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Crop Coefficient Development and Application to an Evapotranspiration Network

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Abstract. *Crop coefficients derived from properly designed, operated and maintained lysimeters provide the most accurate values throughout the growing season and are critical in the computation of hourly and daily, regionally based, crop evapotranspiration (ET) values. Multi-stage crop coefficients can be derived from continuously recording lysimeters, increasing the accuracy of both daily and seasonal irrigation crop demand estimates. These crop coefficients can be used with calculated, network based, reference crop ET to develop and disseminate locally representative crop water use estimates. Subsequently, using these accurate values in estimating crop water demand results in improved validity of regional water demand models, better assessments of proposed water policy measures, and enhanced integrity with crop consultants, water districts, and agricultural producers, ultimately resulting in better (more efficient) irrigation management and water conservation.*

Keywords: crop coefficient, evapotranspiration, evapotranspiration network, ET applications, lysimeter, irrigation demand estimates

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Introduction

In today's research community, debate exists whether the method of using crop coefficients (K_c) and reference ET (ET_{ref} – previously and commonly denoted by ET_o) is the most appropriate method for estimating crop ET (ET_c) as opposed to direct measurement techniques. However, the estimation technique of using K_cs and ET_{ref} is well established from the past, is simple and is generally utilized on a wider scale than other evapotranspiration (ET) methods. While concern regarding precision or accuracy of the method has merit, particularly at a site-specific level, the overall perspective of using ET in irrigation scheduling, irrigation applications, and water planning applications should be considered. Although specific research ET programs can measure ET to an accuracy level at or beyond 0.02 mm (0.001 in.), producers generally at best can apply irrigation only at the 2.5 mm (0.1 in.) level. Furthermore, regionally based water planning scales seldom need estimation to greater than a 25 mm (I in.) basis level.

In any case, the development of ET networks is not new and has resulted in a number of networks in the U.S (and around the world) being designed with multiple purposes and with most including a variety of application tools specific to local and regional needs. Many of these networks (CIMIS, 2010; CoAgMet, 2010; NPET, 2010; SPET, 2010; NDAWN, 2010; TXHPET, 2010; PIN [TWRI, 2008]; KanSched, 2010; Snyder, 2010 and Fipps, 2010) are used in irrigation scheduling applications. Several networks support intensive research and extension based programs (Marek et al., 2009). ET network supplied meteorological data have also been valuable in engineering designs, such as for regional agricultural products storage facilities (heating and cooling loads). However, the principal and most applicable use of ET network data has been in efficient irrigation management applications with the ultimate intent of reducing water use per unit area of crop production.

Estimation of crop water use over time has been approximated by many methods (Blaney et al., 1952; Jensen and Haise, 1963; TBWE, 1960; ASCE, [Jensen et al.] 1990; Eddy-Correlation, [Verma] 1990; Bowen Ratio Energy Balance, [Fritschen and Simpson] 1989; Penman-Monteith, [Monteith] 1965 and ASCE-2005, [Allen et al.] 2005). While these methods provide crop ET estimates, the best method of ET verification is with large, well designed, maintained and correctly operated weighing lysimeters. These units are not inexpensive to construct and install but the larger on-going cost (and benefit) comes from the continual programmatic commitment of personnel and operations. Subsequently, the ongoing expenses and staffing commitment required to maintain these networks have limited the construction and application of lysimeters in many areas of the U.S. Costs and personnel requirements have been discussed by Marek et al. (1998), CWCB (2008) and Straw (2010).

Crop ET estimates derived from ET network data today generally involve multiplying calculated reference ET by a crop coefficient representative of a particular crop, growth stage and climatic conditions. While the technique is not exact or site specific, accuracy and representation to actual field based crop stages are adequate and can be enhanced by increasing the number of growth stages and crop coefficients as compared to the generalized FAO-56 guidelines (Allen et al., 1998). Thus, the objective of this paper is to discuss the development and use of crop coefficients in the computation of crop ET and their application in irrigation scheduling and water planning.

Crop Coefficient Development

The process of determining crop coefficients can be achieved by several methods (Wright, 1991 and Pruitt, 1991) and for differing ET references, but the most recent advocation is to use

localized crop coefficients in conjunction with the ASCE standardized reference ET method (Allen et al., 2005). This method is a modified version of the Penman Monteith equation.

