Evapotranspiration Mapping for Water Security: Recommendations and Requirements

Recommendations from the Participants of
the 2015 Workshop on Evapotranspiration Mapping for Water Security
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Purpose and Background

This white paper focuses on the societal benefits and applications of satellite mapping of evapotranspiration (ET) and its use to address a wide range of water resource management challenges and information needs. It summarizes the findings, conclusions and recommendations from the participants of the *2015 Workshop on Evapotranspiration Mapping for Water Security.* The workshop was convened to: i) capture and highlight progress in the use of satellite data to map ET to address a range of water resource management challenges in the U.S. and internationally; ii) identify current challenges in operational use of satellite-derived ET data; and iii) identify the requirements for future satellite missions to address current and future challenges. The workshop was sponsored by the NASA Applied Sciences Program and the World Bank and organized by the University of Idaho, University of Nebraska, NASA, the World Bank, USDA and USGS. The workshop was attended by 154 participants, including scientific experts on remote sensing of ET, water resources managers, representatives from the agricultural community and state engineers offices, and consumers of ET data. The workshop agenda and presentations are available at https://c3.nasa.gov/water/resources/10/. The full list of workshop contributors and participants is included in Appendix A. This white paper was prepared by the authors on behalf of the workshop participants. The workshop recommendations and findings were distributed to workshop participants for review and comment.

I. Societal Benefits of Evapotranspiration Mapping with Satellite Data

There have been great advances within the past several decades in our ability to compute and map ET over large areas through the use of satellite-based remote sensing and geospatial models. Within the U.S., a broad spectrum of federal, state, and local agencies, as well as commercial entities, are making significant investments in operational use of remotely-sensed ET data to address a wide range of water resources management challenges. As of 2015, there are at least twenty-two U.S. states where Landsat-based ET data are used for water resources monitoring and management (e.g., https://www.idwr.idaho.gov/files/gis/METRIC_in_Other_States.pdf). Use of ET data to address a range of international water resources management challenges is also rapidly increasing. Examples presented at the 2015 workshop include applications of ET data for drought monitoring, water planning, estimating aquifer depletion, water rights compliance, quantifying agricultural water use, irrigation management, nutrient management, hydrologic modeling, protection of endangered species, legal finding-of-fact, development of water markets, water rights buy-back, monitoring in-season water demand, and tribal water rights negotiations. In each of these applications, use of ET data has supported important improvements in decision-making and contributed to increased resiliency to a range of threats to water security and the sustainability of agricultural production. Descriptions of these applications include: Allen et al. (2007b); Anderson et al. (2012a,b); Kilic et al. (2010, 2012); Burkhalter et al. (2013); Semmens et al. (2015); and https://www.idwr.idaho.gov/GIS/mapping-evapotranspiration/.

II. Key Questions

Key science questions associated with satellite mapping of ET to address water and food security challenges are listed below.

1) What is the consumptive use of water in agriculture at the scale of individual fields, and how is consumption changing over time?
2) What is the relationship between crop water requirements, water supply, and agricultural consumptive water use through ET, and how does this affect crop yields?
3) How can we mitigate threats to regional food security through measurement of crop stress from satellite-derived ET data and its application to provide early warning of crop failure during drought?
4) Where do long-term imbalances exist between available water supplies and consumptive use of water by agriculture, and how does this affect both water and food security?
5) Have recent efforts to improve water and food security through construction of water projects and changes in irrigation water management been successful in maintaining or increasing irrigated acreage and the reliability of food production, in balance with other water uses including environmental and municipal?
6) What are the economic benefits of increased efficiency in water management and water transfers enabled by high frequency satellite-derived ET data at the field-scale?
7) How can satellite-derived ET data be combined with data on precipitation and runoff data to improve estimates of groundwater recharge?

III. Why Are These Questions Timely?

<u>As climate change adds further strain on water resources around the world, it is critical that our next generation of Earth observing satellites not only advances our scientific understanding of the global water cycle, but also provides data to support water resource managers responding to threats to water security.</u>

Water for irrigated agriculture is by far the largest component of water diverted and consumed in the United States and globally. Water resource managers are tasked with using available water efficiently, which requires that they know both the maximum amount of water that crops potentially use and the amount of water actually being used or “consumed” through ET.

In the past decade, severe drought has affected major agricultural regions around the world including California, the Midwest, Brazil and Australia (Anderson et al., 2015; AghaKouchak et al., 2014; Swain et al., 2014; Mallya et al., 2013; Saatchii et al., 2013; Dijk et al., 2013) impacting both water supplies and agricultural production. The IPCC identified increasing risks to food and water security as one of the primary impacts of accelerating climate change through increasing climate variability and frequency of extreme events (IPCC, 2014).

