	0.23	4,100
Rural residential	660	190	0.29	10,200
Farmsteads	610	190	0.31	2,200
New subdivisions	610	150	0.24	11,500
Sewage treatment	550	260	0.46	200
Public	550	260	0.48	2,100
Other agriculture	540	240	0.45	2,900
Dairy	520	180	0.35	600
Feedlots	480	210	0.43	1,700
Junk yards	470	190	0.41	100
Abandoned agriculture	460	210	0.46	1,800
Transition	440	200	0.45	2,700
Idle agriculture	440	220	0.49	3,000
Transportation	420	220	0.53	2,300
Commercial and industrial	380	200	0.52	5,800
Barren	340	260	0.77	1,900
Unclassified	300	240	0.80	12,700
Rangeland	240	160	0.66	90,600
Petroleum tank yards	240	110	0.47	18

class are summarized in Table 3. Wetland systems had higher ET than evaporation from open water due to the greater net radiation capture by wetland vegetation surfaces than by water surfaces. A substantial amount of net radiation captured by open water penetrates into the water body and is converted to heat rather than to evaporation. ET from “abandoned agriculture” was about double that of rangeland, apparently due to some periodic watering or presence of some riparian systems or higher precipitation than rangeland due to location at higher elevations in the valley.

4. *Aquifer depletion* and 5. *Ground-water modeling.* The Idaho Water Resources Research Institute (IWRI) associated with the University of Idaho has recently recalibrated MODFLOW ground-water models for the eastern Snake River Plain (ESRP) aquifer (Cosgrove et al. 2004) and for the Boise Valley aquifer (Petrich 2004a, b). Spatial ET information derived from METRIC (unpublished report, A. Morse et al. 2001; R. G. Allen et al. unpublished, 2001; Kramber 2002) significantly improved accuracy of estimated distribution and quantities of depletions from the aquifers caused by pumping, as well as improving estimates of incidental recharge to the aquifers stemming from irrigation diversions from the Snake and Boise Rivers. The result was more accurately calibrated ground-water flow models that are being used in large-scale mitigative and litigious studies involving conjunctive use of ground water and surface water resources.

6. *Water use by irrigated agriculture.* Historically, surface water diversions have been closely monitored within Idaho, whereas ground water diversions were not monitored. There are approximately 300 monitored diversions from the Snake River that irrigate approximately 647,500 ha on the Eastern Snake River

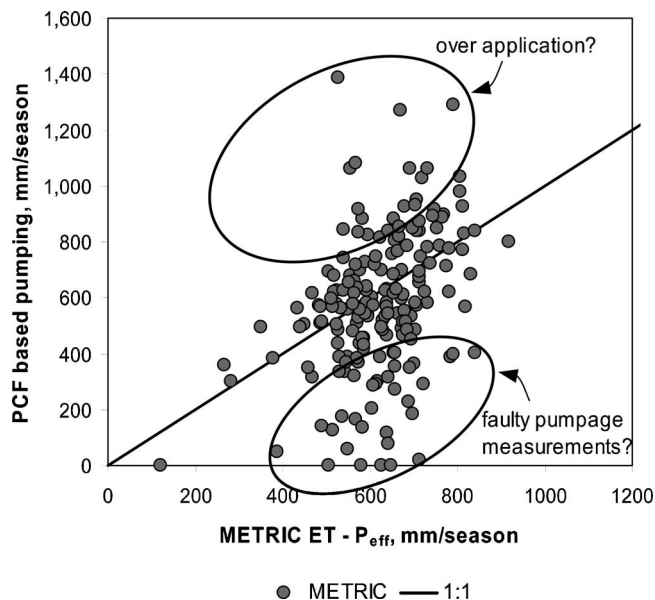


Fig. 5. Groundwater pumpage from power consumption records versus METRIC ET in millimeters for the period April–October, 2000

Plain. The eastern half of this same area also supports approximately 200,000 ha of ground water irrigation from approximately 5,000 wells. From a logistical point alone, monitoring ground-water use is a large endeavor, and the majority of these wells are not equipped with flow-measurement devices, so that electrical power consumption records must be utilized to estimate water use.

