DRAFT_Design Document: Calculating Evapotranspiration during the Growing Season

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Design document description and purpose

The U.S. Geological Survey (USGS), in collaboration with the Idaho Department of Water Resources (IDWR) is constructing a numerical groundwater-flow model of the Wood River Valley aquifer system in order to simulate potential anthropogenic and climatic effects on groundwater and surface-water resources. This model will serve as a tool for water-rights administration and water-resource management and planning. The study will be conducted over a 3-year period from late 2012 until model and report completion in 2015. One of the goals of the modeling study is to develop the model in an open and transparent manner. To this end, a Modeling Technical Advisory Committee (MTAC) was formed to provide for transparency in model development and to serve as a vehicle for stakeholder input. Technical representation was solicited by the IDWR and includes such interested parties as water-user groups and current USGS cooperating organizations in the Wood River Valley.

The design, construction, and calibration of a groundwater-flow model requires a number of decisions such as the number of layers, model cell size, or methodologies used to represent processes such as evapotranspiration or pumpage. While these decisions will be documented in a final USGS report, intermediate decision documents will be prepared in order to facilitate technical discussion and ease preparation of the report. These decision documents should be considered preliminary status reports and not final products.

Problem statement

Evapotranspiration (ET) represents the two processes whereby water is lost to the atmosphere: evaporation from the soil and water bodies, and transpiration from vegetation. In short, ET is the consumptively used fraction of water and is responsible for up to 47% of the annual outflow of water from the Wood River Valley aquifer (Bartolino, 2009). ET is not directly measured like groundwater pumping or surface water diversions, and must be estimated using empirical calculations or indirect observations. This design document discusses methods for calculating ET on irrigated, semi-irrigated, and non-irrigated lands during the irrigation season (April through October). Calculation of winter-time (November through March) ET is discussed in a separate design document.

Options considered

The options considered for estimating ET are:

1) Traditional ET Calculation. Use crop distribution information in conjunction with weather data to estimate ET via a crop coefficient-reference ET method. ET is calculated using the Allen and Robison method.
2) Remote Sensing of ET. Use satellite data in conjunction with weather data to estimate ET via an energy balance. The primary estimation method is the **M**apping Evapo**t**ranspiration at high **R**esolution using **I**nternalized **C**alibration (METRIC) model. Data availability and processing constraints for METRIC necessitate the use of a METRIC-correlated method based on **N**ormalized **D**ifference **V**egetative **I**ndex (NDVI) values to generate a complete set of ET data for the calibration period (1995-2010).

The Allen and Robison Method

The Allen and Robison method of calculating ET uses the ASCE standardized Penman-Monteith equation to calculate reference ET in combination with a method for calculating dual crop coefficients. Reference ET (ETr) represents the ET from a theoretical, standardized reference crop (fully watered, full cover, perfectly managed alfalfa crop), and incorporates net radiation, soil heat flux, air temperature, wind speed, and vapor pressure (Allen and Robison, 2007). Wood River Valley ETr values are calculated using data obtained from the Picabo AgriMet and Hailey NWS weather stations.

The crop coefficient (Kc) is the ratio of actual ET to the ETr for a specific crop or land cover. The Allen and Robison method computes a dual set of Kc values. The first coefficient is the basal Kc (Kcb) which incorporates the non-weather factors of crop height, crop-soil resistance, and surface reflectance that cause actual ET to vary from ETr. The second coefficient is the evaporative Kc (Kce) which considers evaporation due to wetting by estimated irrigation and actual precipitation. The Kcb and Kce are added together to obtain the general Kc value. Once ETr and Kc have been developed, and the land cover has been identified, ET is calculated by Equation 1.

$$ET = Kc \times ETr \qquad \text{Equation 1}$$

Where:

ET = evapotranspiration [ft]

Kc = the crop coefficient [unitless]

ETr = the reference ET from the Picabo AgriMet weather station [ft]

Allen and Robison have performed these calculations and tabulated the daily ET values for various locations and vegetation types on the ET Idaho website. The website has data for the Picabo area throughout the entire calibration period and for the Hailey area during a portion of the calibration period (ET Idaho, 2014).

Issues

If done correctly, the Allen and Robison method can estimate ET within ±10-15% of true ET (Allen, 2013); however, land-cover distribution (crop mix) must be known in order to use this method. For the model years 1995-2000 and 2002-2004 tabulated county crop mix data are available from the National Agriculture Statistics Service (NASS). These data are unreliable for two reasons. First, Blaine County consists of two distinct and very different agricultural areas, and this difference is not reflected in the generalized county crop data (Figure 1). Second, the data are intentionally misreported in an effort to prevent the identification of farmers that grow certain crops (USDA, 2013).

