RGDSS Memorandum

Phase 6 - Evapotranspiration from Groundwater

Final

TO: File
FROM: Mary R. Halstead, P.E.
SUBJECT: RGDSS Phase 6 - Evapotranspiration from Groundwater
DATE: July 20, 2012

1. Introduction

This memorandum summarizes enhancements to the evapotranspiration from groundwater (**ETg**) process as part of Phase 6 of the RGDSS groundwater modeling. The objective of this memorandum is to:

1. *Document the correspondence provided by consulting experts concerning changes to the ETg curves used to estimate native ETg and subirrigation in the groundwater flow model.*
2. *Summarize the Native ETg and subirrigation curves as provided by the consulting experts.*
3. *Summarize the enhancements made to the ETg monthly distribution.*

ETg can account for a substantial fraction of the water budget for a ground-water system. When modeling groundwater flow where ETg is a major aspect of the water budget the method by which ETg is simulated can affect calculated hydraulic heads and subsequent interpretation of the system dynamics (Banta, 2000). For the RGDSS groundwater flow project, the MODFLOW ETS1 package was used to estimate ETg. In the ETS1 Package, the relationship between ETg rate to hydraulic head (depth to water table) is conceptualized as a segmented line between an evaporation surface, defined as the elevation where the ETg rate reaches a maximum and an elevation located at an extinctions depth below the evaporation surface, where the evapotranspiration rate reaches zero (Banta, 2000). In this package the user supplies input to define as many intermediate segment endpoints as desired and the model calculates the ETg based on depth to water and removes that water from the model. **Figure 1** provides an example curve that represents ETg for medium vegetation. Notice that this ETg curve is defined using six segments.

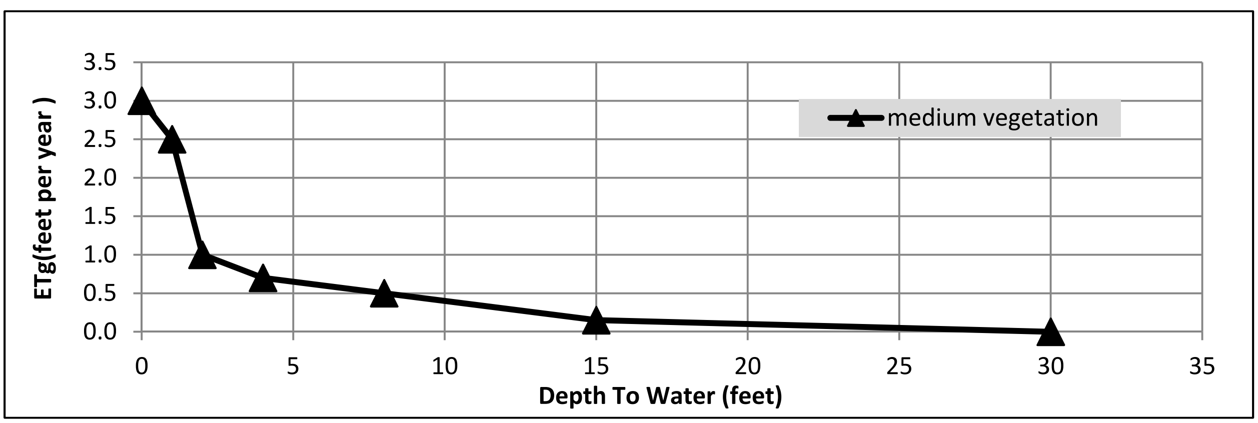

Figure 1: Example ETg Curve Representing ETg for Medium Vegetation

The Phase 6 RGDSS groundwater flow model incorporates the following ETg curves:

- Native Phreatophyte for:
  - Water Hydrophytes (riparian or wetland)
  - Heavy Vegetation (coniferous trees and deciduous trees)
  - Medium Vegetation (non-irrigated meadow)
  - Bare Ground
- Subirrigation for:
  - Meadows
  - Alfalfa
  - Other crops

For native vegetation, the maximum ETg in the curve is set based solely on the requirements of the vegetation and the ETg curves are directly used as input into the ETS1 package. However, ETg for subirrigated crops is handled differently because of the need to include the additional water from irrigation sources. For subirrigated crops, the maximum ET at ground surface is set as either the unmet irrigation water requirement (IWR) or the maximum ETg; whichever is less. Note that the unmet IWR is calculated as the IWR less the amount of effective irrigation water applied from surface water ditches and groundwater wells. The ETg curves for subirrigated crops are edited each time step by the ETS1 package. If the IWR for a structure is completely met through irrigation sources the maximum ETg is set to zero and there is no ETg for that time step.

2. Previous Efforts

Appendix C in the Phase 4 Ground Water Model Documentation provides a detailed discussion on ETg and background information on the initial native vegetation curves used in the Phase 4 model (Colorado Division of Water Resources, 2004). Appendix A1 of that same report provides a comparison of ETg calculated from the groundwater flow model and ET calculated from LANDSAT imagery. An ETg curve for subirrigated alfalfa was defined in Phase 4 of the RGDSS in a separate task memo (Bennett, 2003).

3. Approach

The approach to refining the ETg curves was based on discussions held by the RGDSS Technical Advisory Committee also known as the Peer Review Team (PRT). The PRT concluded that the ETg curves should be refined and updated based on more current data and studies. The original experts were contacted and their recommendations were presented and discussed at the PRT meetings. The references for the expert sources for each of the curves are bulleted below.

- Native Phreatophyte ETg – Cooper, August 19, 2011
- Subirrigation ETg (Alfalfa) - Groeneveld, 2012
- Subirrigation ETg (Meadow) - Sanderson and Cooper, 2008
- Subirrigation ETg (Other Crops) - Thompson and Thompson, 2011

The ETg curves are presented based on feet/year but this yearly value must be distributed on a monthly time step for use in the groundwater flow model. The monthly distribution was changed for both native phreatophytes and subirrigated crops. For native phreatophytes Dr. David Cooper provided a revised monthly distribution. For subirrigated crops a separate task memo was prepared (Heath, 2012).

4. Results

The results for each of the native vegetation types and subirrigated crops are described in the following sub sections.

4.1 Native ETg

Based on email correspondence with Dr. David Cooper at Colorado State University, the maximum ETg for zero water depth was changed from 4 feet/year to 3.11 feet/year for all native vegetation types (Cooper, August 19, 2011). This decrease should result in an overall reduction in the volume of water removed from the ground-water system through ETg. **Table 1** provides a tabular summary of the input data and **Figure 2** provides a graphical presentation for all the native ETg curves. **Appendix A** provides summary emails documenting this slight change and a copy of Dr. Cooper's 2005 Opinion.