The most appropriate method of determining crop coefficients involves using the reference ET computation from meteorological parameters either directly over or adjacent to a representative weighing lysimeter. Other typically less accurate methods can involve the use of a water balance method involving direct crop ET measurement and soil profile measurements such as from soil sampling and by moisture probes. All crop coefficient methods involve the equation:

$$K_c = \frac{ET_c}{ET_{ref}} \qquad (1)$$

where

K_c =crop coefficient (dimensionless),

ET_c= ET of the crop (mm), and

ET_{ref} = ET, either of a short or tall reference (mm)-(see Allen et al., 2005).

The minimum number of crop stages required to estimate ET_c using FAO-56 is three (Allen et al. 1998). Use of more stages typically improves the seasonal ET_c estimate. The number of crop coefficients and stages used within the TXHPET network models are presented in table 1.

Initial K_c values of early crop growth stages can be challenging to determine and are variable in most climates, particularly in highly advective regions. However, these K_c values are typically small during this growth period and thus do not overwhelmingly affect seasonal ET_c values. Also, while K_cs could be obtained on a daily basis from lysimeter studies, this degree of accuracy is not warranted for field based production applications.

Table 1. Texas High Plains ET Network Classification and K_c summary.

Crop	**Planting Dates**	**Varieties/ Classifications**	**K_c Trigger Basis**	**Number of K_c Stages**
Corn	4	2	GDD*	17
Cotton	4	2	GDD	9
Grain Sorghum	4	2	GDD	13
Wheat	4	1	GDD	15**
Soybean	4	1	GDD	15
Peanut	4	2	GDD	10

Turf Grass	--	3	-	-

* GDD = Growing Degree Day

** Two of these stages are divided into secondary stages, making the total of 22 K_c growth stages.

Crop Lysimeter Operations

Lysimeter cropping practices and related maintenance have been addressed previously and discussed (Allen et al., 1991); however, there are general concerns that should be mentioned with the use of crop lysimeters. Initially, because land preparation and tillage can be challenging around a lysimeter, particularly with large equipment (tractor and plow), and around accompanying instrumentation masts, manual rotary tillage on and near the lysimeter is usually recommended. If residue is to be a factor in the crop assessments, care must be taken to mimic the same density and configuration of residue outside and within the lysimeter unit. Crop lysimeter parameters and growth should mimic the surrounding field area with no discernable difference in crop patterns of plant height and density.

Crop stage development in and around (outside) the lysimeter should also be similar. Attention should be given to personnel traffic patterns in and around the lysimeter. Required traffic associated with manual data acquisition, including foot traffic for sampling and site management, should be taken into consideration, particularly regarding plant injury or destruction or soil compaction as these affect infiltration, crop development and associated data values. The use of walkway boards is sometimes warranted to avoid compaction that can affect water infiltration and soil moisture measurements, for instance. Thus, continuous monitoring systems of an automated weighing lysimeter have another advantage over other ET measurement systems (Pruitt, 1991).

A common practice regarding crop establishment is to over-plant the crop population within the lysimeter area and subsequently thin the crop stand to match field density after emergence. Plant thinning should occur shortly after seedlings are fully emerged. Also, since plant available water (PAW) for cereal grains is typically maintained at a level of 50% or higher, transpiration is independent of soil water conditions. For more water sensitive crops, a higher PAW can be maintained but too high a PAW will affect root density development, increase de-aeration of the soil profile, and promote differences within and around the lysimeter. As to the size of crop lysimeter required regarding crop growth differences, see Aboukhaled et al. (1982) and Pruitt and Lourence (1985).

Computation of ET_{ref}

Many methods (and equations) of computing ET_{ref} have evolved and been evaluated over decades of research. Several methods are still in widespread use and advocated for continued use for a variety of reasons including historical use, adequacy of data, simplicity, acceptable representation, and site specific conditions. Because of the many methods and computations available, the Irrigation Association (IA) in 1999 asked an ASCE ET task committee to develop a benchmark ET equation and “standardize” the method of reference ET computation that would be generally representative and accurate across the U.S (and possibly globally with validation). The ASCE Standardized Reference ET Equation (Allen et al., 2005) resulted from a collaboration of leading ET scientists and engineers across the U.S. from work conducted on a wide range of crops and conditions. The basis of the new equation(s) was derived from the ASCE Penman-Monteith equation. The IA and the ET task committee are now advocating use of the method as the standardized ET_{ref} method of computation to assist and promote more valid comparisons of ET data. The ASCE task committee‘s objective was to “establish a methodology for calculating uniform ET estimates and thereby enhance the transferability of

crop coefficients and the comparisons of ET in various climates". The task committee recognized that the terms of "standard" and "benchmark" would create significant concern and could be misconstrued in the ET community. The ASCE method is not absolute and has alternate modes of computation for some parameters; however, it should represent the latest and "best" generalized ET computations. New methodology terms are included with the method and should be additionally adopted for generalized use. More on the method, definitions, nomenclature and data comparisons can be found in Allen et al. (2005).

