**NASA DEVELOP National Program**



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Coastal Mid-Atlantic Water Resources II

Measuring Evapotranspiration using the METRIC Model in the

Mid-Atlantic Coastal Plain

**Technical Report** 

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# I. Abstract

Crop irrigation accounts for a considerable amount of water use in the Coastal Mid-Atlantic region. Better understanding of how much water farmers need to irrigate their fields will help decrease both water waste and the economic burden for farmers. The Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC) model is a powerful tool that calculates evapotranspiration (ET) based on localized data. Executable from a Python script, the model can be used as a decision support tool that allows farmers to make more informed decisions about when irrigation is necessary. METRIC estimates ET using a series of equations where local input variables are acquired from Landsat 8 sensors, a United States Geological Survey (USGS) survey based Digital Elevation Model (DEM), and local weather conditions. While METRIC derived ET estimates are beneficial for irrigation purposes, it can also provide state officials with a useful means of drought monitoring. Utilizing data from NASA Earth observations in the Coastal Mid-Atlantic region will contribute to a large-scale, more-complete, understanding of the water consumption behavior in an area that can be used for both policy and individual agricultural decisions.

**Keywords**

Coastal Plain, remote Sensing, Landsat 8, METRIC Model, Water Resources, Irrigation Management, Drought Monitoring, Mid-Atlantic Region

# II. Introduction

**Background Information**

Current Status

Irrigated agriculture accounts for a significant amount of water consumption nationwide and despite technological advances, at least half of U.S. irrigated cropland rely on traditional, low-efficiency irrigation methods (USDA, 2012). Improving irrigation practices will allow farmers to make more-informed decisions about when irrigation is necessary (Evans et al. 1996). Previous research has also indicated that estimating ET rates can provide a useful method for monitoring drought conditions (Narasimhan and Srinivasa, 2005). Drought monitoring is vital to the agricultural industry because the effects of drought cost US farmers billions of dollars in agricultural loss each year (FEMA, 1995). It is likely that future drought monitoring and irrigation management can be improved by the use of the METRIC model (Allen et al., 2007).

Previous Studies

ET is a major component of the hydrologic cycle (Allen et al. 2007; Telis et al., 2007; Papadavid, 2011) and is defined as the combination of evaporation from the ground and transpiration from agriculture (Michigan DEQ, 2010; Hoedjes et al., 2008; Papadavid et al., 2011). The USGS states that ET levels are directly proportional to crop yield, making it useful for assessing crop health and expected production (Verdin & Eilerts, 2013). A low ET rate during the peak of growing season would indicate crop stress while a high ET rate would indicate a healthy, adequately watered, field. Crop health and production are vital to the agricultural industry due to an expansion in population which has heightened demand for food and agricultural resources (Wenda & Hanks, 1981; Turner et al., 2004). Irrigation increases crop yield beyond what is achieved with non-irrigated farming by mitigating the effects of drought during growing seasons (Turner et al. 2004). While irrigation is often necessary for maximum crop production, higher pumping costs have placed pressure on the agricultural industry to update irrigation technology to optimize efficiency (Hornbaker R.H. & H.P. Mapp, 1988; Turner et al., 2004).

ET can be estimated by multiplying reference crop evapotranspiration rate by a dimensionless crop coefficient, determined by crop height, albedo (reflectance), canopy resistance, and evaporation from soil (Allen et al., 1998). Another method is to use *in situ* ET measurements made at lysimeter stations, which are reliable devices for measuring local ET rates with error as low as 5% (Howell et al., 1991). However, they are ill-suited to represent values for a wide area (Holm et al., 2000). Calculating ET using remotely-sensed data results in higher spatial resolution and coverage than using *in situ* measurements alone (Bastiaanssen, 1998; Allen et al., 2007).

An early model for assessing evapotranspiration using remote-sensing is the Surface Energy Balance Algorithm for Land (SEBAL), established by Bastiaanssen (1998). SEBAL uses minimal requirements for ground-based weather data, giving it a distinct advantage over models which rely exclusively on ground-based data. While a useful model, SEBAL relies on a fixed evaporative fraction for the entire day, typically resulting in an underestimated ET (Nouri et al., 2013). Allen et al. (2005) adapted SEBAL to create the METRIC model, which derives ET values using digital image data collected by Landsat 7 and meteorological variables recorded at local weather stations in Idaho. ET is estimated as the residual latent energy remaining after subtracting the energy lost to the ground and air in an energy balance equation (Allen et al., 2005). The METRIC model improved the accuracy of ET estimates by incorporating a reference evapotranspiration and internal calibration to eliminate the need for atmospheric correction of reflectance measurements (Morse et al., 2006). The internally calibrated METRIC model is more reliable and less complex than SEBAL since it does not rely on crop classification (Allen et al., 2007).

Since its development, the METRIC model has been a useful tool for long-term resource management in the western US (Allen et al., 2007). While the model was originally developed for Idaho, it has also been used in water management throughout the Imperial Valley of California and the Rio Grande Valley by calculating ET from both irrigated farmland and riparian areas (Allen et al., 2005). Areas in the Coastal Mid-Atlantic region could benefit from similar METRIC model applications by improving resource management practices, reducing irrigation costs, and enhancing crop productivity.