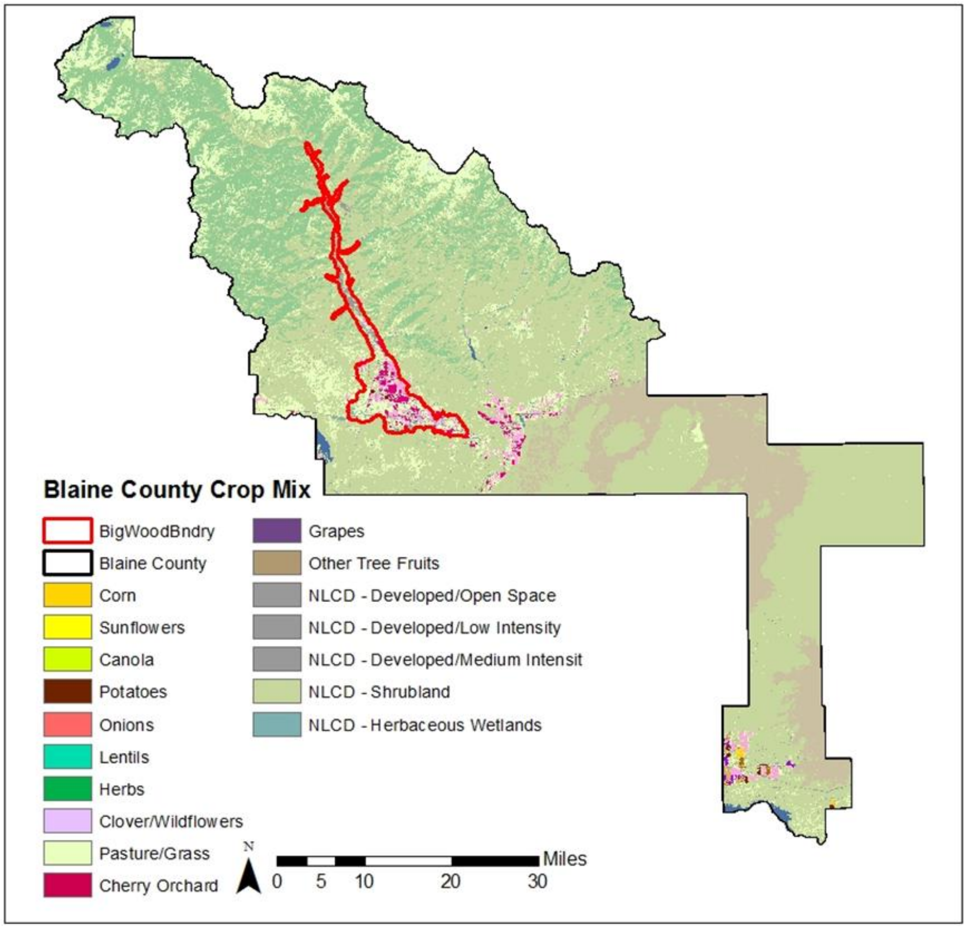

Figure 1. Blaine County illustrating the preliminary model boundary and the 2010 crop mix as defined in the 2010 NASS Crop Data Layer.

Geographic Information System (GIS) land-use data sets are available from the National Land Cover Database for the years 2001 and 2006, and from the NASS Cropland Data Layer for the years 2005 and 2007-2010. Although these data do not possess the deliberate inaccuracies inherent in the county crop data, there is still some variability associated with changes in how land uses are defined over time, as well as inaccuracies due to the remote-sensing methods used to generate the data, which can result in large differences in annual ET volume (Figure 2). Furthermore, the Allen and Robison method does not account for reduced ET due to water shortage, salinity, or vegetative health.

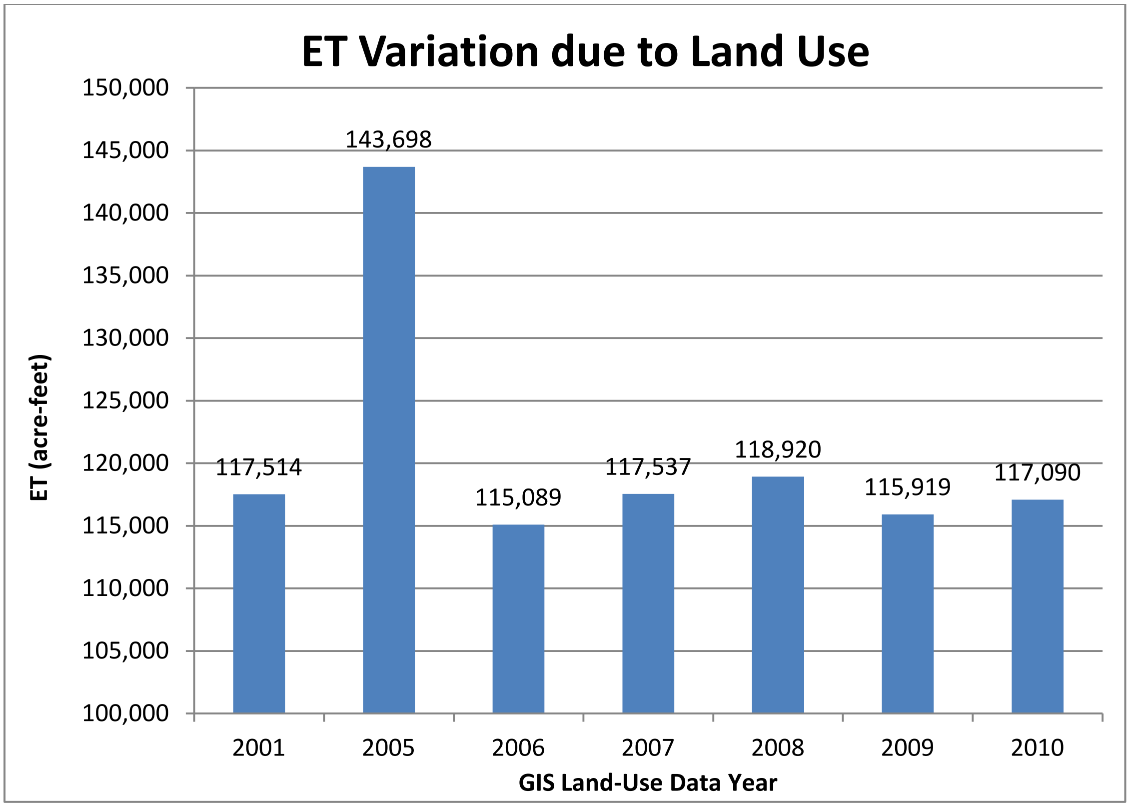

Figure 2. Annual ET volume variability based solely on GIS crop mix data. Average monthly ET rates from ET Idaho were used in conjunction with GIS crop mix data to estimate annual ET.

Uncertainty associated with the county crop mix data was not investigated; however, county-crop reporting policies lead to intentional misreporting and omission of land-use data. Therefore, uncertainty in the county data is assumed to be much greater than in the GIS data.

Effect

Estimating ET using the Allen and Robison method results in values with uncertainty that is likely to be considerably greater than the ±10-15%, which is to be expected if the method is done correctly. Inaccuracies in crop mix data and the inability to incorporate management practices or vegetative health in the estimates may result in unreliable ET estimates.