Table 1: Native Vegetation ETg Curve Data

	Annual Evapotranspiration from groundwater (feet/year)				
Depth	Bare Ground	Sparse Vegetation	Medium Vegetation	Heavy Vegetation	Wetland
0	3.11	3.11	3.11	3.11	3.11
1	2.2	2.50	2.50	2.70	2.50
2	0.5	0.90	1.00	1.40	2.00
4	0.10	0.50	0.70	0.90	0.70
8	0.07	0.35	0.50	0.65	0.25
15	0.00	0.10	0.15	0.20	0.00
30	0.00	0.00	0.00	0.00	0.00

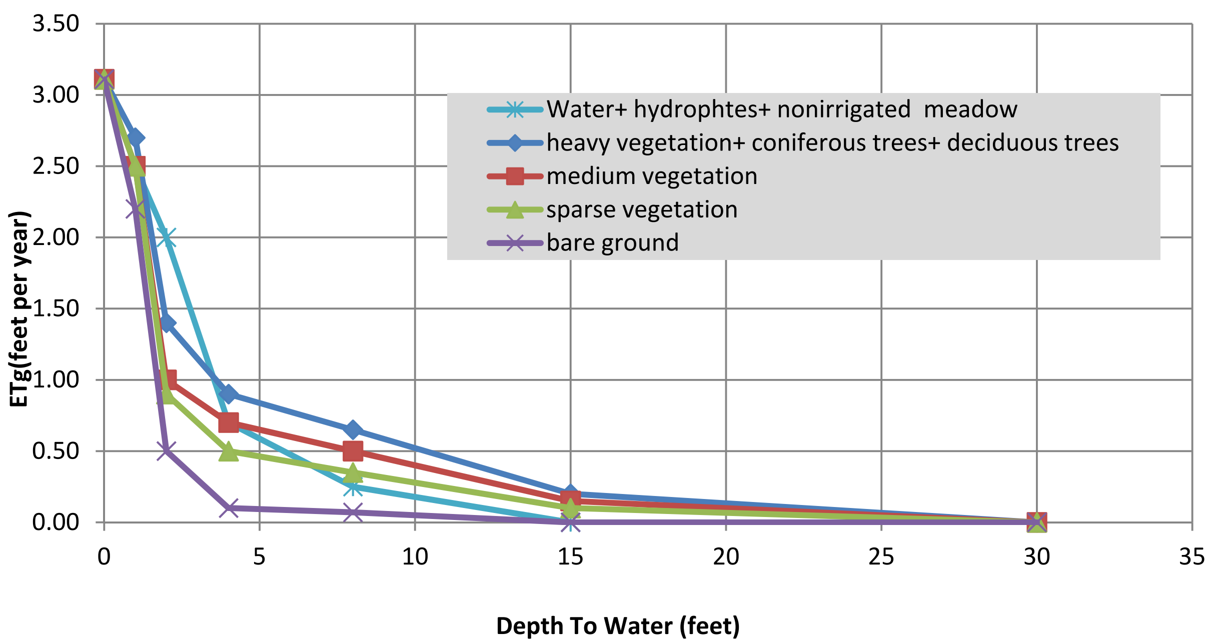

Figure 2: ETg Curves for Native Vegetation

Monthly Distribution for Native Phreatophytes

The monthly distribution of ETg for native phreatophytes was refined by Dr. David Cooper, based on 2008 published data in the Journal of Hydrology (Sanderson and Cooper, 2008) and on email correspondence (Cooper, August 19, 2011). **Table 2** provides the monthly distribution and the monthly multiplier used in the ETS1 package which was based.

Table 2 - Phase 6 Monthly Distribution of ETg for Native Phreatophytes

Month	Monthly Percentage of Total ET	MODFLOW ETS1 Monthly Multiplier (multiply the average monthly ET rate (ft/month) to get the individual monthly ET rate (ft/month)
1	0.82%	0.098
2	0.74%	0.088
3	0.82%	0.098
4	9.49%	1.139
5	14.72%	1.767
6	17.51%	2.102
7	17.64%	2.117
8	15.69%	1.883
9	12.53%	1.503
10	8.43%	1.012
11	0.79%	0.095
12	0.82%	0.098
Total	100.00%	12.000
Average		1.00

Note 1: Estimates are based on models derived calibrated to actual ET measurements, as described in Sanderson et al. 2008 and in the August 19, 2011 email from Dr. Cooper to Mary Halstead

4.2 Subirrigation ETg

The ETg curve for subirrigated alfalfa was refined by Dr. David Groeneveld with HydroBio Advanced Remote Sensing (Groeneveld, 2012) (**Appendix B**). Dr. Groeneveld set the extinction depth for water use by alfalfa at 16 feet with a linear increase in ground-water use up to a depth of 3 feet where the water use from subirrigation is 2 feet/year. He did not extrapolate for higher water use as the water table approaches the ground surface. Instead he held the curve constant at 2 feet/year. This approach recognizes that alfalfa growth will tend to be impacted by very shallow water tables and will likely not grow to its maximal representation (Groeneveld, 2012).

The ETg curve for subirrigated meadows was refined by Dr. David Cooper based on 2008 published data in the Journal of Hydrology (Sanderson and Cooper, 2008) (**Appendix C**). The ETg curve data provided by Dr. Cooper was segmented and linearized by DWR staff.

Mr. Kelley Thompson and Mr. Kirk Thompson with Agro Engineering provided an analysis and documentation to support using one single ETg curve to represent the variety of “other crops” including small grains, potatoes, vegetables fall wheat, new alfalfa, and cover crops (**Appendix D**). In addition the other crop curve will also be used for the few hundred acres of blue grass that have been mapped in the valley.

Tables 3, 4, and 5 provide a tabular summary of the input data for subirrigation of alfalfa, meadows, and other crops, respectively. **Figure 3** provides a graphical presentation for all the subirrigation ETg curves.

Table 3: Subirrigated Alfalfa ETg Curve Data

Depth, feet	ETg (feet/year)
0	2.0
3	2.0
16	0.0

Table 4: Subirrigated Meadow ETg Curve Data

Depth, feet	ETg (feet/year)
0.00	3.111
1.00	2.436
1.97	2.250
3.28	2.084
7.22	0.000