To assess relative uncertainty in the quantification of depletions by pumping, IDWR evaluated correlations between METRIC ET and ground-water use estimated using electric power consumption factors (PCF). An estimated 98% of ground water is pumped from the region of interest using electrical power. The PCF values are unique to each farm irrigation system and are developed using single or periodic measurement of farm irrigation system discharge and associated electrical power consumption. Seasonal volumes of ground water pumped by farms are then estimated by summing power consumption over the season and multiplying by the farm PCFs. The analysis evaluated ET from the field or fields covered by individual water rights as integrated from METRIC products and as estimated from power consumption for identified POU in water rights. Ground-water pumping estimates for 184 POUs versus ET from METRIC, less estimated effective precipitation (P_{eff}) during the growing season, are shown in Fig. 5. Whereas the r^2 for the relationship is only 0.14, some relation is evident ($p=0.70$). The relationship would shift upward for some POUs if adjusted for consideration of pre- and postseason irrigation by farmers to build soil moisture that was not included in seasonal power consumption totals. Points showing zero or nearly zero pumping but substantial ET reflect under-reporting of power consumption data or use of some alternative water supply. Discussions within IDWR have placed more confidence in the METRIC results than in the pumping records for use in estimating net aquifer depletion due to questions concerning repeatability and consistency of power consumption factors, as these change with system management changes by farmers and with ground-water surface drawdown during the growing season, whereas a constant PCF is assumed by IDWR.

IDWR has estimated a 5:1 cost advantage of using METRIC and Landsat coverage to estimate ground-water depletions as compared to the current usage of PCF that require occasional pump discharge measurements and system audits and reporting (T. Morse, personal communication, 2003).

7. *Historical water use for water rights transfers.* Seasonal METRIC ET maps for southern Idaho have been integrated over irrigation project areas by IDWR to quantify historical water use by irrigation projects. The historical water use has been used during negotiated retirements or transfers of water rights and associated dry-up of some high-lift irrigation projects along the Snake River to release consumptive use components to downstream endangered species mitigation. Consumptive components are utilized in buyout and assessments as nonconsumed components already return back hydrologically to the Snake River. ET integrated from METRIC, less ET from natural rainfall, has been compared to historical pumping records by farmers and with traditional crop coefficient based estimates during negotiations to resolve differences in estimates of consumed volumes for purchase.

8. *Populations of crop coefficients and mean K_c curves.* Satellite image scale maps of ET and ET_F have enabled us to investigate statistical behavior of ET and K_c for large populations of fields. A study by Tasumi et al. (2005a) evaluated distributions of K_c by specific crop type over space and time for large numbers of fields in southern Idaho using ET maps created by METRIC. Crop types were determined from a series of satellite-derived vegetation indices (NDVI) using a combination of supervised and unsupervised classification based on a population of ground-truthed crop types. The distribution of K_c had a strong relation to NDVI. However, variation in K_c was found to be substantially larger than the variation in NDVI because of the impacts of random wetting events, especially during initial and development growth stages that are not reflected in NDVI. The large variation in K_c is illustrated in Figs. 6(a–d) for crops of potatoes, sugar beets, winter grain (wheat and barley), and alfalfa. Each individual point in the figures represents ET_F (i.e., K_c) sampled from an individual field on a particular image date. Twelve Landsat images were processed during 2000 and were used to define seasonal K_c curves. The heavy lines and symbols in Figs. 6(a–d) represent K_c averaged over all sampled fields and approximate average, actual K_c for the specific crop for the southcentral Idaho region for year 2000.

Bell-shaped curves in Figs. 6(a–d) plotted vertically on each image date are smoothed probability density functions representing the distribution of individual K_c values. Distributions were wider and more skewed during initial and late portions of growing seasons when evaporation from soil is a dominant factor. During midseason periods with nearly complete or full ground cover, effects of wet soil surfaces are largely suppressed and the distributions of K_c are more tightly grouped and with less skewness. Impact of pre-season precipitation on soil evaporation in mid-March (first image date) is visible for all crops, and especially for winter grain, which exhibited higher K_c in March due to vegetation growth prior to winter dormancy. Residual evaporation following harvest of the winter grain crop is expressed as positive values for K_c during August and September (days 230 on). Effects of typically four harvests (cuttings) of alfalfa during the growing season are evident in the seasonal patterns in K_c observed for alfalfa.