The METRIC model

An alternative to the Allen and Robison method is to estimate ET using remotely-sensed satellite imagery. Instead of identifying land-use and multiplying a crop coefficient by the ETr, the remotely sensed information (heat, reflectance, radiation) are used to calculate an energy balance at the time of the satellite image. The process of ET consumes energy, and ET is calculated by METRIC as the total energy available minus heat fluxes to the ground and air (Allen et al., 2010a). The ratio of the instantaneous ET at the time of the image to hourly ETr is called the realized fraction of ET (ETrF), which is relatively constant throughout the day (Allen, 2010b). ETrF thus provides a relationship between the instantaneous and daily ET that allows the satellite-derived ET to be utilized in calculating 24-hour ET. Once ETrF is determined, ET is calculated in a similar fashion to the Allen and Robison method by which daily ETr from local weather data is multiplied by ETrF (instead of Kc) to obtain daily ET (Equation 2).

$$ET = ETrF \times ETr \qquad \text{Equation 2}$$

Where:

ET = daily evapotranspiration [ft]

ETrF = the realized fraction of evapotranspiration [unitless]

ETr = the daily reference ET from the Picabo AgriMet weather station [ft]

Once 24-hr ET has been developed for all dates for which there is usable imagery, an interpolation based on vegetative growth and senescence is used to interpolate ET to all days between satellite images. After the spline is applied, all daily ET values are summed to monthly ET. Monthly ET estimates using the METRIC model are reported to be within ±10% of actual ET (Mokhtari et al., 2012).

Issues

Due to the dependence on satellite imagery, METRIC ET is not available for all months in the calibration period. Clouds and smoke interfere with the collection of temperature and albedo measurements, and may completely block surface visibility from space.

Images with only partial coverage by clouds can still be used by masking out, or removing, the cloudy portions of the image. ET estimates in the masked-out regions are made by using data from different satellites or different image dates, and ET estimates in the masked areas are more uncertain than clear areas. Images with too much cloud cover may not be usable, and if too many images are unusable, it may not be possible to estimate monthly ET using METRIC.

Another issue is the time and cost of calculating METRIC ET. Because it costs thousands of dollars and takes up to 24 months to complete METRIC for an irrigation season, not all years with cloud-free images are available for this version of the model.

Effect

METRIC does not rely on questionable crop mix data, and captures crop management practices that are otherwise unknown. Therefore, using METRIC to estimate ET results in robust estimates that are within ±10% of actual ET, for the months which METRIC is available. However, another ET estimation method is necessary for the months during which METRIC ET is not available. Table 1 lists METRIC availability during the calibration period.

Table 1. Availability of METRIC ET data.

Year	Available Data
1996	All irrigation season, entire model domain
2000	All irrigation season, entire model domain
2002	May - October, south of Bellevue only
2006	All irrigation season, entire model domain
2008	All irrigation season, entire model domain
2009	All irrigation season, entire model domain
2010	All irrigation season, entire model domain, completion in 2014

Design decision

The recommended design decision is to use METRIC ET when available. This design decision is favored because it likely results in the best ET estimates possible for the METRIC-available months. This decision requires that a different ET estimation method be used for growing-season months lacking METRIC coverage. All ET estimates are illustrated at the end of this document in Figure 7.

Estimation of ET with NDVI

NDVI is a normalized ratio of the difference between red and infrared wavelengths reflected from the earth's surface as seen from satellites, and serves as an index of vegetative condition. ET is strongly dependent on vegetation, and a correlation between NDVI and ETrF can be developed. Because METRIC ET estimates are developed to quantify seasonal ET, if clouds impact too many satellite images METRIC will not be employed during that particular irrigation season – even if some individual months of ET could be estimated. For those individual cloud-free months that do not have METRIC estimates, ET can be estimated via remote sensing with less time and expense using NDVI.

Work done by the developers of METRIC quantified the relationship between ETrF and NDVI in an attempt to develop an ET estimation method that is reliable and, in comparison with METRIC, quicker and cheaper to employ (Allen et al., 2010b). Estimation of ET using NDVI in the Wood River Valley is based on this method. Just as with METRIC, ET is calculated using ETrF derived from remotely-sensed data multiplied by ETr determined from local weather data.

Process

The satellite images must be downloaded and cloud masked before NDVI can be calculated. After the images have been prepared, NDVI is calculated for non-METRIC months with available satellite imagery (Equation 3).

$$NDVI = \frac{(ref_{NIR} - ref_{RED})}{(ref_{NIR} + ref_{RED})} \qquad \text{Equation 3}$$

Where:

$NDVI$ = the normalized vegetative index [unitless]

ref_{NIR} = the reflectance in the near infrared reflectance satellite band [nm]

ref_{RED} = the reflectance in the red reflectance satellite band [nm]

NDVI estimates of ET rely on a linear regression with METRIC-derived ETrF. Regressions between ETrF and NDVI were originally computed for each crop type; however, all crops had similar relationships and a generalized equation was developed (Allen et al., 2010b). The generalized regression equation used to calculate ETrF based on NDVI is defined in Equation 4.

$$ETrF = 0.15 + 1.06 NDVI \qquad \text{Equation 4}$$

Where:

$ETrF$ = the realized fraction of ET for a given month [unitless]

NDVI = the normalized difference vegetative index [unitless]

Once ETrF values have been determined, NDVI estimates of ET are calculated by multiplying the realized fraction by the reference ET, just as in METRIC (Equation 5).

$$ET = ETrF \times ETr \qquad \text{Equation 5}$$

Where:

ET = monthly evapotranspiration [ft]

$ETrF$ = the realized fraction of evapotranspiration [unitless]

ETr = the monthly reference ET from the Picabo AgriMet weather station [ft]

Issues

As with METRIC, NDVI estimates of ET are not available for all months in the calibration period due to the interference of clouds and smoke on the collection of images from space.

Images with only partial coverage by clouds can still be used by masking out the cloudy portions of the image, as is done with METRIC. ET estimates in the masked-out regions are made by using data from different satellites or different image dates, and ET estimates in the masked-out regions are more uncertain than clear regions. Images with too much cloud cover may not be usable, and if too many images are unusable, it may not be possible to estimate monthly ET using satellite data.

Because the NDVI estimation method is based on a linear regression with MERTIC-derived ETrF, the ET values are more uncertain than METRIC estimates. Comparisons of ET estimates generated by METRIC and NDVI for concurrent dates in the Wood River Valley indicate that the NDVI estimates are 9% higher than METRIC estimates, on average (Figure 3).