**Objective**

The current method of using the METRIC model to estimate ET is very complex (Allen et al., 2007).  Applications of this model currently require trained experts with a background in energy balance, radiation physics, and knowledge of vegetation characteristics, as well as access to high-quality hourly weather data.  The METRIC model was originally designed for use in the western US, but could be adapted to other regions, such as the Coastal Mid-Atlantic. The purpose of this project was to develop a more-accurate method of using the METRIC model to determine evapotranspiration in the Mid-Atlantic coastal plains. The findings from this research will contribute information enabling efficient irrigation in the region.

**Study Area**

South-Central Idaho was used for testing and validating the current model. Select locations in the Mid-Atlantic coastal plain were studied once the model was validated.

**Study Period**

Landsat 8 OLI/TIRS data from July 2013 was used exclusively for this project. This date was chosen because it falls within the growing season when the METRIC model would be useful for irrigation planning.

**National Application Addressed**

This project addressed the NASA Applied Sciences National Application Area of Water Resources and Agriculture.  **Project Partners**

The partners for this project included members of the Virginia government and Digital Harvest, a private company working with the State of Virginia. Virginia Secretary of Natural Resources Molly Ward, Virginia Secretary of Technology Karen Jackson, and Virginia Secretary of Agriculture and Forestry Todd Haymore, along the with Virginia Department of Environmental Quality Director of Surface and Ground Water Supply Planning, Scott Kudlas, were the project partners in the Virginia state government.

# III. Methodology

**Data Description**

The crop data layer (CDL) used in this study was acquired from the U.S. Department of Agriculture (USDA) to identify land cover types in the southern Idaho and Coastal Mid-Atlantic sample areas. This layer was used specifically to select separate wet (alfalfa fields) and dry (bare agricultural field) reference regions used to internally calibrate the METRIC model. Landsat 8 images were acquired from the USGS Global Visualization viewer. Data from bands 2-7 and 10-11 were used as input to make the METRIC model compatible with Landsat 8 data. Weather data, recorded from automated surface observing system (ASOS) stations, were retrieved from the NOAA National Climate Data Center (NCDC) for local weather inputs. *In situ* measurements of hourly evapotranspiration rates, used for verification of model output, were based on lysimeter estimates available from AgriMet (<http://www.usbr.gov/pn/agrimet/wxdata.html>). A DEM with a 30-m resolution was acquired from the USGS Center for Earth Resources Observation and Science (EROS) website.

**Basic METRIC Model Equations**

The methodology for calculating ET using the METRIC model follows a set of equations (Appendix A) established by Allen et al. (2007). Landsat imagery, a DEM, and *in situ* weather data are used as inputs for the series of equations in a Python script. ET is first calculated for a sample region in southern Idaho, where the model requires testing and validation. The testing phase of this study is necessary for establishing model accuracy since Allen et al. (2007) designed the METRIC model for specifically calculating ET in the Western US. Model output was displayed using ArcGIS to provide ET maps in specific study areas for end users, such as the DEQ, farmers, and various policy makers. Since ET rates are influenced by radiation, air temperature, humidity, and wind speed, numerous calculations were required to adapt the METRIC model to a specific study area.

The basis of calculating ET using the METRIC model is represented by the following equation:

where **LE** = latent energy consumed by ET, **Rn**= sum of all incoming and outgoing radiation, **G** = soil heat flux conducted into the ground, and **H** = sensible heat flux convected into the air. The availability of **LE** directly relates to the amount of ET that will occur. The first step to deriving LE begins with calculating net radiation flux (Rn), using the following surface energy budget equation:

In this equation, = incoming short-wave radiation, = surface albedo, = incoming long-wave radiation = outgoing-long wave radiation, and = broad-band surface thermal emissivity. **Rn** is largely influenced by the latitude of a study area since incoming solar radiation (insolation) increases as latitude decreases.

After computing net radiation, soil heat flux (**G**) was calculated to determine the amount of energy stored through the conduction of heat into the soil. **G** can be influenced by the amount and type of vegetation present, soil moisture content, and surface temperature. This component of LE is calculated using the following equation:

where **TS** = surface temperature (K), = surface albedo, and **NDVI** = ratio of differences in reflectivity for the near-infrared band and the red band to their sums. To determine the value of **G**, each side of the equation was simply multiplied by the **Rn** value calculated in the previous equation.

The final component necessary for determining LE was sensible heat flux (**H**), which displays a value for energy lost through heat being convected into the air. **H** is calculated using the following equation:

where = density of air (kg m-3), **Cp**= specific heat of air at a constant pressure (J kg-1 K-1), and **rah** = aerodynamic resistance (s m-1) between two near surface heights , z1 and z2.

Using the derived LE value, ET can be computed at instantaneous, daily, and seasonal rates. For this study, instantaneous and daily ET values were calculated and projected onto spatial maps. Instantaneous ET was calculated for each pixel at the instant of the satellite image and is represented by the following equation:

where **ETins**t = instantaneous ET (mm h-1), 3600 converts seconds to hours, = density of water (~1000kg m-3), and = latent heat of vaporization (J kg-1). The value for **ETinst** is important for model validation.

# IV. Results & Discussion

**Evapotranspiration and the METRIC model**The METRIC model was used to calculate instantaneous ET rates for a sample region in southern Idaho (Figure 1). ETinst values ranged from -.031 - .24mm hr-1, representing the rate of ET occurring during the hour of Landsat acquisition (5:00- 6:00 UTC). The higher ETinst values occurred in areas of higher vapor flux where water and lush vegetation were present. The lower ETinst values occurred over drier areas with little vegetation. In Figure 3, irrigated alfalfa fields are easily depicted as areas of high ETinst in circular shapes due to center-pivot irrigation systems.