The average K_c curves derived from the METRIC application were compared with two families of K_c curves that have been widely used in Idaho for crop management and water rights regu-

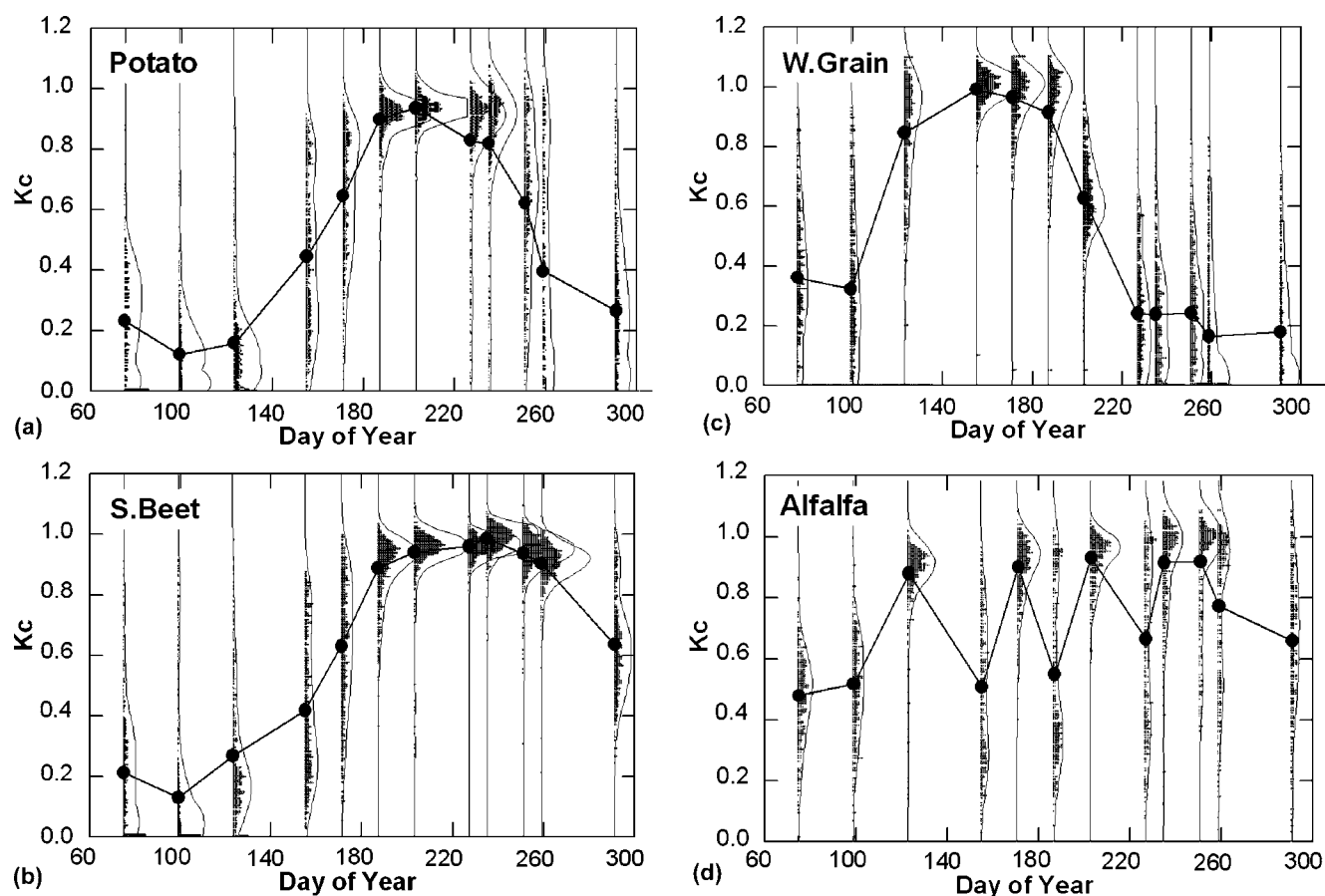


Fig. 6. Values of K_c (small dots) sampled from hundreds of fields from METRIC-derived K_c maps for twelve image dates during 2000 near Twin Falls, Id. and averages over all fields (large circles) for (a) potatoes; (b) sugar beets; (c) winter grain; and (d) alfalfa (bell-shaped curves represent smoothed probability density functions for each image date) (adapted from Tasumi et al. 2005a)