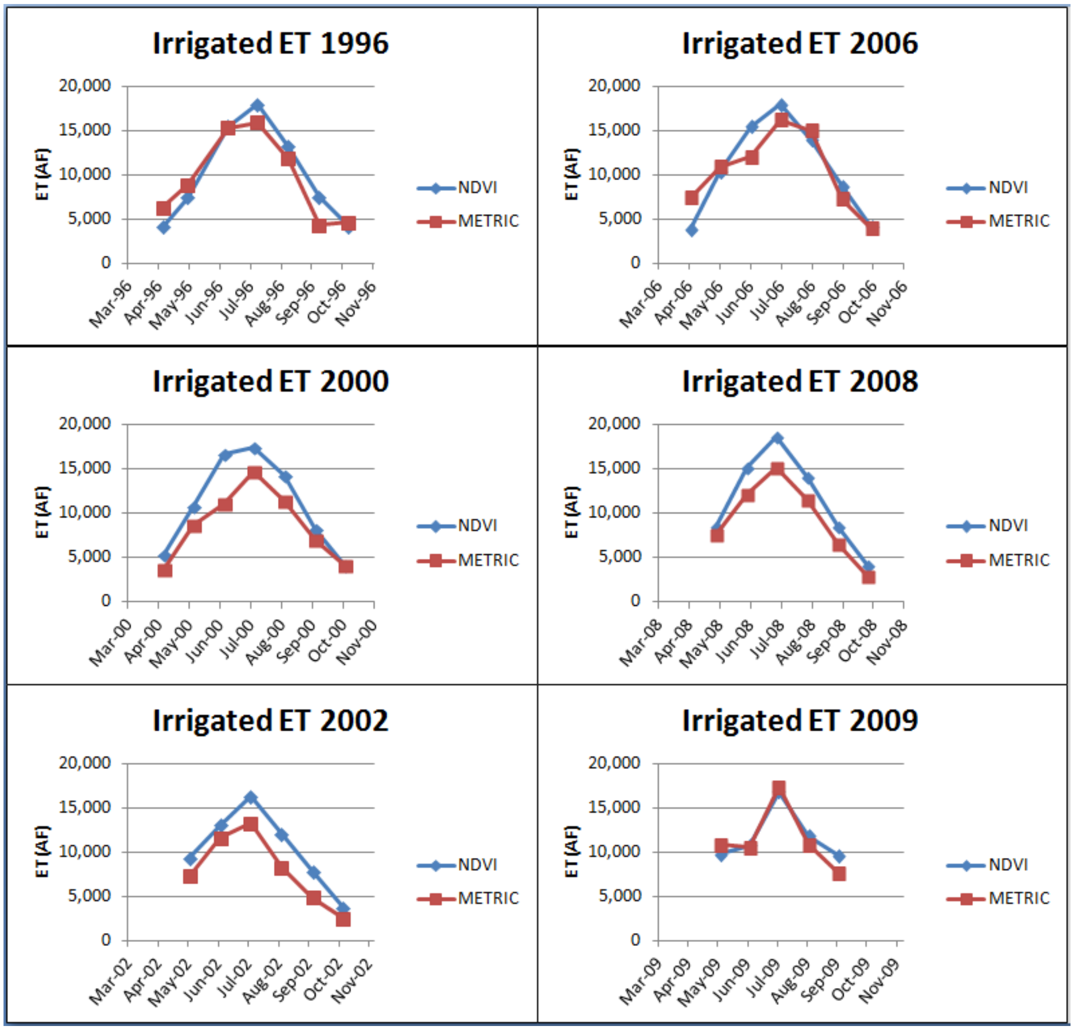

Figure 3. Comparison of ET estimates made by METRIC and NDVI methods for dates with concurrent estimates.

Effect

NDVI-derived ET is based on a relationship between vegetation and ET; as the vegetative volume increases, so does the volume of ET. The calculation of ET based on NDVI relies on a linear regression between METRIC-derived ETrF and NDVI. This procedure circumvents the need to use questionable crop mix data, and captures some of the crop management practices that are otherwise unknown. Therefore, using NDVI to estimate ET for months during which METRIC is not available results in estimates of ET that are based in part on METRIC data, and are likely better than the Allen and Robison method. Although NDVI offers a way to use remotely-sensed data to help complete the ET data set for the calibration period, satellite data are not available for some months. Therefore, another ET estimation method is necessary for the months during which neither NDVI nor METRIC are available. Table 2 lists NDVI availability during the calibration period.

Table 2. Availability of NDVI data.

Year	Available Data
1995	July, entire model domain
1997	September and October, entire model domain
1998	August, September and October, entire model domain
1999	August, September and October, entire model domain
2001	June through October, entire model domain
2003	June through September, entire model domain
2004	April, July and October, entire model domain
2005	All irrigation season, entire model domain
2007	All irrigation season, entire model domain

Design decision

The recommended design decision is to use NDVI ET when available. This design decision is favored because it likely results in the best ET estimates possible for the months during which METRIC is not available. This decision requires that a different ET estimation method be used for growing-season months lacking both NDVI and METRIC coverage. All ET estimates are illustrated at the end of this document in Figure 7.

Interpolation of ET

Because interference by clouds and smoke can hinder the collection of data from satellites, there are 29 out of 112 months during the calibration period for which remotely-sensed data are not available. Because the crop data are of poor quality, an interpolation method proposed in Contor (2012) is favored over the Allen and Robison method. The interpolation uses data from a month in a METRIC year (source year) that are scaled by the ratio of NDVI-ET data from a known month in the year of interest (target year) to NDVI data from the same month in the source year. The scaled METRIC data are then multiplied by ETr from local weather data to compute ET for the month in question (target month).

The rationale behind this interpolation method is that the ETrF from METRIC ($ETrF_{METRIC}$) implicitly reflects long-term information about ET, but is missing information regarding acute crop-mix differences and acute stresses (Contor, 2012). Crop-mix changes and acute stresses are correlated to vegetative index, and these changes are reflected in the ratio of NDVI-derived ETrF ($ETrF_{NDVI}$). Therefore, the NDVI-scaled estimate of ET should incorporate the long-term information available from the source-year METRIC, acute crop differences and stresses from the ratio of NDVI information, and the target-month weather data from ETr.