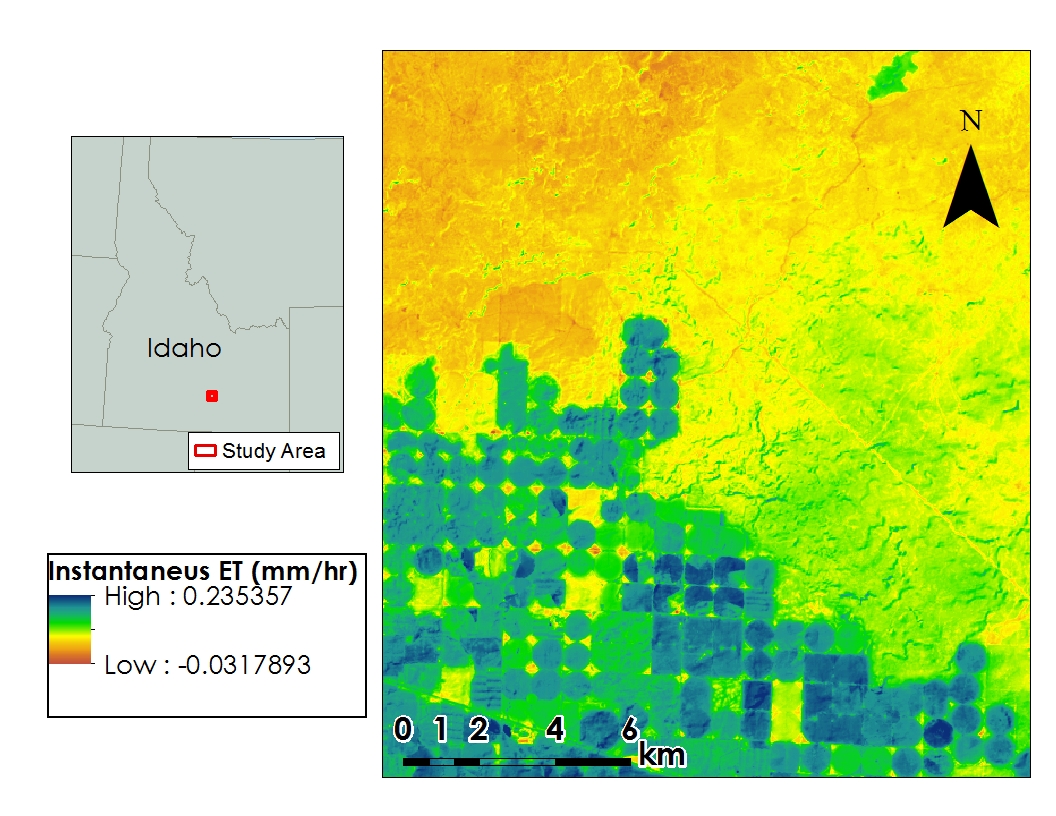


Figure 1: Map of ETinst calculated by the METRIC model for the test and validation study area in southern Idaho. The red square in the state map of Idaho depicts our study area.

ETinst rates were calculated forasample area in North Carolina around the “fields of interest”, provided by a project partner. ETinst values for this area range from -.0422564 - .36738 mm hr-1. The areas with the highest rates represent recently irrigated cropland at the time of Landsat acquisition, while the lower rates represent areas of drier or barren cropland. Negative ETinst are a result of condensation from clouds appearing in the image. Large differences in ETinst are apparent from in the agricultural fields in this image. This difference is likely due to soil moisture differences in irrigated and non-irrigated fields.