Table 5: Subirrigated Other Crops ETg Curve Data

Depth, feet	ETg (feet/year)
0	2.0
2	2.0
4	0.0

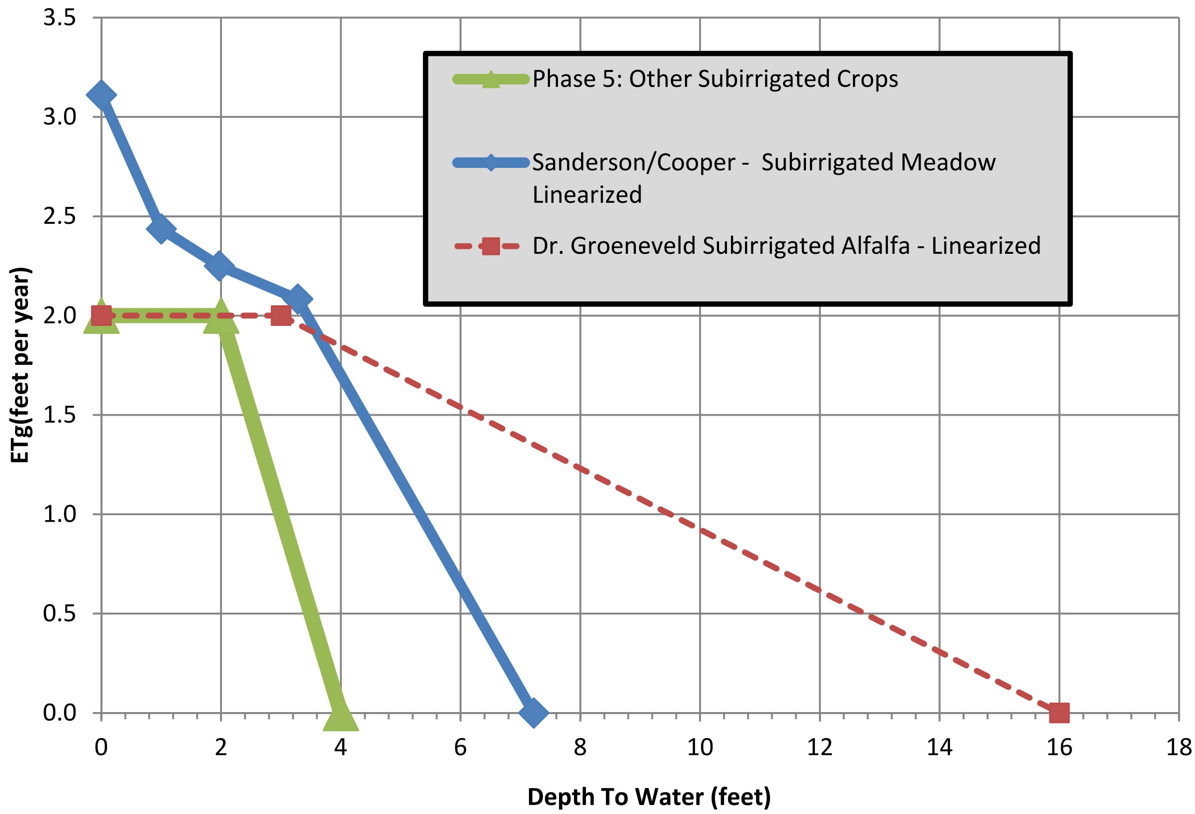

Figure 3: ETg Curves for Subirrigated Crops

Monthly Distribution for Subirrigated Crops

Based on discussions with the Peer Review Team and Dr. Groeneveld, the irrigation water requirement curve based on annual climate information developed through the StateCU modeling, is the best approach to disaggregate the annual rates to monthly rates. Further, the groundwater model currently utilizes StateCU output related to crop irrigation water requirement shortages on a monthly basis. It was further discussed that a maximum monthly limit should be imposed so as to constrain the simulated ETg to a level consistent with the maximum annual rates. For subirrigated crops a separate task memo was prepared (Heath, 2012) and summarized herein.

Table 6 summarizes the maximum monthly ETg set for each of the subirrigated crops.

Table 6 – Maximum Monthly ETg for Subirrigated Crops.

Subirrigated Crop Type	Maximum Monthly ETg (feet)
Alfalfa	0.391
Meadow	0.740
Other	0.695

5. References

Banta, Edward, R., 2000, MODFLOW-2000, *The U.S. Geological Survey Modular Ground-Water Model – Documentation of Packages for Simulating Evapotranspiration with a Segmented Function (ETS1) and Drains with Return Flow (DRT1)*, U.S. Geologic Survey Open-File Repot 00-466, Denver, Colorado.

Bennett, Ray R., September 12, 2003, Draft RGDSS Memorandum to the file entitled *RGDSS Ground Water Phase 4 Task 11 Include Alfalfa as a Subirrigated Crop*, Colorado Division of Water Resources, Denver, CO.

Colorado Division of Water Resources, August 2004, *Preliminary Draft, Rio Grande Decision Support System Phase 4 Ground Water Model Documentation*, Appendices C and A1 prepared for Colorado Water Conservation Board and Colorado Division of Water Resources, Denver, CO.

Cooper, David, August 19, 2011, email correspondence to Mary Halstead (Colorado Division of Water Resources, *SLV ET curves for native phreatophytes.*

Cooper, David, Ph.D., August 3, 2005, Court Opinion on Native Vegetation ET Curves Used in the RGDSS.

Cooper, David, J. Sanderson, D. Groeneveld, R. Chimner, June 2004, Chapter 5 Evapotranspiration Rates for Non-Wetland Phreatophyte Communities – 1966-2002, Research performed for: Rio Grande Water Conservation District.

Groeneveld, David P., July 14, 2012, letter report to Mike Sullivan and James Heath (Colorado Division of Water Resources), *Alfalfa Extinction Curve for Use in the San Luis Valley Groundwater Modeling*, HydroBio Advanced Remote Sensing, Santa Fe, New Mexico.

Heath, James R., July 20, 2012, RGDSS Memorandum, RGDSS Phase 6 - Subirrigation Maximum Monthly ETg.

Sanderson, John, S., and David J. Cooper, 2008, *Ground Water Discharge by Evapotranspiration in Wetlands of an Arid Intermountain Basin*, Journal of Hydrology, pages 344-359.

Thompson, Kelley, and Kirk Thompson, November 22, 2011, Memorandum to Mike Sullivan, Mary Halstead, and James Heath with Colorado Division of Water Resources, *RGDSS Groundwater ET Curves for "Other" Crops.*

Appendix A

Native Phreatophyte Documentation

A1 – Email correspondence from Dr. David Cooper to Mary Halstead dated August 19, 2011

A2 – Original email correspondence from Mary Halstead to Dr. David Cooper dated August 18, 2011

A3 – Dr. David Cooper's 2005 Opinion

Appendix A1

Email correspondence from Dr. David Cooper to Mary Halstead dated August 19, 2011

Halstead, Mary

From: David Cooper [davidc@warnercnr.colostate.edu] Sent: Friday, August 19, 2011 9:08 AM

To: Halstead, Mary Cc: Heath, James; willem.schreuder; Sanderson, John Subject:

Re: SLV ET curves for native phreatophytes

Attachments: 5drylandET2004.pdf; ATT17522.htm

Mary

I've gone over your questions, and our papers, reports, and data. Regarding question 1, I think that ET for 0 water depth should be reduced to 3.11 feet per year. This is the best estimate based upon the data available. Regarding question 2, this is a bit more complex. We have some decent winter ETg data, acquired with much pain in 2002 and other years. ETg certainly is not zero in the winter. Et occurs from the water table, and ET also occurs from snow on the ground, sublimation of ice, and other processes. In the attached report from 2004, which you may have, if you start on page 40 we address winter ET at our Crestone study site. I would suggest Nov-March ET should be calculated at an average of 0.3 mm/day. If you wish to use a broader concept of winter, which we did, Oct-April, you could use the formulas and data in this report on the pages I have referenced.

I'm around today if you wish to communicate or talk on the phone. Let me know and we can find a time to talk. I'm headed to Eastern Europe to work in Poland and Slovakia next week, so try me today if you need more help. I'm not working on campus, so if you want to talk, email me.