Process

The interpolation of METRIC ET to months without satellite data involves five steps. The first step is to identify months without available satellite imagery (target months) as well as months during the same year (target year) with NDVI data available. Step two is to identify a proximal year (source year) with METRIC estimates. The third step is to take the ratio of the known monthly $ETrF_{NDVI}$ values from the target year to the source year (Equation 6).

$$ratio_{target/source} = \frac{Target\text{-}year\text{-}month\ ETrF_{NDVI}}{Source\text{-}year\text{-}month\ ETrF_{NDVI}} \qquad \text{Equation 6}$$

Where:

ratio$_{target/source}$ = the ratio of the known-month, target-year ETrF to the source-year ETrF for the same month-of-the-year. This ratio is used to scale METRIC estimates [unitless]

Target-year-month ETrF$_{NDVI}$ = Known NDVI-derived ETrF value from a month in the same year as the target month [unitless]

Source-year-month ETrF$_{NDVI}$ = NDVI-derived ETrF value for the same month of the year as *Target-year-month,* from the year with known METRIC estimates [unitless]

Step four is to multiply the ratio of target to source years by the source-year $ETrF_{METRIC}$ of the month-of-the-year in question. By making an assumption that the calculated ratio applies to all months of the target and source years, step four results in a scaled ETrF for the target month (Equation 7).

$$ETrF_{target\ month} = ratio_{target/source} \times ETrF_{METRIC} \qquad \text{Equation 7}$$

Where:

ETrF$_{target\ month}$ = Scaled ETrF value for the target month [unitless]

ratio$_{target/source}$ = Ratio of the known-month, target-year ETrF to the source-year ETrF for the same month-of-the-year [unitless]

ETrF$_{METRIC}$ = METRIC-derived ETrF value for the same month-of-the-year as the target month [unitless]

The fifth step is to multiply the scaled ETrF value by ETr that is based on local weather data, just as is done in METRIC and NDVI-ET calculation (Equation 8).

$$ET_{target\ month} = ETrF_{target\ month} \times ETr \qquad \text{Equation 8}$$

Where:

$ET_{target\ month}$ = Scaled evapotranspiration for the month in question [ft]

$ETrF_{target\ month}$ = Scaled realized fraction of evapotranspiration for the month in question [unitless]

ETr = Reference ET from the Picabo AgriMet weather station [ft]

All of the processing steps for interpolating ET to months without satellite imagery are performed on a pixel-by-pixel basis, which produces ET datasets that are the same resolution as METRIC and NDVI. To facilitate understanding of the interpolation process, a graphical example of interpolating ET is located in Appendix A.

May – October 2002

For the year 2002, April ET estimates are interpolated as described above. For the period May through October, METRIC data are available for the area south of Bellevue (Bellevue Triangle), and NDVI estimates are available for the entire model area (Figure 4). Because METRIC is likely the best estimate of ET available, METRIC data are used directly where available. In the area where only NDVI estimates are available, the data have been scaled based on a comparison of METRIC and NDVI-ET estimates in the area where both data sets are available.

Scaling of the NDVI estimates consists of differencing the monthly ET volume from irrigated land in the model area for which both NDVI and METRIC data are available. The ET differences are calculated as percentage of NDVI ET, and the NDVI-ET estimates for the entire model domain are reduced by the corresponding percentage. This adjustment procedure assumes that the percentage difference calculated in the Bellevue Triangle applies to the entire model domain.

Once the adjustments to the NDVI estimates have been made, the METRIC data are stitched together with the NDVI data so that METRIC data are used in the Bellevue Triangle and adjusted NDVI data are used in the remaining model domain.

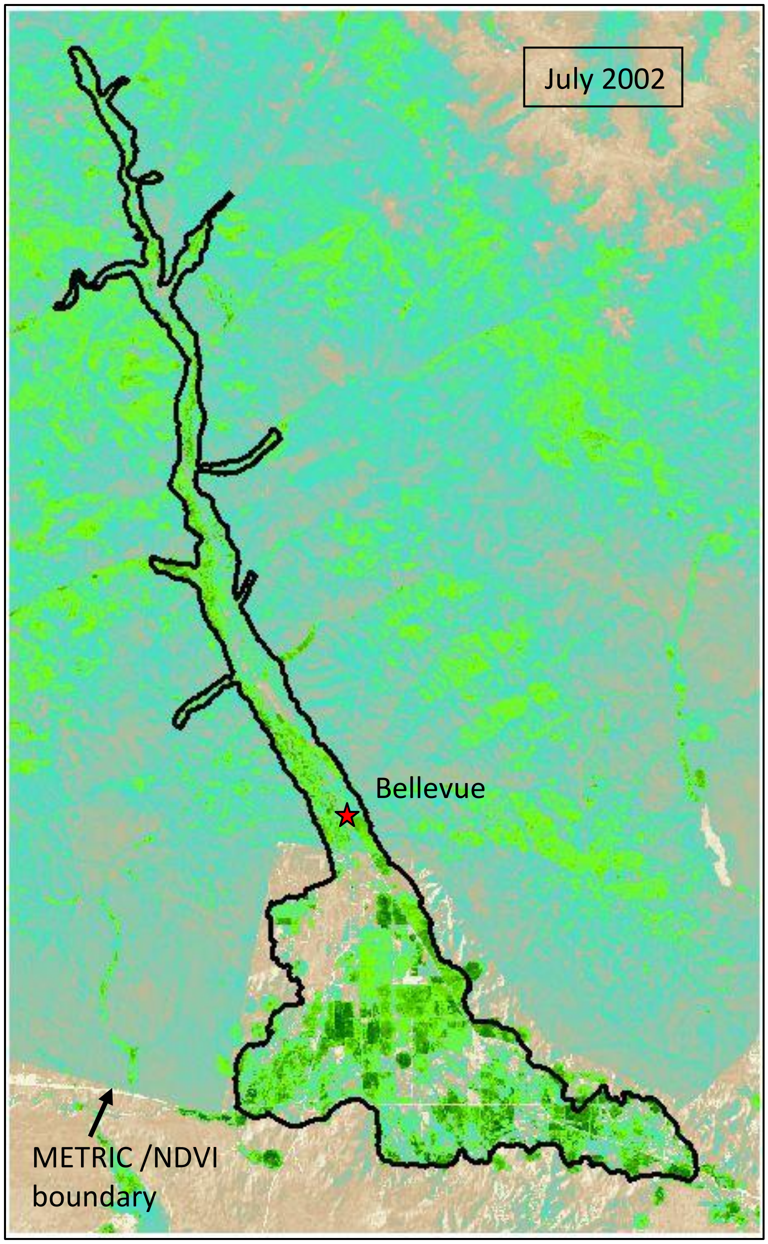

Figure 4. The boundary between 2002 METRIC data, which only cover the southern portion of the model area, and NDVI data is illustrated as an abrupt color change.