It is at the field scale that water rights are generally enacted and contested, and where water management changes are implemented. As a consequence, ET information is required at the field scale. Advances in satellite data processing and modeling of ET have facilitated increasing use of satellite-derived ET information in operational water resources management (Bastiaanssen et al. 1998a,b; Allen et al., 2007a,b). This move from applied research to operational monitoring and management of water resources is indicative of the increasing maturity of both the satellite sensors and models required to estimate ET from satellite observations. The accuracy of satellite derived ET data has been shown to be sufficient for use in legal disputes over water rights. ET maps generated using Landsat data and the METRIC model (Allen et al., 2007a,b) have supported judicial decisions that were upheld in reviews by state Supreme Courts (https://www.idwr.idaho.gov/files/gis/Delivery_Call.pdf), as well as by the U.S. Supreme Court (State of Montana *v*. State of Wyoming, *et al*., *No. 137, Original*, U.S. Sup. Crt.).

While important progress has been made and benefits have been achieved through the use of satellite-derived ET data, further advances and operational use in some regions have been hampered by a shortage of cloud-free, high spatial resolution, thermal infrared satellite data required for calculation of land surface temperature and ET at the field scale. <u>This limitation can be resolved by increasing the number of satellite observations of land surface temperature at the field scale.</u>

Furthermore, upcoming missions such as ECOSTRESS have the potential to demonstrate one pathway towards achieving a higher temporal resolution of these measurements. Mission concepts for free-flying thermal instruments operating in a constellation with missions like Sentinel 2A and Landsat 8 also demonstrate a cost effective approach for increasing the frequency of retrieval of the full suite of satellite observations needed to accurately calculate ET. <u>A key challenge for the next Decadal Survey will be to build upon these mission concepts and technological advances to achieve reliable global, weekly, cloud-free measurements in the visible, near-infrared, shortwave infrared, and thermal infrared wavelengths at the field scale.</u>

IV. Need for Space-based Observations

Space-based remote sensing is the only feasible option for obtaining routine, consistent, field-scale observations of ET over areas larger than a watershed. ET is highly variable spatially and temporally and difficult and expensive to measure on the ground. Surface flux towers typically cost $10,000 to $100,000, and weighing lysimeters are as expensive. The expense and difficulty associated with deploying and maintaining a spatial network of field instrumentation for ET measurement inherently limits its utility for continuous monitoring over large areas. Aircraft, including unmanned aerial systems (UAS), offer a range of promising technologies for precision agriculture where mapping of row-to-row variation in high-value crops can identify within-field plant stress caused by lack of water, pest infestation or nutrient deficits. However, future spatial and temporal coverage by UAS and other aircraft will not be broad enough to produce, at a minimum, new information monthly over large areas, such as the Central Valley of California or the High Plains Aquifer region of the central U.S., regions of substantial water stress and water resource depletion.

V. Specific Recommendations

The Workshop participants urge the NRC Decadal Survey Panel to consider the following specific recommendations:

1. The U.S. Government should increase its support for Earth Observation satellites that collect measurements of land surface temperature at the field scale.
2. Future satellites to support water resources management should provide visible and near infrared data with pixel sizes of ~ 30m x 30m, and thermal infrared pixel sizes of no more than ~100m x 100m.
3. Future satellites, or satellite constellations, producing imagery at the field scale should provide weekly cloud-free coverage for most regions of the globe.
4. The U.S. Government should continue its open-data policy, which provides free access to all NASA, USGS, and NOAA satellite data.
5. All countries with thermal infrared satellite imaging capabilities should share their Earth observation data freely via web interfaces that meet international standards for exchange of scientific data.
6. The participants commend the USGS for working to minimize data latency for Landsat and other data, and recommend that US agencies continue to target data availability within 24 hours of data acquisition and make data accessible through cloud computing resources.
7. A free-flying satellite having at least the standards of the Landsat 8 thermal infrared sensor should be placed in orbit to fly in close proximity to the present and future European Sentinel 2-type satellites, which lack thermal sensing capabilities. In addition, a thermal free-flying satellite should be launched in close proximity to the orbit of Landsat as a backup for potential failure of the TIRS thermal imager on Landsat 8 or to provide intervening thermal imagery between Landsat 7, 8 and 9 overpasses. These activities should be viewed as a complement to Landsat, and should not delay the launch of Landsat 9.
8. The International Space Station (ISS) should be considered as a long-term platform for thermal instruments that provide insight into the diurnal cycle of land surface temperature and ET to complement field-scale polar-orbiting systems.