Best,

DAVID

Appendix A2

Original email correspondence from Mary Halstead to Dr. David Cooper dated August 18, 2011

From: Halstead, Mary
Sent: Thursday, August 18, 2011 3:05 PM
To: 'Cooper,David'; David Cooper
Cc: Heath, James
Subject: SLV ET curves for native phreatophytes
Attachments: RGDSS April 2011 Meadows and Open Water.xlsx; Cooper2005Opinion.pdf; Sanderson&CooperJ Hydro 2008.pdf

Hi David,

I hope you can help us out on two quick clarifications:

1. Provided below is a table showing the native phreatophyte curves you provided in your 2005 opinion (attached).

	Annual ET from ground water (feet)				
Depth	Bare Ground	Sparse Vegetation	Medium Vegetation	Heavy Vegetation	Wetland
0	4.00	4.00	4.00	4.00	4.00
1	2.2	2.50	2.50	2.70	2.50
2	0.5	0.90	1.00	1.40	2.00
4	0.10	0.50	0.70	0.90	0.70
8	0.07	0.35	0.50	0.65	0.25
15	0.00	0.10	0.15	0.20	0.00
30	0.00	0.00	0.00	0.00	0.00

Willem thought that you had suggested reducing the ETg at zero depth from 4 feet down to 3 feet. ***Are you be okay with this reduction? Would you prefer to use the 3.11 value you had for the meadow/grass pasture (See attached spreadsheet)?***

2. James would like to cut off the monthly distribution to the months of April-October. In the spreadsheet (Open Water tab) you sent you have the monthly distribution going from March-November. This March-November distribution was based on the shallow open water evaporation. Reducing the months to April-October is in line with your 2008 hydro article (Table 2 – attached***). Are you okay in the reducing the native phreatophyte and the meadow curves to just April – October?***

I want to make sure that we don't make any changes that you disagree with. Hopefully, I have attached all the relevant documents so you don’t need to hunt anything down. Please give me a call if you need any additional information. I will be on vacation starting Monday, so I would appreciate if you could answer the questions in red by tomorrow. If not please email your response to James. Thanks again for your help.

Thanks, Mary

Appendix A3

Dr. David Cooper's 2005 Opinion

David J. Cooper, Ph.D. – Opinions

Experience:

I am a plant ecologist with expertise in vegetation analysis, hydrology, ecosystem functioning, evapotranspiration, plant physiology and ecosystem restoration. My current research and consulting includes projects on riparian, wetland and phreatophyte ecology throughout the western U.S., as well as in Peru and Canada. I am a senior research scientist in the Department of Forest, Rangeland and Watershed Stewardship, and faculty advisor in the Graduate Degree Program in Ecology at Colorado State University, and have my own ecological research and education company as sole proprietor. I have a number of ongoing applied ecology research projects in National Parks, including Yellowstone, Yosemite, and Rocky Mountain National Parks, and also work closely with many National Forests, Forest Service regional and national scientists, as well as regional offices of Bureau of Land Management, Bureau of Reclamation, Environmental Protection Agency, water conservation districts, ski areas, non-profit organizations, mining companies, cities, counties and other agencies and corporations that manage land and water.

Continuously since 1989 I have done research on vegetative consumptive use of ground water issues in the San Luis Valley (SLV). I first worked on the potential effects of ground water drawdown by American Water Development, Inc., on wetlands in the SLV as an expert for the State of Colorado, the U.S. Fish and Wildlife Service and the Rio Grande Water Conservation District (RGWCD). The results of that investigation are published in Cooper and Severn 1992. In 1995 we began an analysis of root distribution in phreatophyte communities in the SLV funded by the RGWCD (Cooper et al. 1996). We have analyzed the disappearance of interdunal wetlands at Great Sand Dunes National Monument, funded by the National Park Service Water Resources Division, the results of which are published in the Journal of Hydrology (Wurster, Cooper, Sanford 2002). Since 1996 we have analyzed evapotranspiration (ET) from native non-wetland phreatophyte and wetland communities in the San Luis Valley. This work, funded by the RGWCD, is ongoing. We have published one paper (Chimner and Cooper 2003) containing results from this study, and have another paper on this topic accepted for publication pending revisions (Cooper et al. revision in progress), and have submitted interim reports and progress reports to the RGWCD. My *Curriculum Vitae* is attached.

Based upon my education, professional experience, and my research in the San Luis Valley, I will provide the following 4 opinions on ET as used in the State of Colorado Rio Grand Decision Support System (RGDSS).

Opinion 1: Boundary of plant communities known to use ground water

A boundary that identifies the area occupied by plants that are known to use ground water, known collectively as phreatophytes, is useful in ground water modeling for bounding the area where consumptive use of ground water by plants is occurring. The RGDSS uses a boundary that identifies the area supporting phreatophytes that use ground water. That boundary was identified by on-the-ground investigations as well as aerial overflights in a light airplane, and air photographs. The location of plant communities containing phreatophytes can be readily seen and delineated both on the ground and from the air. The boundary of plant communities known to use ground water used in the RGDSS ground water model is an accurate mapping of the area supporting phreatophytes capable of using ground water.

Opinion 2: Classification of ET cover types used in the RGDSS

A number of factors control evapotranspiration rates from plant communities in the SLV. Water table depth controls the duration of soil saturation in the root zone of plants, and ground water availability. Soil salinity and nutrient content influences plant density, leaf area and species composition. Soil texture influences water holding capacity and nutrient availability. These factors combine to create a mosaic of communities across the SLV supporting a range of wetlands, areas with bare soils and phreatophyte communities, as well as uplands.

Because different communities have different ET rates and ET processes, it is appropriate to use different ET curves for different plant communities. Thus, developing a classification of communities with different ET functions is an important first step in modeling ground water use by phreatophytes in the San Luis Valley.

The community classification used by the RGDSS ground water model is a scientifically appropriate classification because it includes bare ground, wetlands, and several non-wetland phreatophyte communities. However, I would suggest in future revisions of the RGDSS ground water model that a few slight modifications to the classification be considered. **ET Category 1** is now termed Riparian or Wetland. I suggest that it be changed to Wetland and wet meadows and include all areas that have water tables that reach to within 2 feet of the soil surface seasonally, or in many years. **ET Category 2** is heavy vegetation, and I suggest removing coniferous trees because they are non-phreatophytic, and keeping riparian forests and shrublands dominated by cottonwood and/or willows, as well as dense non-riparian stands of greasewood and rabbitbrush that have high ET rates. An example is our "Thicket" study site, located SE of Saguache, near Hickey Bridge. **ET Category 3** is medium vegetation, and this should include only phreatophyte communities, not native meadows. **ET Category 4** is sparse vegetation, and this is fine as is, and should continue to contain only native phreatophyte communities with low plant cover. **ET Category 5** is bare ground, and is fine.

Opinion 3: ET curves used in the RGDSS

I have looked at the ET curves used in the RGDSS ground water model. They conform to the scientifically established principle that different plant communities have different ET rates along a water table gradient. The concept of using a single ET curve, as done by Emery (1969, 1991), and used in earlier ground water models in the SLV, is overly simplistic and was properly abandoned in favor of multiple curves. The concept of multiple curves was first proposed by Nichols (1991) for areas in Nevada, and is appropriately used in the RGDSS ground water model and those curves are reasonably accurate.

We have collected ET data in the SLV for several years prior to and following the development of the RGDSS ground water model. Our data were used in the development of the RGDSS ET curves. However, our recently collected data allow me to suggest that future model revisions incorporate some minor changes in the shape and position of ET curves used for the 5 ET categories discussed above. I suggest that the data presented in Table 1 be used to create ET curves for each of the 5 categories. While the bare ground and wetland category curves are reasonable approximations of ground water ET, they need some refinement. This is because sites with bare soils lack phreatophytes, and when the water table and capillary fringe drop below the soil surface, ET rates drop off very quickly, and are very low at water table depths of 4-6 feet. Similarly, wetland plants have very shallow roots because the seasonally or perennially saturated soils prevent the development of deeper root systems. Therefore, as with bare ground, when the water table drops below the rooting zone of wetlands plants, ET rates drop off very sharply. The other suggested modifications are based upon our data collected from our Moffat site (for sparse), Crestone (for medium), and Thicket (for heavy vegetation categories). Wetland data are derived from our study sites named Rito Alto, Bulrush, Alamosa Wildlife Refuge, and Higel.