lation. The traditional curves were from Allen and Brockway (1983) and from the AgriMet internet based system operated by the U.S. Bureau of Reclamation (AgriMet 2002). Both sets of traditional curves are traceable to K_c curves developed by Wright (1981) using the weighing lysimeter systems near Kimberly. The AgriMet K_c curves are adjusted each year to account for variation in mean cropping dates. For most crops, agreement between METRIC averaged curves and those from Allen and Brockway (1983) and from AgriMet agreed well in magnitude and in timing (Tasumi et al. 2005a). In some cases, however, curves from the various sources disagreed primarily in time. An example of this is presented in Fig. 7, where the mean K_c curve determined from METRIC lagged behind the reported AgriMet K_c curve by about 20 days. Adjustment to the key cropping dates of emergence, effective full cover, and harvest that are used to construct the AgriMet curves (Wright 1981) was effective in forcing the AgriMet curves to agree better with those from METRIC [Fig. 7(b)]. This example illustrates the utility of using METRIC as a means for establishing key cropping dates for general observed field conditions for an area by which representative cropping dates and curves can be assembled.

9. Relative performance of irrigation projects. Quantification of evapotranspiration over large areas is valuable for monitoring relative performance of irrigation projects, where total ET from a project can be compared against total diversions. The following illustrates a monitoring process for the 106,000 ha (261,000 acre) Twin Falls Canal Company (the Company) project in northern

Twin Falls County of Idaho. Irrigation water is diverted by the Company from the Snake River and is transported via three primary gravity canals. Within the 106,000 ha tract, approximately 4,300 ha are classified as city or town and 7,200 ha are identified as canyon/riparian, leaving approximately 93,500 ha classified as potentially irrigated agricultural lands (R. G. Allen and C. E. Robison, unpublished internal report, 2004). Of these 93,500 ha, gravity delivery is possible to 81,700 ha (202,000 acres). The primary farm irrigation method is furrow irrigation on silt loam soils and major crops are alfalfa, sugar beets, winter and spring grain, corn, beans, peas, and potatoes. This particular analysis for Twin Falls Canal Company was done at the request of the Company to help them identify constraints to delivery of water during specific months and to assess the impacts of drought and reduced divertable river supplies in 2003 on project ET.

Landsat images were processed for the Twin Falls regions for the 2000 and 2003 growing seasons and ET for these years was compared against net diversions by the project. In 2003, with the demise of usable images from the Landsat 7 satellite (launched in 1998 and damaged in May 2003), only Landsat 5 images were available, and no cloud-free Landsat 5 images were taken during September–October. Therefore, only the April–August period of 2003 was evaluated. For the entire 2000 irrigation season, March through October, the canal company diverted approximately 1,440 million m^3 (1,165,000 acre ft) compared with 722 million m^3 (585,000 acre ft) of ET from the entire tract, determined by integrating seasonal ET maps from METRIC over