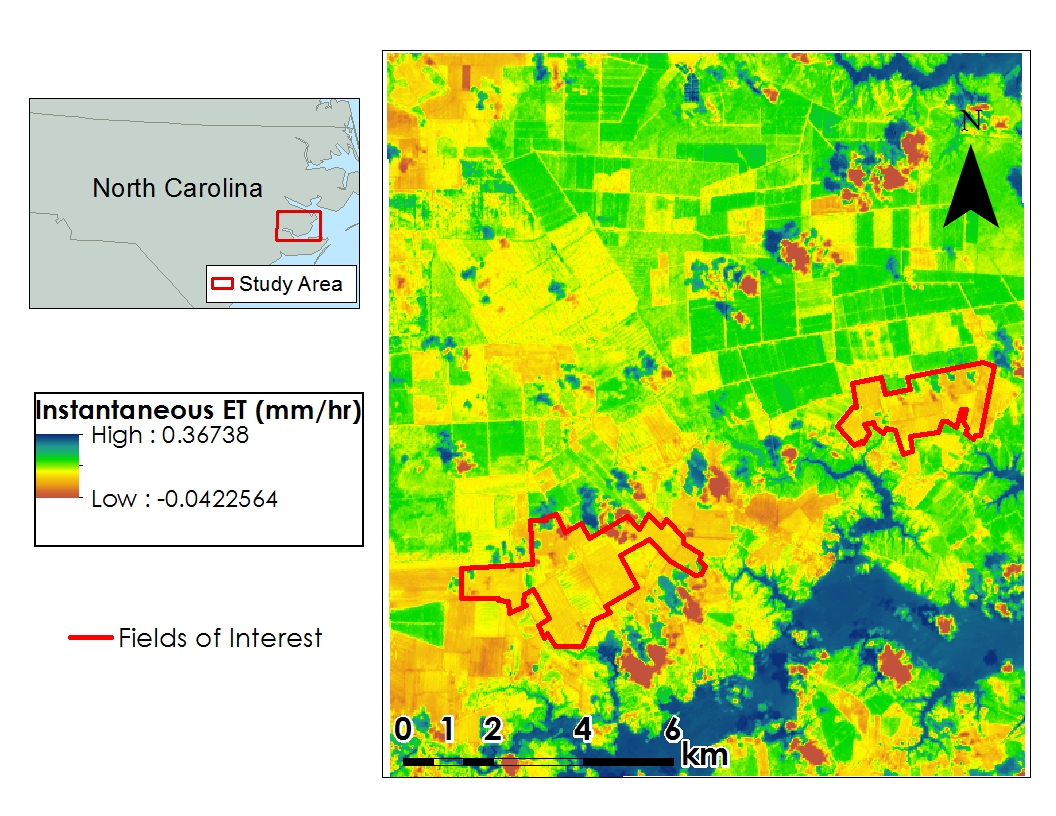


Figure 2: Map of ETinst calculated by the METRIC model for the Mid-Atlantic Coastal Plain. The red square in the North Carolina state map depicts our study area. The outlined fields are the fields of interest for this study.

# V. Conclusions

The use of the METRIC model will be beneficial to government officials and private industries involved in the agriculture industry. The Python script written to run the METRIC model successfully calculated ETinst using Landsat 8 data, hourly weather data, and a DEM. Deriving ETinst was a vital step toward producing a model that calculates an ET24 estimate. The model is in the final stages of becoming a useful tool for calculating ET24 to improve irrigation planning and drought monitoring in the agriculture industry. The completed model will greatly improve current irrigation methods, which rely on climatology for irrigation planning. End-Users are also interested in incorporating weather model data in place of weather station data to predict ET24 rates up to a week in advance. This forecast will give farmers information to predict how much and how often to irrigate in advance. Better planning could reduce the events of heat stress on crops, improving productivity. State officials can use the METRIC model as a means of drought monitoring by applying the model to various types of land cover. This application will allow state officials to monitor drought conditions on a larger scale. Using this model will allow data to be continuous rather than relying primarily on sparse weather station measurements.

# VI. Future Work

Future work will need to focus on the methods of Allen et al. (2007) to derive ET24 and validate the model in Idaho and the Coastal Mid-Atlantic region. Research comparing the METRIC model output with reliable *in situ* ET data is required to determine if adjusting any of the model’s empirical equations to suit the Mid-Atlantic Coastal Plain is necessary. Although the METRIC model’s equations are considered to be dependable outside of Idaho, Allen et al. (2007) has shown that adjustment of one or more of its component equations is sometimes necessary, even within the Western US. The METRIC model’s temporal resolution could be enhanced by supplementing Landsat 8 images – which are only taken every sixteen days – with other moderate to high resolution remotely sensed radiation data, such as those available from ASTER and Landsat 7, to estimate ET between Landsat 8 images. Also, a possible improvement to daily ET could be made by incorporating the effects of nighttime ET into the 24-hour ET calculation (Tolk et al., 2006). Once a validated model for deriving ET24 rates is established, it should be packaged into a tool, available in ArcToolbox. This tool will create a more user-friendly and adaptable METRIC model for the benefit of state officials and private companies associated with the agriculture industry.

# VII. Acknowledgements

We would like to thank Dr. Kenton Ross, Nathan Owen, Lauren Childs and Jamie Favors for their support and assistance throughout the course of our project. We would also like to thank our project partners at Digital Harvest, Young Kim and Ed Hassell, for their valuable input, suggestions, and data.

# VIII. References

Allen, R.G., Pereira, L.S., Raes, D., and Smith, M. (1998). Crop evapotranspiration: Guidelines for computing crop water requirements. *Food and Agriculture Organization (FAO) of the United Nations.*

Allen, Richard G.; Pereira, Luis S.; Howell, Terry A.; and Jensen, Marvin E., (2011). Evapotranspiration information reporting: I. Factors governing measurement accuracy. Publications from USDA-ARS / UNL Faculty. Paper 829. *http://digitalcommons.unl.edu/usdaarsfacpub/829*

Allen, R.G., Tasumi, M., Morse, A., and Trezza, R. (2005). Satellite-based evapotranspiration by energy balance for western states water management. *Impacts of Global Climate Change*, 1-18.

Allen, R.G., Tasumi, M., and Trezza, R. (2007). Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) – Model. *Journal of Irrigation and Drainage Engineering*, *133(4), 380-394.*

Allen, R.G, et al. (2007). Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration METRIC—Applications. *Journal of Irrigation and Drainage Engineering, 133(4), 395-406.*

Bastiaanssen W.G.M, Menenti, M., Feddes, R.A., and Holtslag, A.A.M. (1998). Remote sensing surface energy balance algorithm for land (SEBAL). *J. Hydrol. 212-213(1-4),* 198-212.

FEMA (1995). National mitigation strategy: partnerships for building safer communities. Federal Emergency Management Agency, Washington, DC.