***Table 1**. Annual ET from ground water (ET_g) for 7 water table depths for the 5 ET categories discussed in this report.*

Depth (ft)	BareGr	Sparse	Medium	Heavy	Wetland
0	4.0	4.0	4.0	4.0	4.0
1	2.2	2.5	2.5	2.7	2.5
2	0.5	0.9	1.0	1.4	2.0
4	0.1	0.5	0.7	0.9	0.7
8	0.07	0.35	0.5	0.65	0.25
15	0	0.1	0.15	0.2	0
30	0	0	0	0	0

Because there is ongoing research on ET rates from native communities in the SLV, I suggest that the ET curves used in the RGDSS be adjusted periodically as new data and refined understanding of the concepts become available.

Opinion 4: Use of Satellite images in developing ET estimates

Satellite images can be used to accurately map vegetation and identify the "greenness" or leaf area of pixels anywhere that such images exist. The best procedure for using satellite images for mapping vegetation is to first do an on the ground classification using field data. Then the locations of representative pixels in each vegetation class are identified using GPS and are then used in a computer program to create a supervised classification of vegetation using satellite image reflectance data. This was the methodology followed by Agro Engineering for use in the development of the 5 ET categories discussed above and is done in an appropriate and accurate manner. It is one of the best ways to develop a vegetation classification and is a generally accepted means for doing so in the scientific community.

Satellite images can also be used to quantify the "greenness" or leaf area of plant communities. Metrics such as the Normalized Difference Vegetation Index, NDVI, can be used to measure "greenness" of pixels, and if this is referenced to field measurements of leaf area for known pixels, NDVI can be directly related to leaf area with regression analysis. The use of NDVI for this purpose is an established technique generally accepted in the scientific community. Our ongoing work on ET in the SLV indicates that greenness or leaf area, is the best single measure of total ET rates. Sites with large leaf areas have higher ET rates than sites with lower leaf areas.

The estimate of total ET based upon NDVI developed by David Groeneveld appears to be an accurate calculation because it relies upon data from our ongoing research sites for which we have Leaf Area Index (LAI) and ET measurements. Other forms of remote sensing data have been used to map ET rates, for example those of Richard G. Allen (University of Idaho).

Appendix B

Subirrigated Alfalfa Documentation

Reference: Groeneveld, David P., July 14, 2012, letter report to Mike Sullivan and James Heath (Colorado Division of Water Resources), *Alfalfa Extinction Curve for Use in the San Luis Valley Groundwater Modeling*, HydroBio Advanced Remote Sensing, Santa Fe, New Mexico.

Attachment B

HydroBio
Advanced Remote Sensing

Draft for CDWR Review

July 14, 2012

Mike Sullivan, Deputy State Engineer
James Heath P.E., Lead Modeler
Colorado Division of Water Resources
1313 Sherman Street, Room 818
Denver, Colorado 80203

RE: Alfalfa Extinction Curve for Use in San Luis Valley Groundwater Modeling

Dear Mike and James:

This letter recaps my analysis and findings from investigating San Luis Valley subirrigation by cultivated alfalfa. As noted in the description that follows, the data for water table level and water use from the alfalfa fields is inherently noisy, despite the fact that the monitoring system and available records are state-of-the art and generated from what I believe is the most intensively monitored and modeled groundwater system in the world.

Given that the data will likely be noisy for the comparison, I have generated this analysis to provide an unbiased estimation of subirrigation for alfalfa. The method was calibrated to your SPDSS StateCU alfalfa water use accounting and applied to remotely sensed San Luis Valley data. The results were compared to a scaled representation of subirrigation that I generated and published for scrub vegetation. To constrain possible systematic error within the groundwater model this relationship was then linearized.

Within the final curve the extinction depth for the groundwater use by alfalfa is 16 feet with a linear increase in groundwater use up to a depth of three feet where the subirrigation use peaks at two feet per year. Rather than extrapolating for higher water use as the water table approaches the surface, I have held the curve constant with a water use of two feet per year. This approach recognizes the fact that alfalfa growth will tend to be impacted by very shallow water tables and will likely not grow to its maximal representation.

Sincerely,

David P. Groeneveld, Ph.D.
President, HydroBio

1. Calculation of Subirrigation from ETa, rainfall and irrigation.

Groundwater use by alfalfa from subirriation was investigated using the remotely-sensed data of greenness as a scalar against ET_0. This method was calibrated against alfalfa water use data published by the Colorado Division of Water Resources (CDWR) for the South Platte Decision Support System (StateCU). The calibration was used to estimate actual ET from alfalfa (ETa) on a daily basis through the summers of 2009 and 2010. The estimation of ETa was used to calculate the proportion of crop irrigation requirement (CIR) supplied by groundwater from metered center pivots, from local weather stations, and from Landsat TM5 and ETM7 satellite data. The subirrigation (ETg) component was calculated as an annual residual sum following Equation 1:

ETg = ETa – precipitation – irrigation **Equation 1**

The precipitation that was used within Equation 1 was kriged from CoAgMet stations located in four quadrants of the San Luis Valley (SLV). Given the relatively high CIR for alfalfa, precipitation is a relatively small contributor to the annual water balance in arid SLV, but necessary for calculation of ETg.

Crop greenness was estimated using a transformation of the normalized difference vegetation index NDVI, NDVI*, that is stretched from zero to one for the full theoretic range of greenness covering the landscape. This full range in NDVI runs from zero plant cover for bare soil to saturation for a closed, maximally verdant canopy. This transformation removes the influence of soil background and atmospheric aerosols for portrayal of vegetation response (Groeneveld and Baugh, 2007). NDVI* was shown to be a more accurate index for vegetation response to hydrologic inputs than all other commonly used indices (Baugh and Groeneveld, 2006). Groeneveld et al. (2007) showed that NDVI* permitted accurate estimation of ETa from native phreatophyte vegetation when used as a scalar for reference ET, ETo (Penman Monteith grass reference; Allen, 2005). HydroBio (2007) subsequently used this method to estimate the consumptive use (CU) by phreatophye vegetation in the South Platte Decision Support System (SPDSS) published and applied by the CDWR. NDVI and NDVI* are presented in Equations 2 and 3.

$\mathbf{NDVI_i = (NIR_i - Red_i) / (NIR_i + Red_i)}$ **Equation 2**

Where “i” refers to the ith pixel and NIR and red are near infrared and red reflectance values for bands of earth observation satellite data.

$\mathbf{NDVI^* = (NDVI_i - NDVI_0) / NDVI_S - NDVI_0)}$ **Equation 3**

Where $\mathbf{NDVI_i}$ is the value for the ith pixel, $\mathbf{NDVI_0}$ is the NDVI at zero vegetation cover, and $\mathbf{NDVI_S}$ is saturated NDVI, a theoretic value for the highest greenness that can occur.

The method for reconstructing ETa of subirrigated alfalfa fields in SLV was calibrated using alfalfa data from SPDSS for 2001. The method developed a calibration curve for alfalfa ETa by first extracting the monthly alfalfa CU from SPDSS and developing statistics for its water use. The CU for alfalfa in the SPDSS were accepted as the best available estimate by the CDWR and were made using the Blaney-Criddle method with factors that were specifically calibrated for the South Platte environment. These CU estimates had been cross calibrated with gage data to ensure their accuracy. The area used is shown in Figure 1.