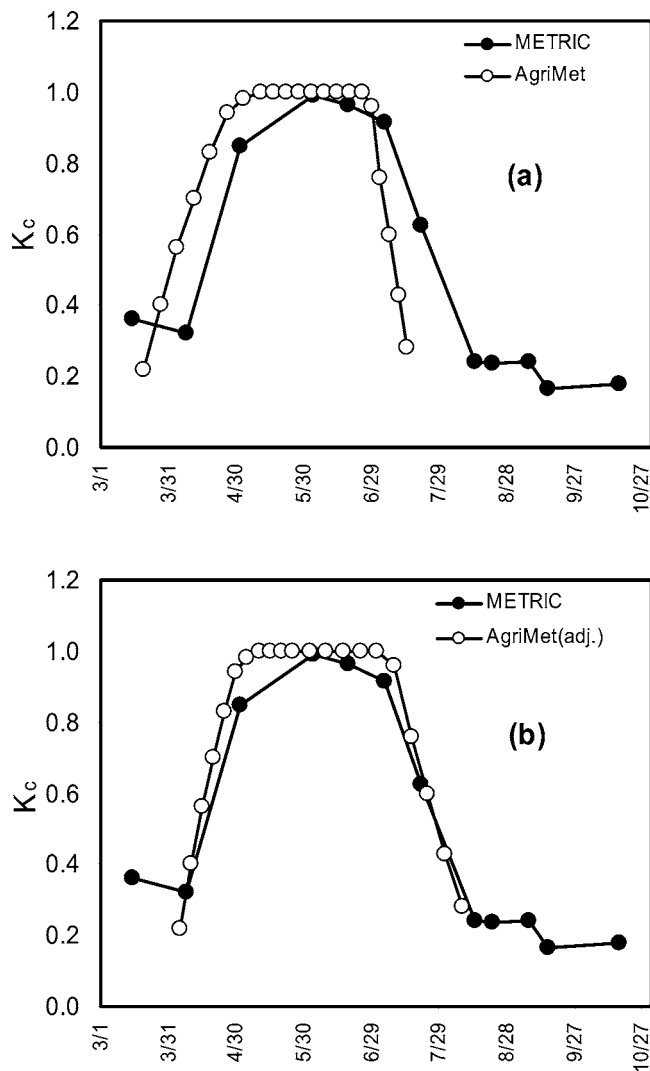


Fig. 7. Average K_c curves from METRIC for winter grain in southcentral Idaho during 2000 and AgriMet system K_c curve for winter grain as originally presented (a); following adjustment of emergence, effective cover and harvest dates for the AgriMet curve to better fit the METRIC curve (b) (adapted from Tasumi et al. 2005a)

the canal coverage area. The seasonal ET volume totaled 50% of diversions. For 2003, the April through August diversion was, 1,015 million m^3 with an associated integrated ET from all zones of 562 million m^3 , or 55% of diversions.

The monthly distribution of ratios of ET to diversions (plus precipitation) for Twin Falls tract is shown in Fig. 8. Diversions were higher in 2000 than during 2003, in contrast with the overall ET volumes during corresponding April–August periods, which were lower in 2000. The percentage of ET relative to total water supply increased by 9% for 2003 as compared with 2000 for April–August. When rainfall during the April–August period was considered by adding rainfall volumes to diversions, ratios of ET to diversions was 40 and 46% for 2000 and 2003. These values are within 6% of each other because of higher rainfall volumes in 2003. The fractions of diversions plus precipitation that is evaporated are considered to be reasonable given surface irrigation methods and long lengths of canals. The nonevaporated fractions of diversions are stored in soil, contribute to ground water recharge, or return to the Snake River via surface and subsurface flows.

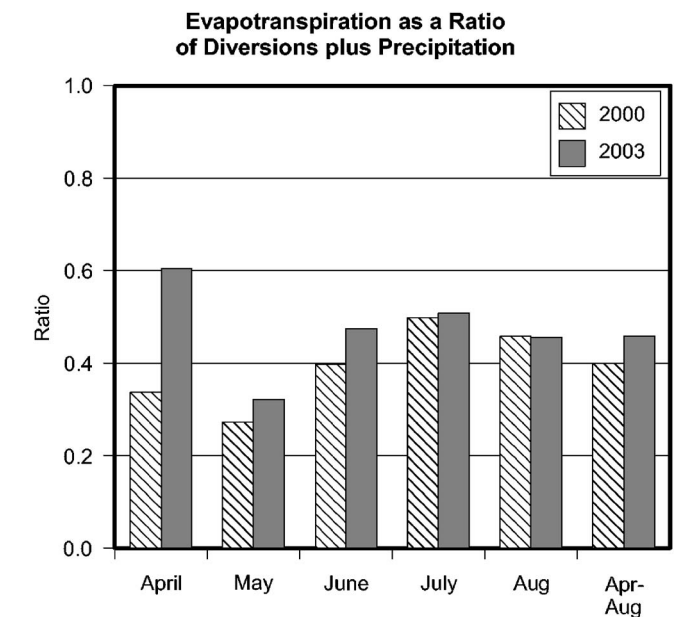


Fig. 8. Monthly ratios of ET to diversions by the Twin Falls tract and precipitation during 2000 and 2003