Correlation from Reference Data and Lysimeter

While some may assume that reference ET should be derived directly from the mass weight of a reference lysimeter, this is generally not the case. As most ET_{ref} computations will be made from reference condition sites without lysimeters, the computation of ET_{ref} should be used as computed using the ASCE-2005 equation and the mass weights of the reference lysimeter should only be used for validation of the computation of ET_{ref}. Crop lysimeter mass balance data are used to acquire ET_c in equation 1. The number of stages and respective crop coefficients for each stage used in the seasonal crop model are thus derived accordingly per stage according to these mass balance measurements. Generally, the greater the number of crop stages and accompanying K_cs, the more accurate the seasonal ET_c model. Also greater flexibility to the adjustment of K_c per site specific area or per application is achieved with greater refinement of the K_c curve (i.e. more K_c stages).

Field Based Representation and Presentation

Progressive producers and crop consultants using the K_c method (or any method) expect accurate, reliable and stable field based representative crop development and water use estimates. Deviations from the predicted model(s) are virtually inevitable due to the number of varieties and maturities that are commercially available, and to changing crop genetics, management, etc. Nonetheless, categorization of crops by some selected means such as maturity level, days from emergence, or days to pollination generally can provide satisfactory representation for field applications.

Presentation of the ET_c data (and use of ET_{ref} and K_c data in a program) should be simple and limited in terms of time consumption and offer an obvious advantage or benefit beyond what method end-users presently utilize. It should be indicated that regulatory compliance can be a valid reason for adoption and use of any irrigation scheduling tool or program. The NRCS in the Texas High Plains has recently required producers to access ET_c based network data regularly for program compliance and payments.

While ET_{ref} computations may be complex, producers and other agricultural end users (such as crop consultants and irrigation managers) expect ET_c data to be presented in a concise format that can be easily and readily utilized. Generally this entails either tabular or graphically (see figure 1) presented data. Most end users, while sometimes recognizing the complex scientific and engineering equations involved, do not want to engage in much or any additional computations. The need for this simplicity arises particularly for less computer-literate users, some of whom may still be large scale and experienced irrigation managers. An example of such a condensed format that has multiple crops and category outputs format as determined by end users can be seen from the TXHPET network in figure 2.