Issues

Because the interpolation method uses two estimations of ET from dates other than the month in question, interpolated values are likely more uncertain that either the METRIC or NDVI estimates. Furthermore, the assumption that the ratio developed using data from the same month in two different years applies to all months in the target year may not be valid.

An issue of some importance that has been identified is that of large changes in NDVI from the source year to the target year. The method assumes that there is some variability in the crop mix, which is the reasoning behind calculating the ratio of target year to source year. However, if the change is too great the method breaks down. Two scenarios that can derail the method are those of recent crop cuttings and water shortage. Both of these scenarios can result in vastly different NDVI values. For example, if an alfalfa field was cut shortly before an image date during the source year, the NDVI will be artificially low. In calculating the ratio of target year to source year, the ratio becomes unreasonably high, and the ET estimate is unreasonably high. It is probable that if the cutting happened shortly before a target year image, the ratio and ET estimates would be too low; however, it does not appear that this type of error has occurred during the processing of interpolated ET in the Wood River Valley.

Unreasonably high interpolated ET estimates occur over portions of the irrigated agriculture in 13 of the 29 months that require interpolation. The areas of overestimation occur in only part of the model area, and frequently on the same fields (Figure 5). This observation, together with a comparison of source years with monthly Palmer Drought Indices, indicates that early cutting of alfalfa appears to be a more likely cause than water shortage. Therefore, the overestimated fields have been limited to the actual ET for alfalfa as calculated using the Allen and Robison method, while all other interpolated ET estimates in the images are retained.

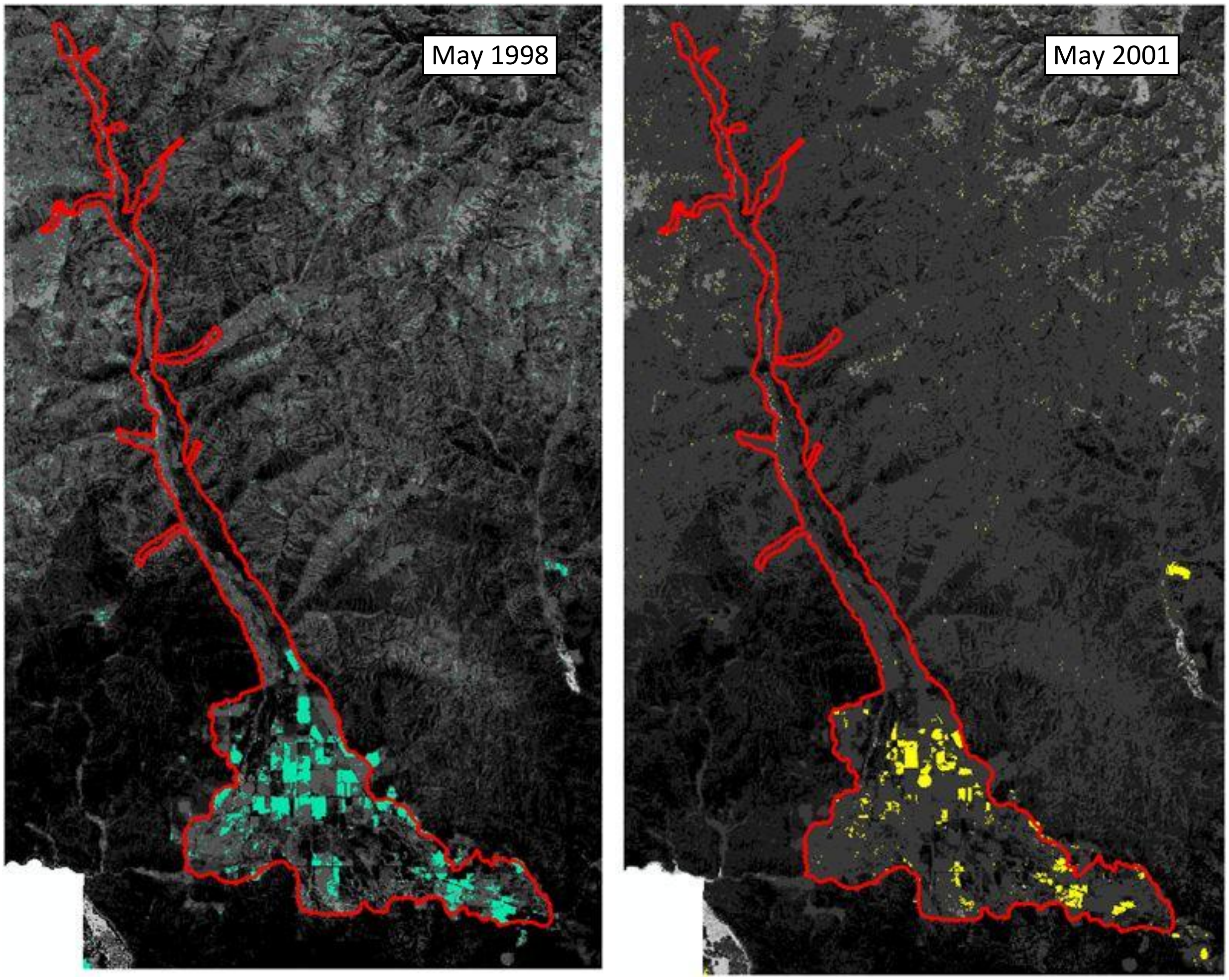

Figure 5. Reduced interpolated ET values (highlighted in green and yellow) generally occur in the same area of the model.