Applications in the Imperial Valley

Evapotranspiration maps have been created for much of Imperial Valley, Calif. using METRIC and Landsat 7 images for the January–March periods of 2002 and 2003 (R. G. Allen et al. unpublished report, 2003). One use of the high resolution maps from Landsat was to compare ET from “lower” ends of surface irrigated fields in the Imperial Irrigation District with ET from “higher” ends of the same fields to assess whether ET from lower ends of surface irrigated fields suffered due to low irrigation uniformity or from effects of salinity and inadequate leaching of salts. More than 4,000 fields were sampled after buffering in 75 m from field boundaries to avoid sampling Landsat ET pixels that may have suffered from some thermal contamination from areas outside the field. Results are shown in Fig. 9 for the January–March 2003 period, where vegetation amounts, as represented by the NDVI index [see Allen et al. (2007) for definition of NDVI] are plotted for the low quarters of fields versus NDVI for high quarters of fields and ET_F for low quarters of fields are plotted versus ET_F for high quarters of fields. As shown in Fig. 9, no significant differences were found between NDVI or ET_F between high quarters of fields and low quarters, indicating that water salinity, coupled with irrigation uniformity, was not causing reduction in crop growth and ET. However, because the lowest and highest 75 m of each field were not included in the sampling and analysis, some impacts typically displayed at the extreme ends of fields might have gone undetected. Other uses of METRIC in Imperial Valley were to quantify ET from riparian systems and from city land uses to improve ET estimates used in project water balances.

Applications along the Middle Rio Grande

METRIC was applied with Landsat 5 and 7 images during 2002 to spatially and temporally quantify ET from irrigated crops and riparian vegetation (native and invasive tree species and wetlands) along the Middle Rio Grande River of northern and central New Mexico. The high resolution of Landsat was extremely valu-

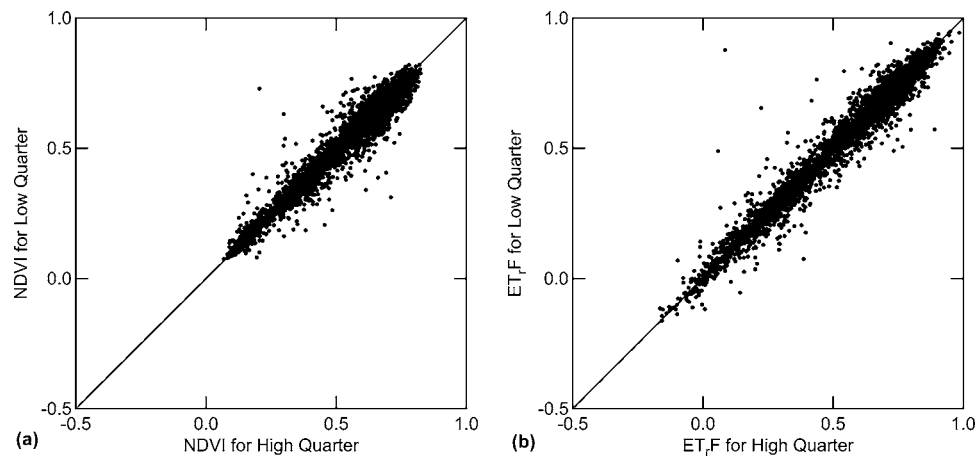


Fig. 9. NDVI index for the low quarters of fields versus NDVI for high quarters of fields (a); ET,F for low quarters of fields versus ET,F for high quarters of fields (b) for the January–March 2003 period for 4,000 fields within Imperial Irrigation District of California (adapted from R. G. Allen et al., unpublished report, 2003)

able for assessing ET on a field by field basis and for estimating ET from riparian (tree) systems that were often less than 100 m in width. One outcome of the application was the assessment of amounts of evaporation occurring from abandoned agricultural fields along the Middle Rio Grande Valley having high water table conditions. The high water tables have precluded farming operations and supply water to the surface for nonbeneficial evaporation. Fig. 10 shows monthly evaporation (ET) from identified waterlogged fields along the Middle Rio Grande River of New Mexico as determined by METRIC along with monthly precipitation. The evaporation from the high water table soils exceeded precipitation during all months, especially those during springtime. Reducing these evaporation losses by lowering water tables would constitute a real conservation of water in the valley.

Fig. 11 shows a frequency distribution of monthly and seasonal ET for cottonwood and salt cedar along the Middle Rio Grande Valley between San Acecia (near Socorro) and Cochiti (near Santa Fe) derived from METRIC ET maps and land use classifications during 2002. ET from salt cedar had larger variance due to its tendency to grow across a wider range of water availability (water table depth), soil types, and salinity conditions, whereas cottonwoods are typically found close to stream channels.