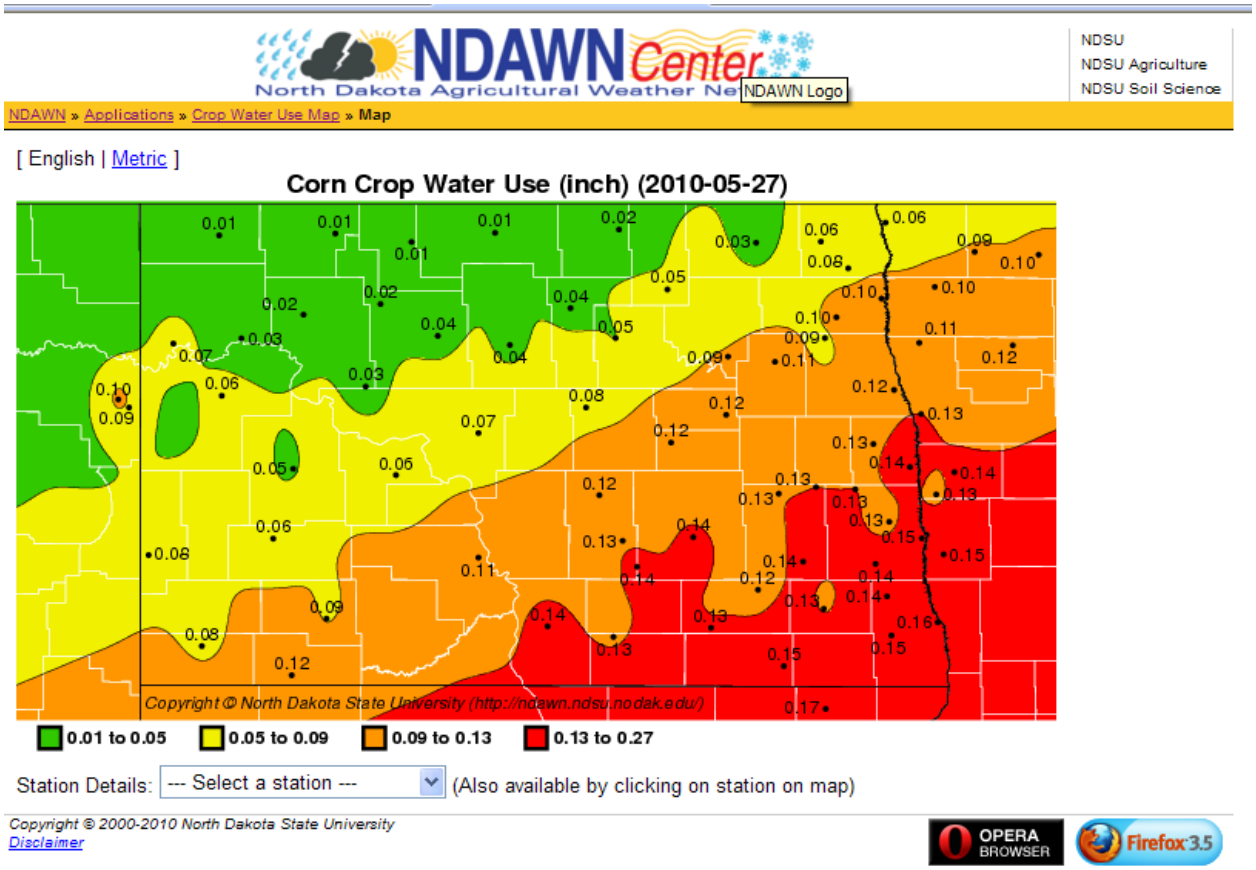

Figure 1. Example of graphically displayed ET_c data for corn from NDAWN network. (Source: http://ndawn.ndsu.nodak.edu).

North Plains ET Network Weather Station, Dalhart, TX

Date	ETo in.	Temperatures (F) ---Air-- Max	Min	Soil Min 2in.	6in.	Prec. in.	Growing Degrees Days (F) Crn	Srg	Pnt	Cot	Soy	Wht
05/25/10	.20	79	41	58	65	0.02	15	15	0	0	17	28
05/26/10	.21	82	54	63	67	0.00	18	18	0	8	22	35
05/27/10	.27	87	58	66	69	0.00	22	22	0	12	26	36

10-day avg min soil temp 59 64 Wind 8.7 mph from 155 deg.

CORN		Short Season Var. Water Use					Long Season Var. Water Use				
Seed Date	Acc GDD	Growth Stage	Day	3day	7day	Seas. in.	Growth Stage	Day	3day	7day	Seas. in.
			-----in/d-----					-----in/d-----			
04/01	665	4-leaf	.19	.16	.20	5.0	4-leaf	.19	.16	.20	5.0
04/15	501	4-leaf	.12	.10	.13	3.0	4-leaf	.12	.10	.13	3.0
05/01	361	Emerged	.09	.08	.10	1.8	Emerged	.09	.08	.10	1.8
05/15	204	Seeded	.07	.06	.07	0.7	Seeded	.07	.06	.07	0.7

SORGHUM		Short Season Var. Water Use					Long Season Var. Water Use				
Seed Date	Acc GDD	Growth Stage	Day	3day	7day	Seas. in.	Growth Stage	Day	3day	7day	Seas. in.
			-----in/d----					-----in/d----			
05/01	369	Emerged	.11	.09	.11	2.5	Emerged	.11	.09	.11	2.5
05/15	208	Seeded	.11	.09	.11	1.2	Seeded	.11	.09	.11	1.2

COTTON		North Plains Area Water Use					South Plains Area Water Use				
Seed Date	Acc GDD	Growth Stage	Day	3day	7day	Seas. in.	Growth Stage	Day	3day	7day	Seas. in.
			-----in/d----					-----in/d----			
05/01	85	Seeded	.03	.03	.03	0.8	Seeded	.03	.03	.03	0.8
05/15	68	Seeded	.03	.03	.03	0.4	Seeded	.03	.03	.03	0.4