Effect

Interpolated estimates of ET rely on an assumption that a ratio of known monthly ETrF values from the target year and source year applies to all months in the target year. Although the interpolated ET estimates are likely more uncertain than either the METRIC or NDVI estimates, the majority of the monthly estimates appear to be reasonable. Due to overestimation, interpolated estimates on some fields in some months have been adjusted down to the maximum alfalfa ET, as determined using the Allen and Robison method. The resulting set of interpolated ET values also appears to be reasonable. A plot of ET estimates by method indicates that there does not appear to be a bias in the errors associated with each method (Figure 6). Winter ET estimates are included in Figure 6, the development of which is discussed in WRV Design Document titled "Calculating Winter-time Evapotranspiration".

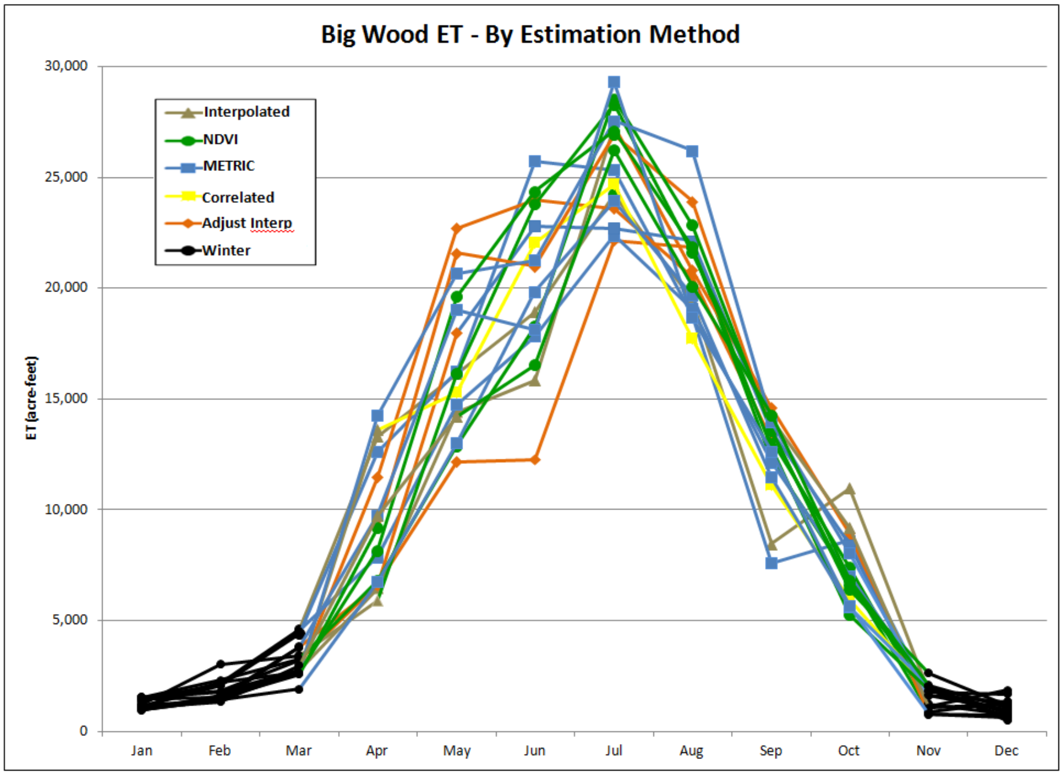

Figure 6. ET estimates for all lands, plotted by estimation method. Winter ET estimates (November-March) are included in the figure.

Design decision

The recommended design decision is to use interpolated ET values for months without usable satellite data. This design decision is favored because it likely results in the best ET estimates possible for the months during which METRIC and NDVI estimates are not available.

Conclusion

The Allen and Robison method of estimating ET is a proven technique that can produce estimate that are within ±10-15% of true ET, if done correctly. Because data on crop mix is very uncertain, and information on crop management and stress are completely lacking, estimates using the Allen and Robison method are considerably more uncertain than reported.

Using ET based on remotely-sensed data circumvents much of the uncertainty associated with crop data, and METRIC is considered the best estimate of ET available for this modeling effort. Although METRIC is not available for all months in the calibration period, estimates that use a correlation between NDVI and METRIC fill in most of the missing months with reliable ET estimates. Despite the use of two different methods to estimate ET during the calibration periods, cloudy images prevent the use of satellite data in 26% of the time. For months with no satellite images, an interpolation technique based on a ratio of available data is employed to estimate ET. Although more uncertain than either the METRIC or NDVI-based ET, the interpolated estimates appear reasonable. All ET estimates are illustrated in Figure 7. Winter ET estimates are included in Figure 7, the development of which is discussed in WRV Design Document titled “Calculating Winter-time Evapotranspiration”.