Additional Information for Consideration (beyond 1500 words)

VI. Limitations of Current and Future U.S. and International Programs

<u>Summary: Planned satellite measurements will likely provide visible, near-infrared and shortwave infrared data but there remains a scarcity of thermal infrared data at appropriate spatial and temporal scales.</u>

Measurement characteristics and temporal resolution:

The spectral, spatial, and temporal characteristics of instruments onboard the current Landsat 8 mission are included in Appendix B, along with the specifications for instruments planned to operate from the ISS as part of the ECOSTRESS mission. Current information on the planned Landsat 9 mission indicates that the instruments will closely follow Landsat 8 specifications. The growing operational use of Landsat-derived ET information indicates that the spectral bands, spatial resolution, accuracy and precision of the Landsat 8 instruments are sufficient to support mapping of ET, especially the thermal imagery at sub-field scale resolution, and <u>future missions should meet or improve upon these sensor specifications.</u>

Daily, weekly, monthly and growing-season ET maps are essential inputs to management of water resources, water rights, irrigation, and for hydrologic process modeling. Time integration of ET into datasets and maps representing ET over daily, weekly, monthly and longer time-periods is based on ET obtained as ‘snapshots’ determined on the day of a satellite overpass. The ET ‘snapshots’ require cloud-free image pixels, and increasing the frequency of acquisition of field-scale, cloud-free ET data leads to direct improvements in the accuracy of ET over time. The probability of obtaining cloud-free pixels within a relevant period, such as during each one-month period of the growing season, increases twice as fast as the corresponding imaging frequency of a satellite (Morton et al., 2015). In other words, if a satellite-imaging frequency is doubled so that the repeat-imaging period is halved (e.g., from eight days to four days), the probability of obtaining a cloud-free image of a location will increase fourfold.

The current temporal resolution and revisit frequency of the existing Landsat satellites is inadequate to consistently provide at least one cloud-free image per month globally. The ECOSTRESS mission, which will measure field-scale ET data at different times of day from the ISS, will provide the observations required to enhance our understanding of the evolution of ET throughout the day, but is only scheduled to operate on ISS for a short duration. Future satellite missions should increase the temporal resolution of thermal infrared measurements, at a spatial resolution of 100m or finer, to provide at least one cloud-free observation per week globally.

Spatial resolution:

Half of U.S. farms are smaller than 18 ha (45 acres), and 80% of U.S. farms are smaller than 95 ha (234 acres) (MacDonald et al., 2013). Many of these farms are split into smaller parcels to produce multiple crops. Even on large farms (which account for the majority of total cultivated acreage in the U.S.), the largest irrigation management unit would typically be a quarter-section (i.e., 64 ha or 160 acres). Furthermore, average field size in Africa and across Southern Asia is typically much smaller than in North America and Europe (Fritz et al., 2015). Thus, a spatial resolution of 1 ha (100m x 100m) or finer is required to reliably resolve field-scale ET patterns globally. This resolution is essential to a wide-range of applications related to management of water rights and irrigation, all of which occur at the field scale, and for mapping of drought impacts on crop yields.

Instruments such as the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Terra and Aqua satellites and the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi-NPP satellite provide thermal infrared measurements at spatial scales from 375m to 1000m. Even at 375m, this translates to a spatial scale of 14 ha per pixel. While data from these instruments is useful for regional hydrologic modeling and drought monitoring, they are too coarse to accurately capture ET at the scale of individual fields and irrigation management units.

Data latency and data systems:

Short data latency is critical to many operational applications of remotely-sensed ET data products, including the increasing use of near-real-time ET data in irrigation management (Gowda et al., 2008; Mendez-Costabel et al., 2012; Melton et al., 2012). The USGS, for example, has a target of making 95% of all Landsat data available within 24 hours after data acquisition by a satellite. In practice, most images are available within a few hours of data acquisition. Maintaining this short data latency is critical to many operational applications of remotely-sensed ET data products.

Recent advances in cloud and high performance computing represent an important opportunity to advance the use of satellite-derived ET, especially in developing regions where network bandwidth can constrain access to satellite data. Platforms like the NASA Earth Exchange (Nemani et al., 2011) can support rapid mapping of field-scale of ET from satellite data over regional to continental scales. Publicly available cloud computing platforms like Google’s Earth Engine and OpenNEX also allow users to process satellite data without having to download satellite scenes, thereby removing a key barrier to the operational use of ET data in regions where network bandwidth or local computing capacity is limited.

VII. Linking Space-based Observations with Other Observations:

Most models and techniques used to derive daily, weekly, monthly and seasonal ET data from satellite observations rely on meteorological data as inputs used in time integration. ET data from Earth observing satellites can be used as a key input to inform weather models. ET data can also be combined with hydrologic models and satellite or surface observations of precipitation, streamflow, topography, soil texture, and land cover to improve estimates of hydrologic variables, including critically needed estimates of groundwater recharge.