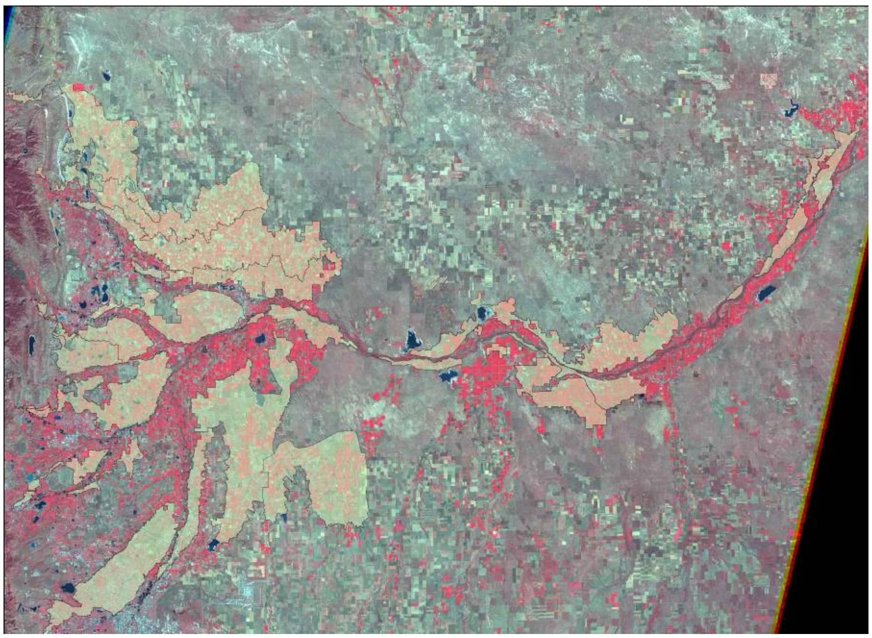

Figure 1. South Platte drainage with areas chosen for extraction of alfalfa water use data from the State CU files of SPDSS.

Calibration for alfalfa ETa in the SPDSS region was accomplished in four steps:

1. Derive NDVI* using Landsat TM5 and ETM7 satellite data and interpolate to daily time steps.
2. Estimate ET_0 using the published relationship used for calculation of the ASCE Penman Monteith representation (Allen, 2005).
3. Multiply the NDVI*, a surrogate for the intensity of crop water use, by ET_0, a surrogate for the climatic driving force for ET. This was accomplished in daily time steps. These daily data were summed to monthly time steps for comparison to the SPDSS monthly estimates of alfalfa crop water use.
4. The monthly comparisons were graphed as an XY scatter plot and a formula was developed to align the first order remotely sensed estimate of crop water use, represented by the product of ET_0 and NDVI* with the SPDSS derived water use estimates. The resulting formula was accepted as the calibration curve for alfalfa ETa for application within equation 1.

The graphs developed in the SPDSS-based alfalfa calibration are shown in Figure 2. The calibration curve is not specific to the SPDSS region and can be used anywhere in Colorado because it scales NDVI*, that varies only through crop health, against ET_0 that contains the regional signal for evaporative driving force. Only ET_0 is expected to vary widely in various locations and weather. The calibration curve is presented as Equation 3. The calculations for this operation are found in spreadsheet 1-SPDSS_Alfalfa_Calibration.xls.

ETa (alfalfa) = 2.02 * (ET_0 · NDVI*) – 1 **Equation 3**

Where ETa is alfalfa water use in millimeters per day.

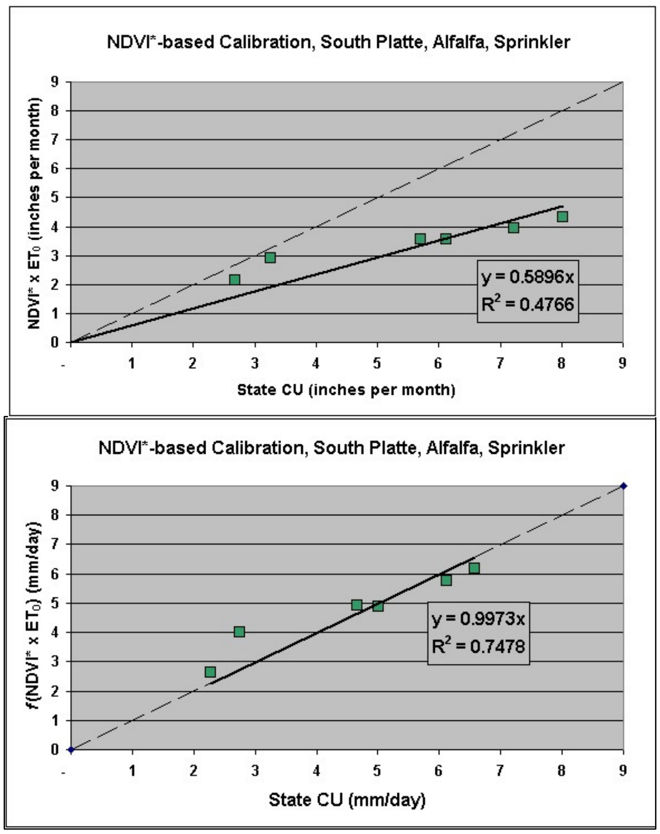

Figure 2. Calibration of alfalfa using State CU data from SPDSS, before (above) and after (below) calibration. The dashed line represents the desired 1:1 relationship that is met by the calibrated data on the right hand graph.

Equation 3 was applied for daily ETa estimation for alfalfa in SLV during 2009 and 2010 using weather measured at two Center, Colorado stations by CoAgMet for derivation of ET_0. ET_0 was estimated using the published relationship used for calculation of the ASCE Penman Monteith representation (Allen, 2005). The two ET_0 values were averaged for use in calculation of ETa. The calculations for SLV ETa by field are found in spreadsheet 2-SLV_Field_Extractions_NDVIstar.xls. ENVI 4.8 (Environment for Visualizing Images) software were used to extract the data for interpolation of NDVI* for daily time steps. NDVI* data were extracted from fields of SLV alfalfa that were selected for 2009 and 2010 by CDWR staff—these are shown in Figure 3, and provided in detail in spreadsheet 0-Data from CDWR.xlsx.

2. Determining Depth to Water at Each Field

Irrigation application was known from metering records provided by CDWR. Because water tables were not measured at the test fields, test well data from around the valley were kriged to determine rasters of depth to water (DTW). Field extractions of DTW from these rasters for four points during the growing season were averaged for each field for comparison to the calculated ETg derived by Equation 1.

Projecting the water level for each field of interest in this examination is likely the greatest source of potential error for developing the alfalfa extinction curve. This is because such curves are best modeled as power or natural log functions and any error in DTW near the surface has a profound affect on the ET component from groundwater (ETg) result obtained.