SOYBEANS		Late Group 4-Var. Water Use				
Seed Date	Acc GDD	Growth Stage	Day	3day	7day	Seas. in.
			-----in/d----			
05/15	243	Emerged	.15	.13	.12	1.3

WHEAT			Water Use			
Seed Date	Acc GDD	Growth Stage	Day	3day	7day	Seas. in.
			-----in/d----			
08/15	4960	Heading	.28	.24	.31	22.3
09/10	4034	Heading	.29	.25	.31	19.1
10/01	3457	Heading	.29	.25	.31	17.7
10/15	3184	Heading	.30	.25	.31	16.6

Fescue/Bluegrass lawn water use 0.27 inch
Bermuda grass lawn water use 0.20 inch
Buffalo grass lawn water use 0.13 inch

Figure 2. Example of daily crop ET output (using ET_{ref} times K_c) from the Texas High Plains ET network.

Forecasted ET_c Value Applications beyond Irrigation Scheduling

ET_c can have widespread use beyond irrigation scheduling applications. In Texas and other states, regional water planning depends on accurate seasonal crop water use values. Correlations against actual water meter readings have validated the soundness of the approach in using crop K_cs and the ET_c method. In many cases, this ET_c information provides current and forecasted irrigation demand values on a per unit area basis, which may be on a field, farm, county, basin or watershed scale. An example in the Texas panhandle of how ET_c is being used in water planning for Region A (top 21 counties; TWDB, 2010) is to forecast county by county

crop demands and predict future conditions over the next 50 years with the result being displayed graphically through the use of a groundwater availability model (GAM)-(see figure 3). Having accurate assessments of future conditions allows for the evaluation of potential management strategies to be adequately evaluated to mitigate negative conditions. As water use becomes recorded on a smaller area (field) and per crop basis, resultant comparisons should get even better. ET_{ref} and a grassland coefficient can potentially even have application in non-irrigated applications for use to determine groundwater recharge since most water balance models are driven by ET.

ET_{ref} and ET_c are also needed for research based assessment of spatial and temporal aspects of local and regional ET imagery efforts. As remote sensing technologies improve, ground-truthing requirements through the use of accurate ET networks will be required. Comparative error rates associated with these assessment techniques have decreased 50% over the last decade, and these methods are expected to be in widespread use in the near future.

Previously, most ET networks would not directly engage in forecasting but a relatively recent development in partnership with selected regional National Weather Service (NWS) centers now provide 7 day forecasted reference ET based on parameters generated by NWS temperature, relative humidity, wind, cloud cover and solar radiation models. This data opportunity now offers "forward looking" projections for ET networks regarding ET_{ref} demands (and ET_c utilizing crop coefficients) without the networks assuming liability of the forecasts. An example of the graphical output of this NWS programming is illustrated in Figure 4 for northern Oregon for two days. The Oregon NWS forecast uses an alfalfa reference and the 1982 Kimberly-Penman model (Palmer, 2008), whereas prediction from the NWS office of northern California uses a short canopy reference and the ASCE-2005 equation. While this regional computation program could alleviate some of the ET network station(s) requirement within a particular geographical region, many NWS based stations are not located in irrigated areas and only predict values through interpolation algorithms. The ET_{ref} value data from the NWS sites are also available in tabular format. Numerous additional data features are available on the NWS site and complement the agricultural applications that many ET networks promote.

Results and Conclusions

Crop coefficients are important in many ET network applications. The basis of the reference ET and the K_c should be computed and stipulated, as the values are different for short and tall reference conditions. While the accuracy of the ET_{ref} times K_c method may not be absolute in terms of accuracy in comparison to some research based efforts, nearly all modern representations using the ET_{ref} and K_c method exceed the accuracy at which producers apply water, whether on a per irrigation event or on a seasonal basis. It is recommended that adoption of the new ASCE standardized reference ET equation, methodology and nomenclature be implemented to improve crop coefficient transferability and allow ET based comparisons for differing regions and conditions of the U.S. The ET_{ref} times K_c method has proven to be acceptable for many agricultural applications, including groundwater based irrigation demand modeling.