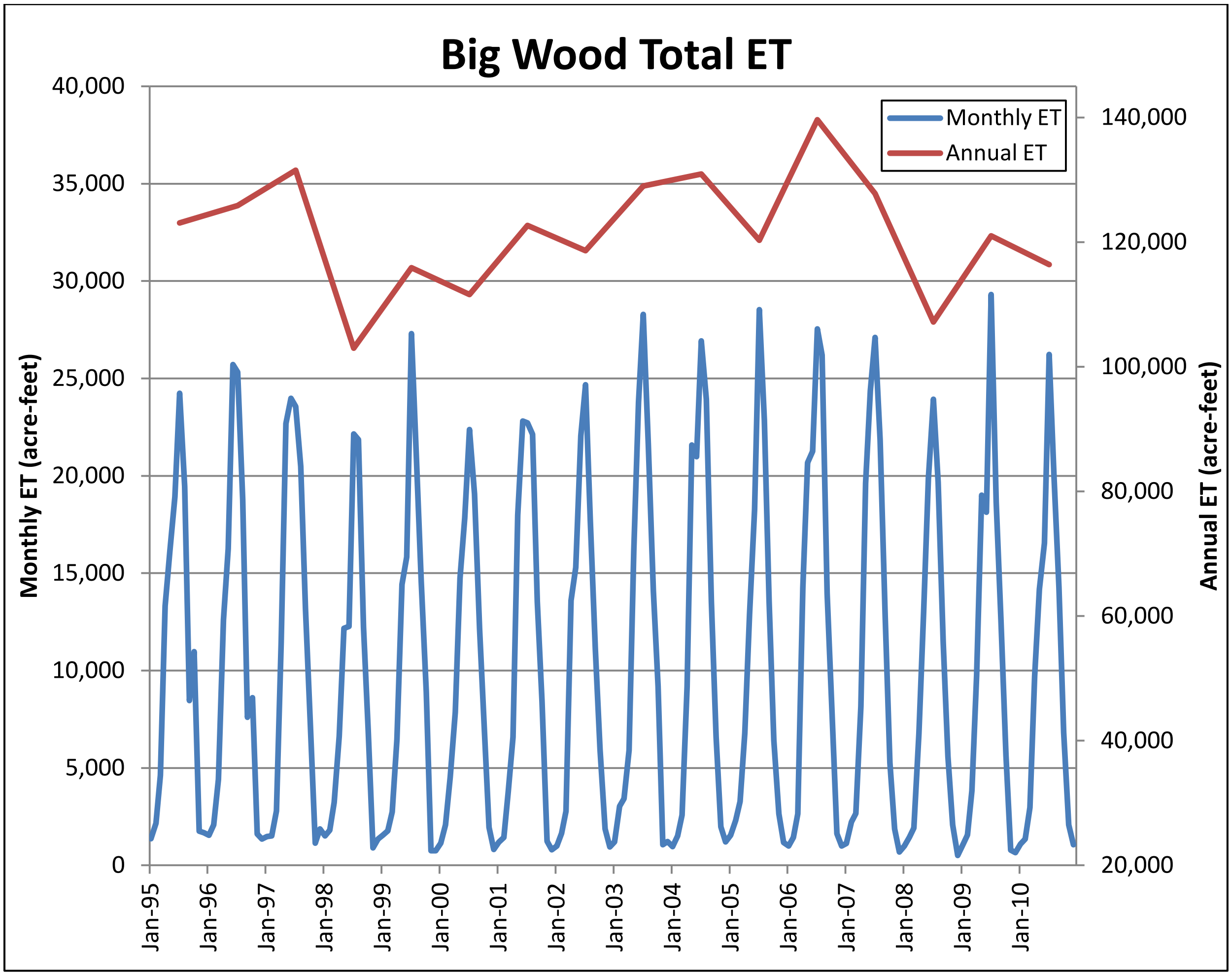

Figure 7. Monthly and annual ET for all lands. The ET volumes are based on a preliminary model area, and include winter-time ET.

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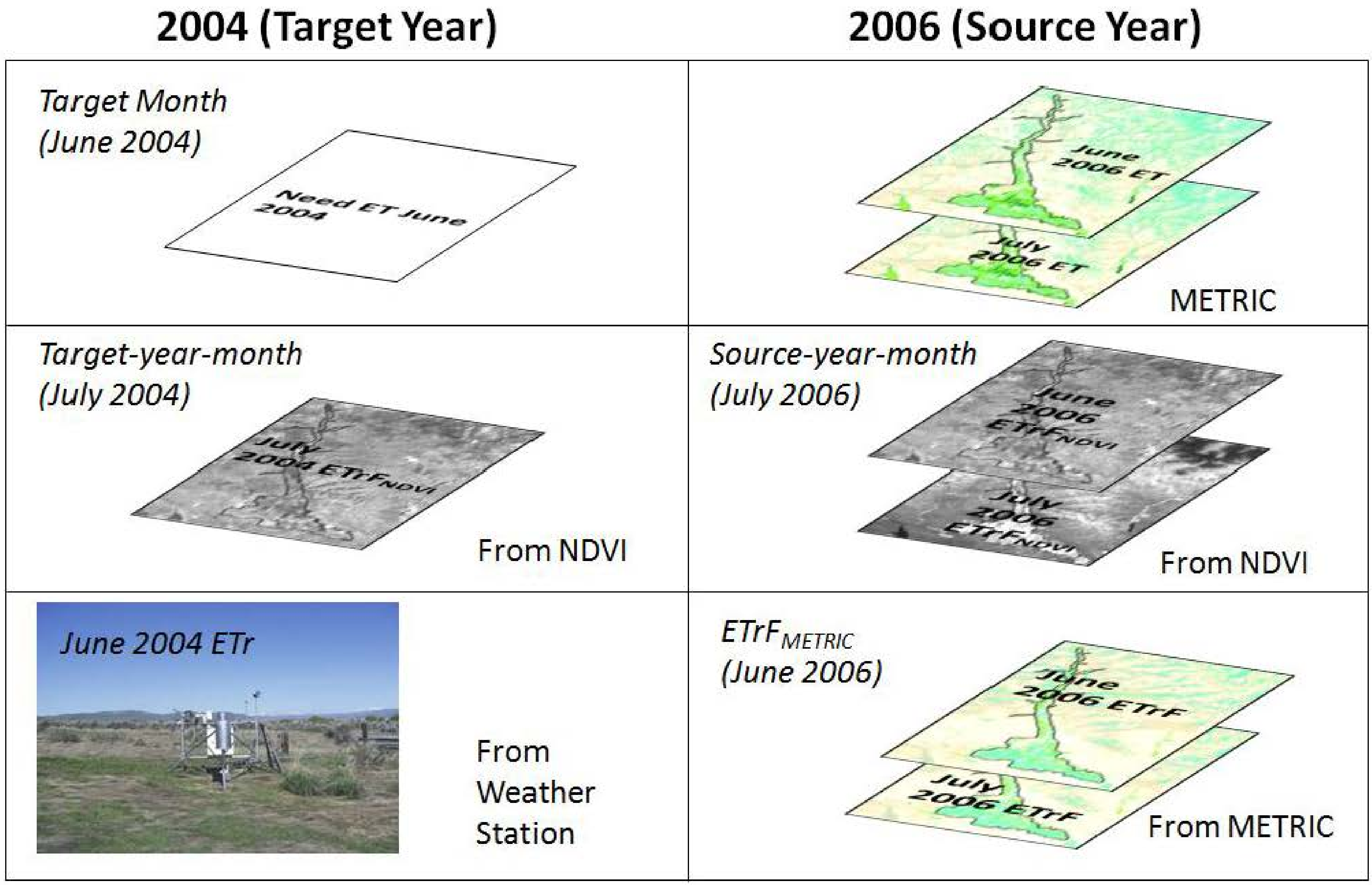
APPENDIX A

Graphical Example of Interpolating ET

ET Estimation by Interpolation – Available Data June 2004



ET Estimation by Interpolation – Processing for June 2004