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Appendix A: List of Workshop Participants

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Appendix B: Sensor Specifications

Landsat 8, Operational Land Imager (OLI)

Table 1. OLI and ETM + shortwave spectral bands.

OLI spectral bands			ETM + spectral bands		
#	Band width (μm)	GSD (m)	#	Band width (μm)	GSD (m)
1	0.433–0.453	30			
2	0.450–0.515	30	1	0.450–0.515	30
3	0.525–0.600	30	2	0.525–0.605	30
4	0.630–0.680	30	3	0.630–0.690	30
5	0.845–0.885	30	4	0.775–0.900	30
6	1.560–1.660	30	5	1.550–1.750	30
7	2.100–2.300	30	7	2.090–2.350	30
8	0.500–0.680	15	8	0.520–0.900	30
9	1.360–1.390	30			

NASA placed stringent radiometric performance requirements on the OLI. The OLI is required to produce data calibrated to an uncertainty of less than 5% in terms of absolute, at-aperture spectral radiance and to an uncertainty of less than 3% in terms of top-of-atmosphere spectral reflectance for each of the spectral bands in Table 1. These values are comparable to the uncertainties achieved by ETM + calibration. The OLI signal-to-noise ratio (SNR) specifications, however, were set higher than ETM + performance based on results from the ALI. Table 2 lists the OLI specifications next to ETM + performance (Markham et al., 2003) for ratios at specified levels of typical, Ltypical, and high, Lhigh, spectral radiance for each spectral band. Commensurate with the higher ratios, OLI will quantize data to 12 bits as compared to the eight-bit data produced by the TM and ETM + sensors.

Table 2. Specified OLI signal-to-noise ratios (SNR) compared to ETM + performance.

OLI band	Ltypical SNR		Lhigh SNR	
	ETM + performance	OLI requirements	ETM + performance	OLI requirements
1	N/A	130	N/A	290
2	40	130	140	360
3	41	100	186	390
4	28	90	140	340
5	35	90	244	460
6	36	100	183	540
7	29	100	137	510
8	16	80	90	230
9	N/A	50	N/A	N/A

Excerpted from Remote Sensing of Environment 122, James R. Irons, John L. Dwyer, and Julia A. Barsi , The next Landsat satellite: The Landsat Data Continuity Mission, 11-21, Copyright 2012, doi:10.1016/j.rse.2011.08.026.

Landsat 8, Thermal Infrared Sensor (TIRS)

Table 3. TIRS spectral bands and spatial resolution (as built).

Band #	Center wavelength (µm)	Minimum lower band edge (µm)	Maximum upper band edge (µm)	Spatial resolution (m)
10	10.9	10.6	11.2	100
11	12.0	11.5	12.5	100

Like OLI, the TIRS requirements also specify cross-track spectral uniformity; radiometric performance including absolute calibration uncertainty, polarization sensitivity, and stability; ground sample distances and edge response; image geometry and geolocation including spectral band co-registration. The TIRS noise limits are specified in terms of noise-equivalent-change-in-temperature (NEΔT) rather than the signal-to-noise ratios used for OLI specifications (Table 4). The radiometric calibration uncertainty is specified to be less than 2% in terms of absolute, at-aperture spectral radiance for targets between 260 K and 330 K (less than 4% for targets between 240 K and 260 K and for targets between 330 K and 360 K).

Table 4. TIRS saturation radiance and noise-equivalent-change-in-temperature (NEΔT) specifications.

Band #	Saturation temperature	Saturation radiance	NEΔT at 240 K	NEΔT at 300 K	NEΔT at 360 K
10	360 K	20.5 W/m2 sr µm	0.80 K	0.4 K	0.27 K
11	360 K	17.8 W/m2 sr µm	0.71 K	0.4 K	0.29 K

A major difference between OLI and TIRS specifications is that TIRS required only a three-year design life. This relaxation was specified to help expedite the TIRS development. The designers were able to save schedule through more selective redundancy in subsystem components rather than the more robust redundancy required for a five-year design life.

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ECOSTRESS Level 1 Science Requirements and Margins

Parameter	Science Requirement (from PLRA)	Current Best Estimate @ 400 km
Ground Sample Distance (m) Crosstrack x Downtrack at nadir	≤ 100 x ≤100	68.5 x 38.5
Swath width (ISS nominal altitude range is 385 to 415 km)	≥ 360	402
Wavelength range (µm)	8-12.5	8-12.5
Number of bands	≥ 3	5
Radiometric accuracy (K @300K)	≤ 1	0.5
Radiometric precision (K @300K)	≤ 0.3	0.15
Dynamic Range (K)	270-335	200-500
Data collection	CONUS, twelve 1,000 x1,000km key climate biomes and twenty-five FLUXNET sites. On average 1 hour of science data per day.	1.5 hours per day of science data