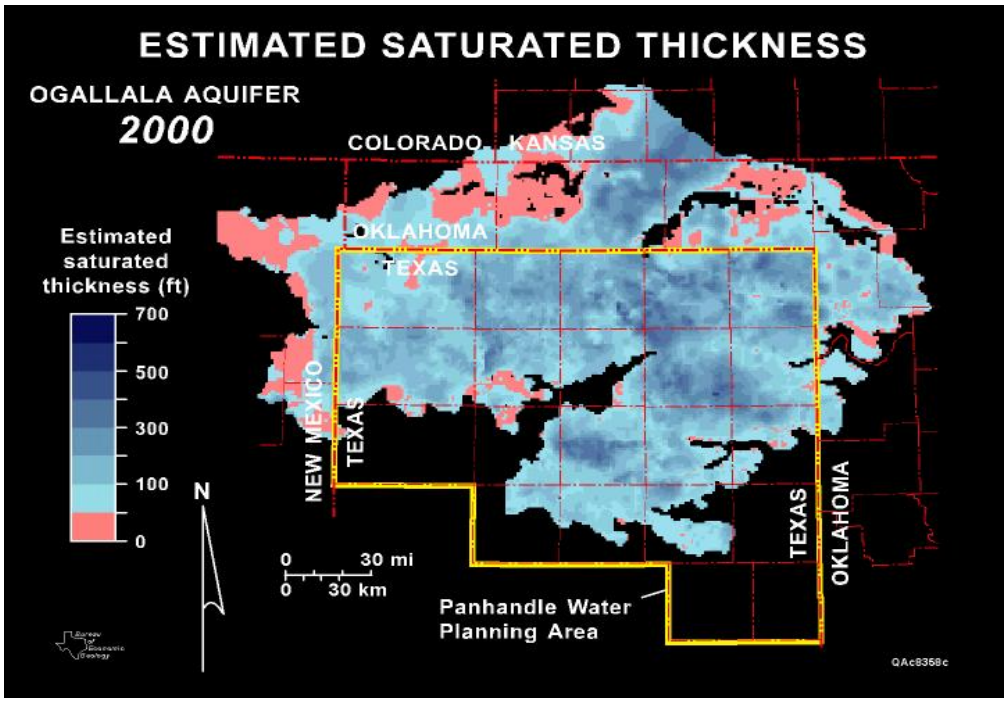

Figure 3a. Year 2000 GAM output for northern Texas.

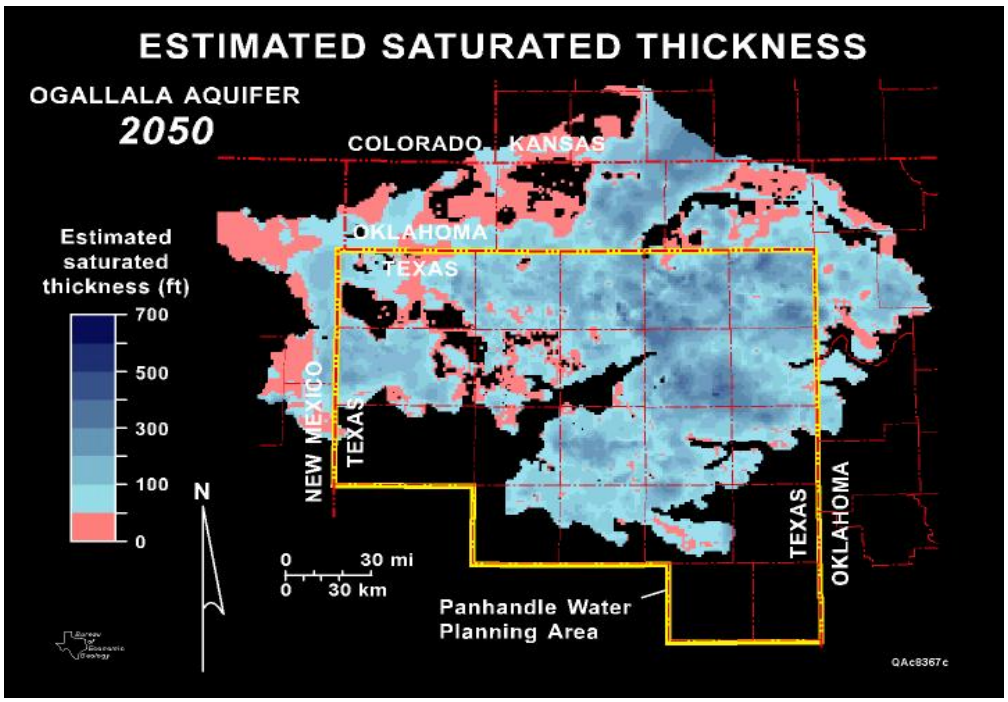

Figure 3b. Year 2050 GAM output for northern Texas. Note the black areas in the top left of Texas indicate prediction of aquifer depletion. (Source: Panhandle Water Planning Group, 2010).