Hornbaker R.H., and Harry P. Mapp. (1988). A Dynamic Analysis of Water Savings from Advanced Irrigation. *Western Journal of Agricultural Economics, 13(2), 307-315.*

Howell, T.A. (2003). Irrigation Efficiency*. Encyclopedia of Soil Science. 467-472.* Retrieved October 6, 2014 from<http://www.cprl.ars.usda.gov/pdfs/Howell-Irrig%20Efficiency-Ency%20Water%20Sci.pdf>

Howell, T.A., Schneider, A.D., and Jensen, M.E. (1991). History of lysimeter design and use for evapotranspiration measurements. *Lysimeters for Evapotranspiration and Environmental Measurements,* 1-9. 14

Irrigation (2012). *EPA Ag 101.* Retrieved October 6, 2014 from <http://www.epa.gov/agriculture/ag101/cropirrigation.htm>

Michigan Department of Environmental Quality, Land and Water Management Division. (2010). *General Guidelines for Calculating a Water Budget.* Retrieved October 6, 2014 from<http://www.michigan.gov/documents/deq/lwm-waterbudget_202791_7.pdf>

Morse, A., Kramber, W.J., Allen, R.G., Tasumi, M. (2006). Mapping evapotranspiration using Landsat and the METRIC evapotranspiration Model. In Proceedings of the 2006 ASPRS Conference.

Nouri, H., Beecham, S., Kazemi, F., Hassanli, A.M., and Anderson, S. (2013). Remote sensing techniques for predicting evapotranspiration from mixed vegetated surfaces. *Hydrologic Earth System Science Discussion, 10,* 3897-3925.

Narasimhan, B., & Srinivasan, R. (2005). Development and evaluation of Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) for agricultural drought monitoring. *Agricultural and Forest Meteorology*, *133*(1), 69-88.

Papadavid G., Hadjimitsis D.G., Perdikou S., Michaelides S., Toulios L., and Seraphides N. (2011). Use of Field Spectroscopy for Exploring the Impact of Atmospheric Effects on Landsat 5 TM / 7 ETM+ Satellite Images Intended for Hydrological Purposes in Cyprus*. GIScience and Remote Sensing*, *48(2), 280-298.*

Telis A. and Koutsogiannis D. 2007. Estimation of Evapotranspiration in Greece. PhD Thesis, Athens.

Tolk, J.A., Howell, T., and Evett, S. (2006). Nighttime Evapotranspiration from Alfalfa and Cotton in a Semiarid Climate. *Agronomy Journal*, *98, 730-736.* Retrieved October 7, 2014 from <http://www.cprl.ars.usda.gov/wmru/pdfs/Tolk%20et%20al%202006%20AJ%20730.pdf>

Turner, K.,Georgiou, S., Clark, R., Brouwer, R., and Burke, J. (2004). Economic Valuation in Water Resource in Agriculture. *Food and Agriculture Organization (FAO) of the United Nations.*

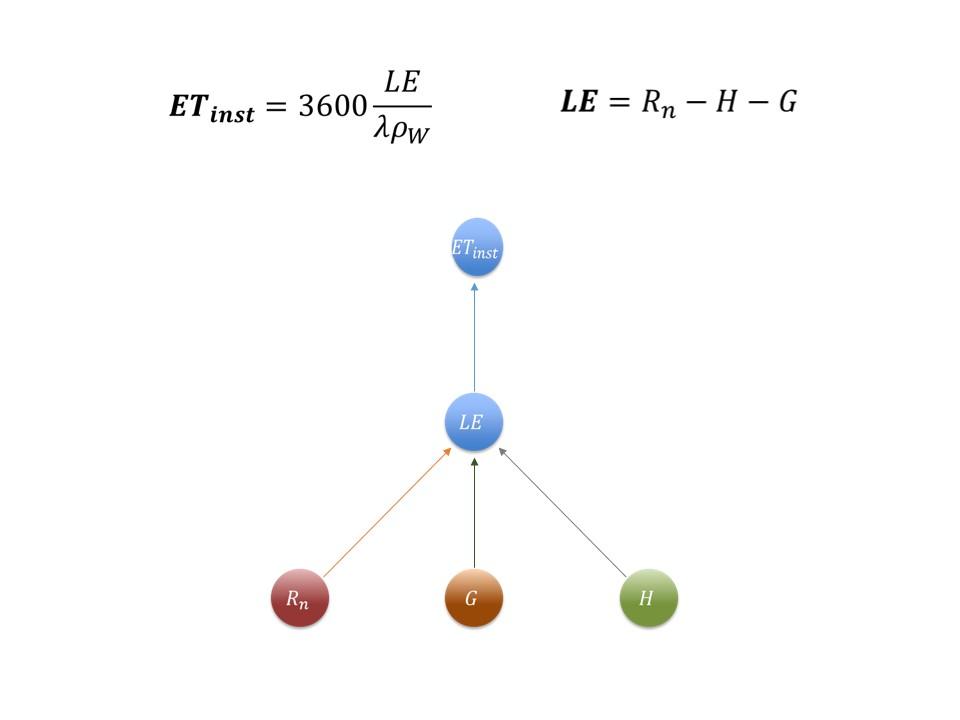
Verdin, J., and Eilerts, G. (2013). Remote Sensing of Evapotranspiration: A new tool for early warning of drought and food crises. *Forum for Agricultural Risk Management in Development.* Retrieved October 6, 2014 from