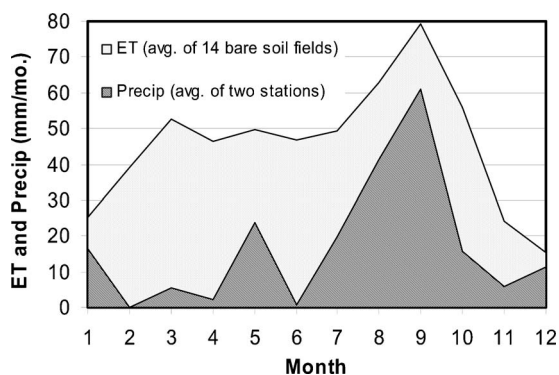


Fig. 10. Monthly evaporation (ET) from waterlogged fields along the Middle Rio Grande River of New Mexico as determined by METRIC versus monthly precipitation

Applications with MODIS

Much of the utility of METRIC is with Landsat imagery or imagery having similar resolution (and a thermal band) so that field-level detail can be defined. Unfortunately, problems with Landsat 7 in 2003 and recent problems with the aging Landsat 5 have revealed the vulnerability of these two satellites with high resolution thermal bands. Therefore, there is a need to look elsewhere for thermal imagery coincident with short wave. One such system is the MODIS Terra and Aqua satellite system. The MODIS Terra satellite, activated in 2000 by NASA, is a large format polar orbiting satellite that acquires short-wave and thermal images for all parts of the earth's surface at least once per day (NASA 2000). MODIS Aqua was activated in 2002. Although the temporal frequency of MODIS is much vaunted by some, it is seriously compromised by large view angles on many days, causing blurring, and the spatial resolution of MODIS is insufficient to provide the same level of information as Landsat. MODIS images on at least two of every three days for a specific location are acquired from such a large, lateral distance (i.e., from a large view angle), that the pixel size for short-wave information stretches from the specified size of 0.5×0.5 km to an effective $1 \text{ km} \times 1.5 \text{ km}$ size and thermal pixels stretch from the specified size of 1×1 km to an effective $2 \text{ km} \times 3 \text{ km}$ size. This "blurring" of the image is problematic for determining "crisp" ET images from which individual land holdings (farms) can be identified. An example of the blurring is shown in Fig. 12, where the top portion of the figure is an image of ET,F from METRIC determined using a Landsat 5 image ($30 \text{ m} \times 30 \text{ m}$ pixel size for short wave and $120 \text{ m} \times 120 \text{ m}$ pixel size for thermal) for a land area in south-central Idaho comprised of irrigated agriculture and desert, and the lower left image is for the same area, but processed by METRIC from the MODIS Terra image corresponding to the same date (August 31, 2003). The substantial blurring and lack of clarity and definition of individual fields is striking. The effective view angle from the MODIS satellite to the area of interest was 57° . The lower right-hand portion of Fig. 12 shows ET,F from METRIC and MODIS for the same area, but using a MODIS image for August 9, 2004, when a near nadir view angle (2°) for the area occurred. The improvement in definition of spatial ET over the August 31, 2003 MODIS image is substantial, but still significantly less than

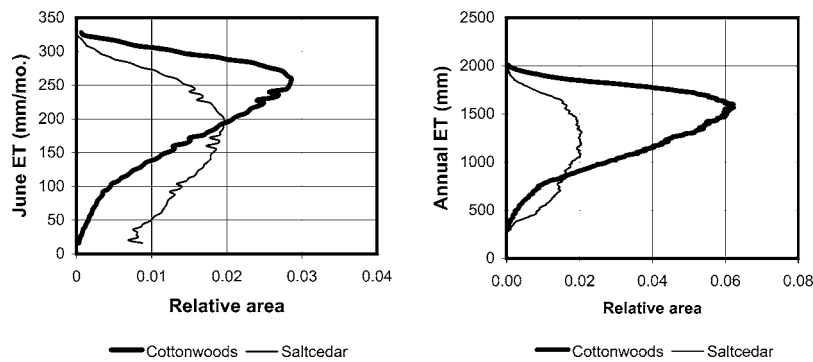


Fig. 11. Estimated frequency distributions of ET from 6,000 ha of cottonwood and salt cedar along the MRG between Cochiti and San Acacia, N.M. during June and all of 2002

possible from Landsat, where outlines of individual center pivot irrigated fields are discernible. These fields are not discernible from any of the MODIS images.

The potential accuracy of METRIC when applied with MODIS is nearly as good as with Landsat when ET is integrated over areas of at least 10×10 km (Hong et al. 2005). This type of resolution is useful for basin scale water balance and hydrologic studies, but is much less useful for water rights management and use in litigation.