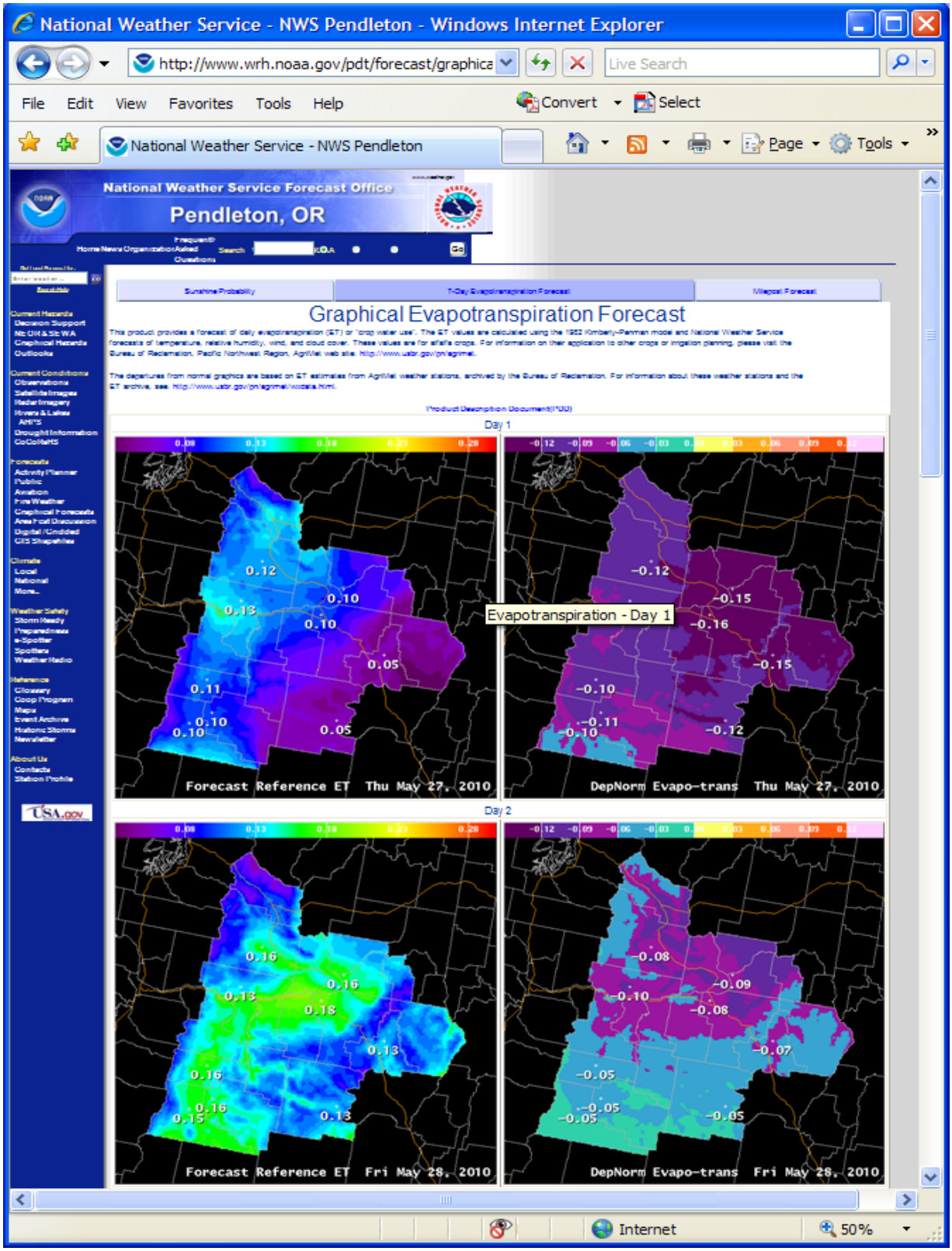

Figure 4. Example of NWS graphically forecasted ET_{ref} for Pendleton, OR. (Source: NWS, 2010).

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