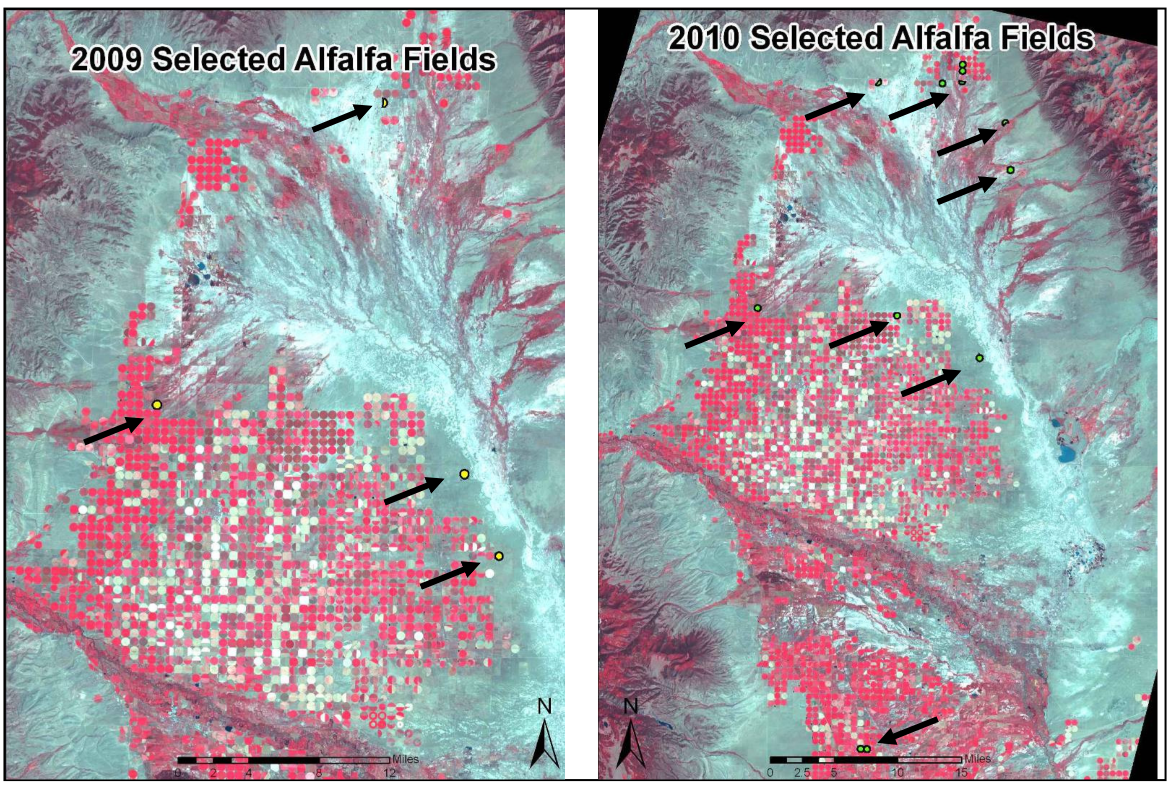

Figure 3. Fields of alfalfa that were evaluated for the ETa/DTW relationship. The 2009 data yielded data points and 2010 yielded twelve.

3. Comparing Subirrigation Calculated as a Residual to DTW

Comparison of calculated subirrigation to DTW was accomplished graphically. Three of the fields were removed from the comparison because of issues with the data that included (1) mid season crop emergence (this analysis is valid only for full growing seasons because the comparison is dealt with in annual time steps), (2) supplemental irrigation that was applied from a surface source (the total applied was therefore unknown), (3) water in excess of the crop requirements (over watering creates a negative subirrigation result because water that percolates past the root zone violates conditions for Equation 3). Other sources of error noted but not used to remove data were (4) questionable accuracy from DTW projected across multiple miles and with monitoring wells likely in unrepresentative locations for the field chosen (i.e., recharge mound versus region with pumping and no surface recharge), and (5) limitations for growing alfalfa not directly related to its water supply, for example high salinity that is the consequence of shallow groundwater supply and inadequate flushing by rain, irrigation or flood irrigation. These last two influences likely account for the noise inherent in the calculation of alfalfa ETg versus DTW.

Although the SLV represents one of the best instrumented groundwater basins in the world, the complexity in field-related cultural practices, soil constraints and the depthwise sensitivity of a logarithmic ETg curve necessarily cause such data to be noisy. Hence, an ETg/DTW curve must be formulated to be unbiased, and to constrain error due to the scatter inherent in these data.

The three fields that were removed from the analysis are highlighted in Figure 4 and are described further in spreadsheet 3-SLV_Alfalfa_ETg.xls. Two fields that were not removed from Figure 4 are two adjacent fields, 1602 and 1603. The water table position for these fields was projected from a region of apparent recharge mounding with about 12 feet of elevation difference. These points are annotated to show that the actual position of the points is probably at a far deeper DTW positions were the water table measured at these fields. The points encircled at the lower end of the distribution indicate the noisiness of these data. These points are clustered around zero but vary almost 10 inches plus and minus. The actual zero point for the ETg/DTW curve lies somewhere near this circle.

4. Curve fitting to Represent ETg/ DTW for Alfalfa

For mathematical certainty in portraying and ETg/DTW curve, many points should be located in the near-surface zone where the curve begins to curve asymptotically toward some peak value—this is within the region of the soil at depths less than about five feet, or so. The data from this investigation are not sufficient, alone, for creating such a curve and so, additional consideration was made using data taken from another study. ETg for scrub vegetation was calculated as a function of DTW in a declining water table system in Groeneveld (2008). Regardless of the species involved, NDVI* is known to have a strong linear relationship to water use (Groeneveld et al., 2007), and so the spatial average peak value for NDVI* measured for scrub in Groeneveld (2008) was used to calculate a ratio of the peak mid-summer scrub NDVI* against the mid summer peak NDVI* measured for the alfalfa fields during this investigation. This ratio was 3.92 (work shown in 3-SLV_Alfalfa_ETg.xls). This value was used as a multiplier to project an approximation for an ETg/DTW curve for alfalfa (Figure 5). Figure 6 presents the derived data with the alfalfa curve calibrated using the scrub data shown.

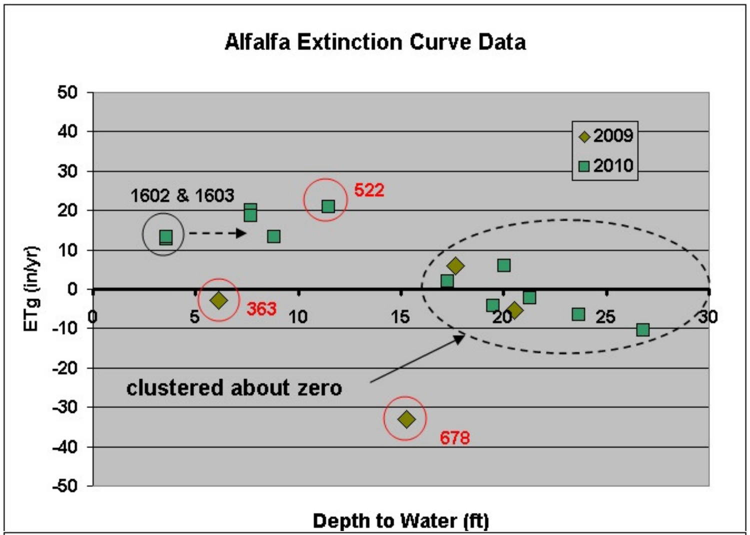

Figure 4. ETg generated for 2009 and 2010. Points indicated with red field numbers were removed:
363 – had a mid-season start;
522 –received supplemental irrigation from surface water; and
678 – was watered well in excess of CIR (4.5ft).
The dotted circle contains values clustered around zero that indicated scatter.