Summary and Conclusions

METRIC uses digital image data collected by Landsat and other remote-sensing satellites that record thermal infrared, visible, and near-infrared radiation from the earth's surface. ET is computed on a pixel-by-pixel basis for the instantaneous time of the satellite image. The process is based on a complete energy balance for each pixel, where ET is predicted from the residual amount of

energy remaining from the classical energy balance, where $ET = \text{net radiation} - \text{heat to the soil} - \text{heat to the air}$.

In comparisons with evapotranspiration lysimeters in the Bear River basin and near Kimberly, Id., differences between METRIC and the lysimeters for growing seasons were less than 4%. These comparisons represent a small sample, but are probably typical. Errors as high as 10–20%, if distributed randomly, could probably be tolerated by state water resource departments and other water management entities. Comparisons of METRIC ET with weighing lysimeter data at Kimberly, Id. from the 1980s and early 1990s provided valuable information on the conditions required to obtain maximum accuracy with METRIC and best procedures for obtaining ET monthly and annually. ET was calculated for the entire Snake River Plain of SE Idaho and has improved the calibration of ground-water models by providing better information on ground-water recharge as a component of water balances. Ground-water pumpage from over 5,000 wells has been estimated using ET from METRIC through correlations between ET and pump discharge at measured wells and then extrapolating over large areas using ET maps from METRIC.

Reasons why METRIC is attractive to western water resources management are:

- METRIC calculates *actual* ET rather than *potential* ET and does not require knowledge of crop type (no satellite-based crop classification is needed);
- METRIC 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 reference ET_r in calibration of METRIC and the use of $ET_r F$ 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 =alfalfa reference ET calculated using the ASCE-EWRI standardized Penman-Monteith equation (ASCE-EWRI 2005). This congruency is valuable for using ET maps generated by METRIC water rights management where water rights are based on previous $K_c ET_r$ calculations; and
- METRIC is autocalibrated 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.

ET maps created using METRIC, SEBAL, and similar remote-sensing based processing systems may some day be routinely used as input to daily and monthly operational and planning models for reservoir operations, ground-water management, irrigation

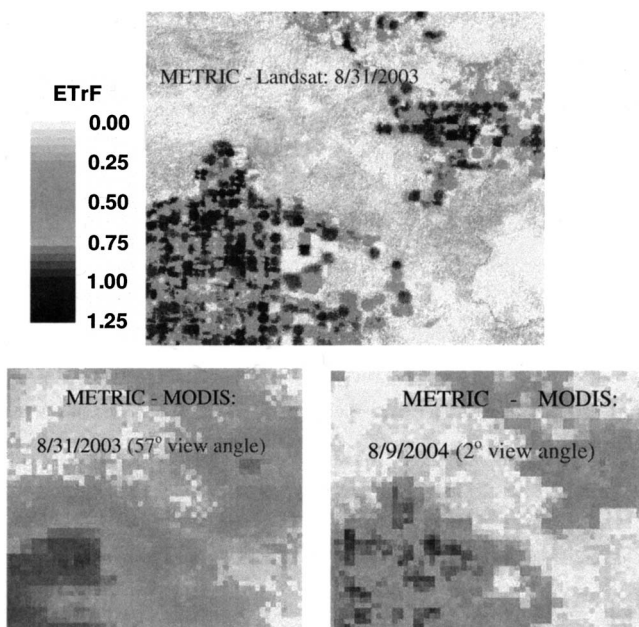


Fig. 12. $ET_r F$ by METRIC from a 25×25 km area of desert and irrigated agriculture in southern Idaho from Landsat and MODIS images

water supply planning, water rights regulation, and hydrologic studies.

Acknowledgments

The writer acknowledges long-term lysimeter data collection by Dr. James L. Wright, USDA-ARS, Kimberly, Id. and Dr. Robert W. Hill, Utah State University, that provided the means for comparing ET measurements with ET estimated by METRIC. Funding for the various applications and development came from NASA, Raytheon, U.S. Department of Agriculture, Idaho Department Water Resources, U.S. Bureau of Reclamation, Metropolitan Water District of Southern California, U.S. Department of Justice, Keller-Bliesner Engineering, Idaho Agricultural Experiment Station, Idaho Engineering Experiment Station, and Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria of Spain. The writers acknowledge the very helpful comments and suggestions by reviewers to improve clarity of this manuscript.

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