**IX. Appendix**

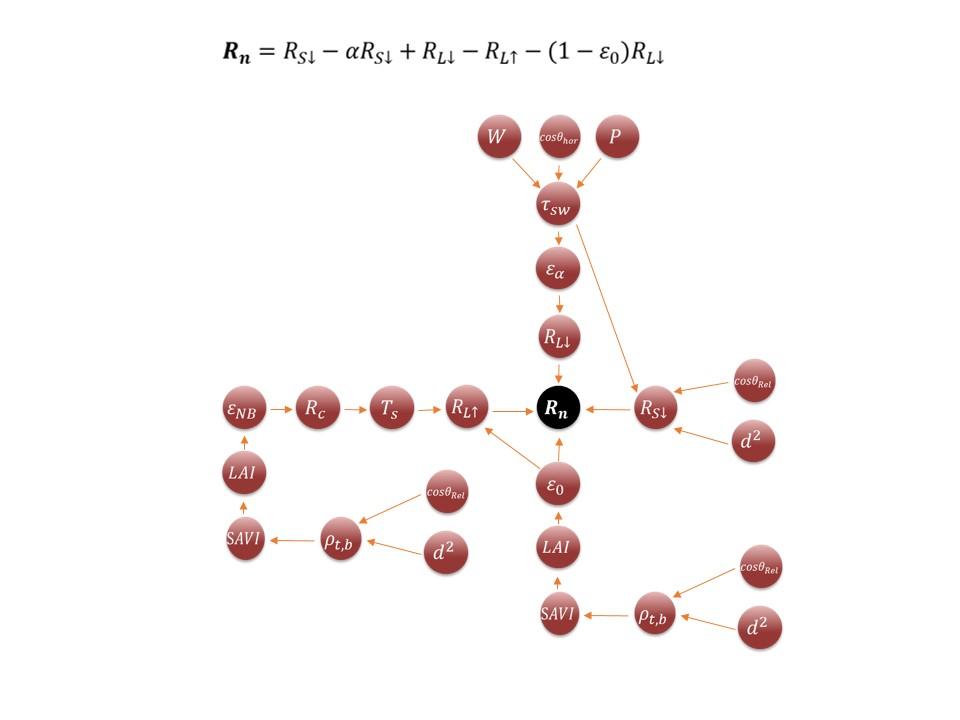
**Appendix A**

This appendix depicts the flow of equations in the Allen et al. (2007) paper.

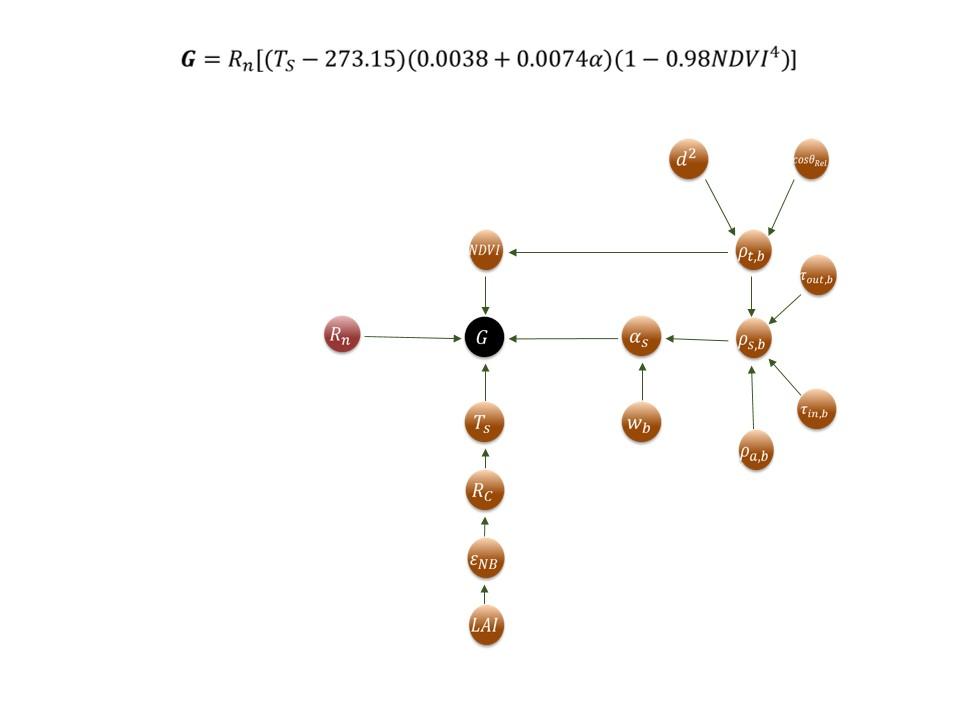
**A1**. Evapotranspiration estimated from Latent Energy

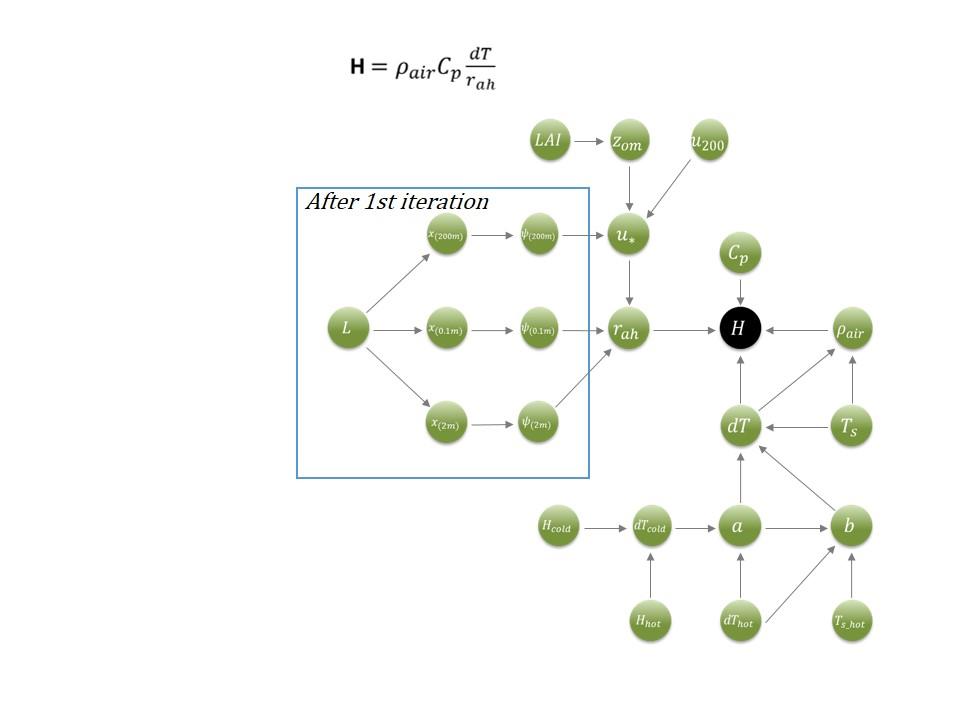


**A2**. Calculation of net radiation

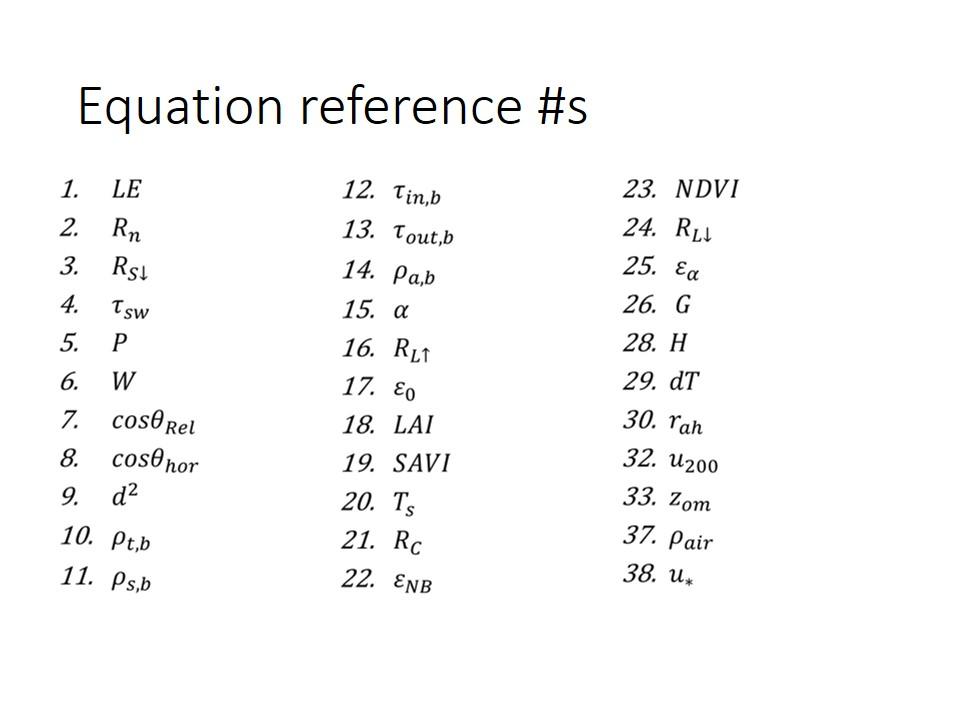


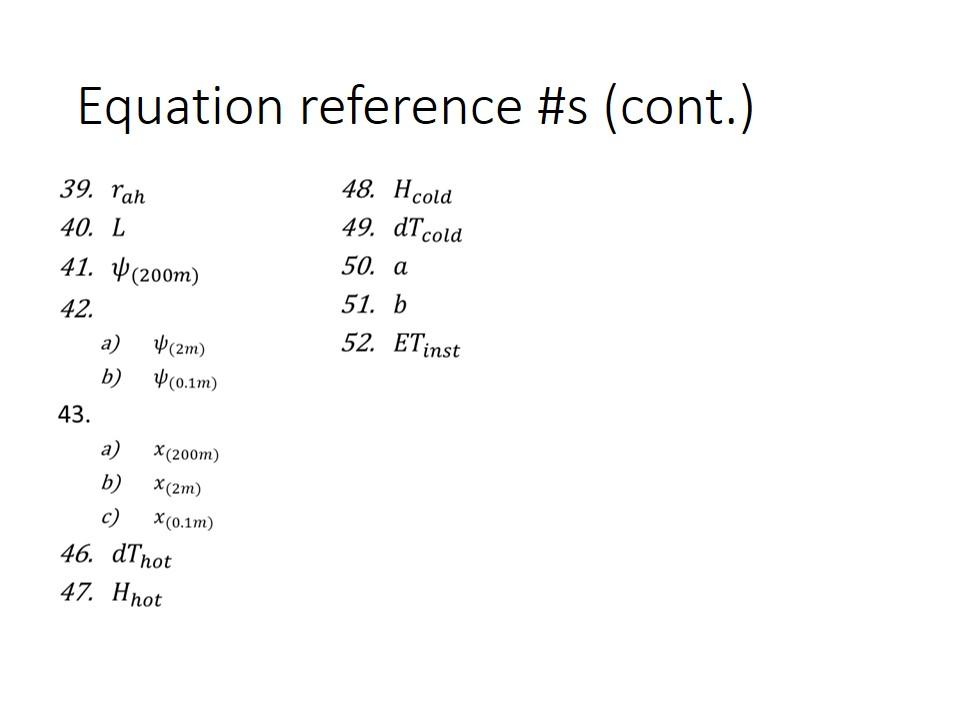
**A3**. Calculation of soil heat flux



**A4**. Calculation of sensible heat flux (initial and iterative equations)

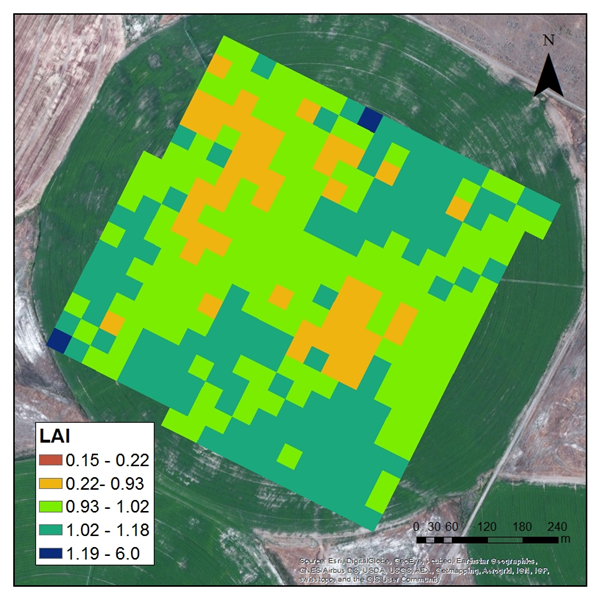
**A5**. Equation reference numbers from METRIC Model paper by Allen et al., 2007



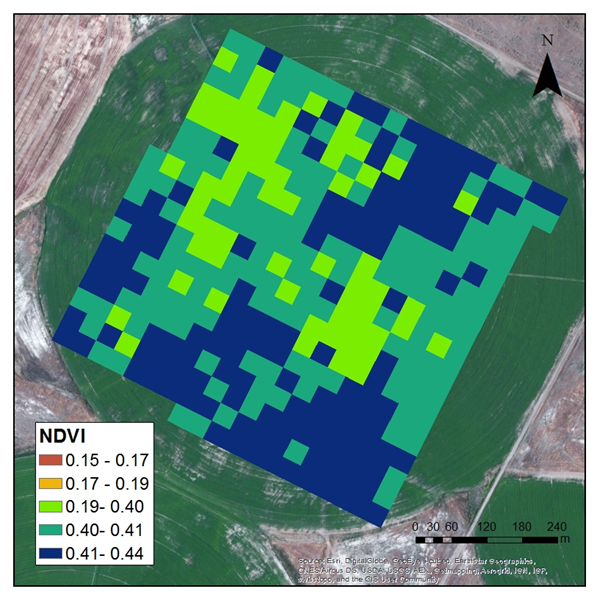


**Appendix B:**

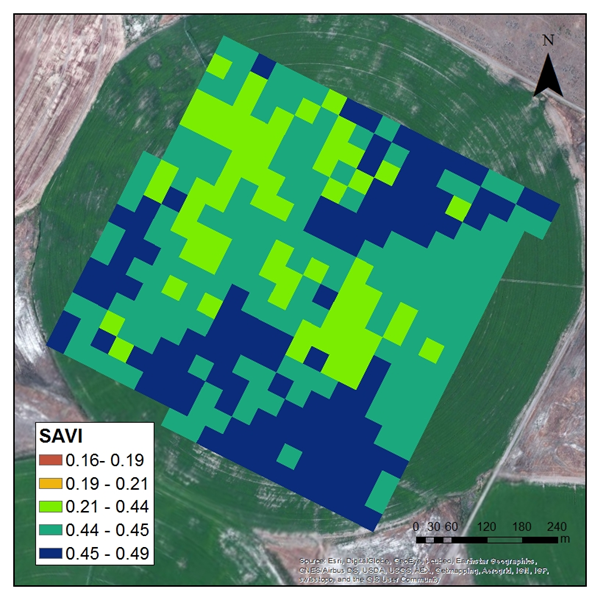
This appendix depicts intermediate results from the alfalfa field that represents the “cold pixel” region for model calibration.



**A6**. Leaf Area Index (LAI), an index that displays the ratio of leaf area to ground area.



**A7**. Normalized Differential Vegetation Index (NDVI), an index that represents the amount of green, healthy, vegetation present.



**A8.** Soil-Adjusted Vegetation Index (SAVI), an index that is derived from NDVI to account for soil brightness. It represents the amount of green, healthy, vegetation present.