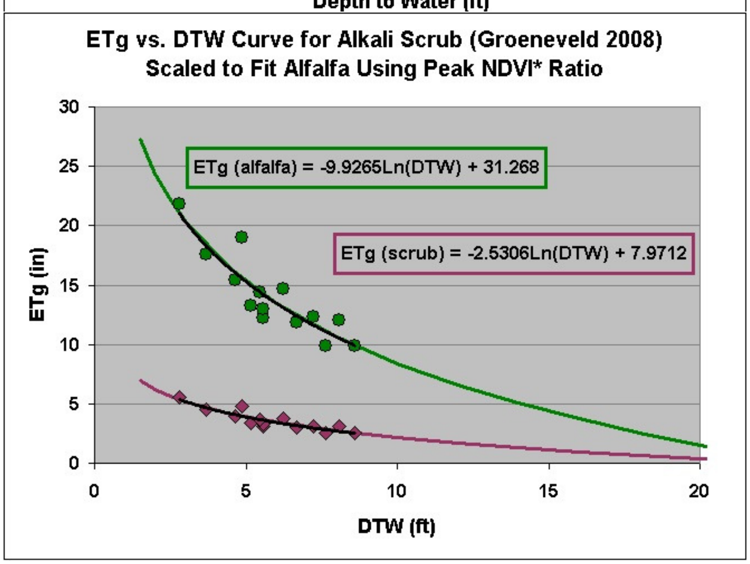

Figure 5. ETg/DTW curve extrapolation from a curve generated using remote sensing for phreatophytic San Luis Valley scrub (Groeneveld, 2008).

The curve generated by extrapolation in Figure 5 does not have an additional component for soil surface evaporation as was also presented in Groeneveld (2008). The reason surface water evaporation was not included was that the physics of the alfalfa crop will likely (1) shade the ground, therefore reducing the driving force for soil surface evaporation, and (2) since it grows thickly and uses about four times the water used by scrub vegetation, any capillary rise from the water table will likely be intercepted by the alfalfa roots before it has a chance to reach the surface and be evaporated. Thus, soil surface evaporation is a comparatively minor component of an established alfalfa stand.

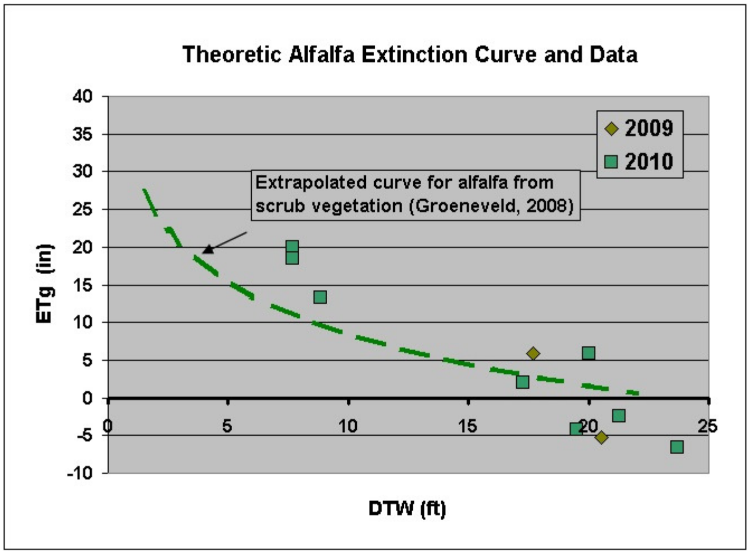

Figure 6. The extrapolated curve presented along with the ETg/DTW derived in this investigation.

Figure 7 provides the final curve for alfalfa subirrigation derived in this investigation with the extrapolated alfalfa ETg/DTW curve. The extrapolated curve agrees reasonably with the data points. Rather than modeling the curve as a log function, however, uncertainty in DTW and a logarithmic relationship for ETa would likely cause a systematic tendency to over predict ETg regionally. Hence the curve to represent alfalfa ETg/DTW was linearized for application in groundwater modeling. Figure 7 represents the alfalfa ETg/DTW curve that was linearized. The curve statically predicts ETg as 2 feet from 3 feet or less DTW (i.e. no ETa enhancement from near surface water tables) because very shallow water tables are detrimental to alfalfa growth.

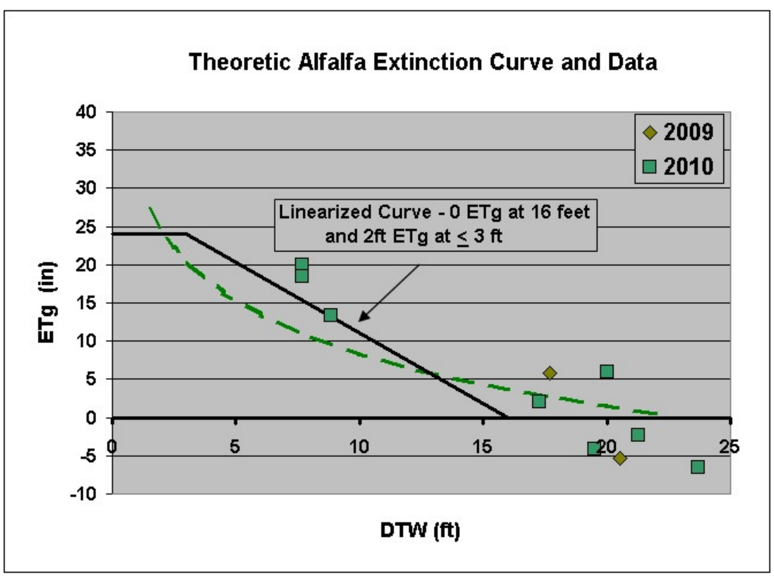

Figure 7. Linearized curve representing alfalfa ETg/DTW. Sixteen feet was chosen as a conservative zero point since cultivated alfalfa over water tables of 16 feet or greater will likely be supplied the majority of their water by irrigation.

5. Using the ETg/DTW Curve

For use in groundwater modeling in San Luis Valley the Figure 5 relationship expressed in feet is:

Water Table Depth 0 to 3 feet:	ETg = 2 ft/yr
Water Table Depth >3feet < 16 feet:	ETg = 2.4615 - 0.1538DTW(ft)

6. Literature Cited

Allen, R.G. 2005. The ASCE standardized reference evapotranspiration equation. American Society of Civil Engineers. ISBN 0-7844-0805-X.

Groeneveld, D.P. 2008. Remotely-sensed groundwater evapotranspiration from alkali scrub affected by declining water table. *Journal of Hydrology* 358: 294-303.

Groeneveld, D.P. and Baugh, W.M. 2007. Correcting satellite data to detect vegetation signal for eco-hydrologic analyses. *Journal of Hydrology* 344:135-145.

Groeneveld, D.P., Baugh, W.M., Sanderson, J.S., and Cooper, D.J. 2007. Annual groundwater evapotranspiration mapped from single satellite scenes. *Journal of Hydrology* 344:146-156.

HydroBio, 2007. Estimating South Platte Phreatophyte Groundwater Evapotranspiration. Report prepared for the State of Colorado South Platte Decision Support System available at ftp://dwrftp.state.co.us/cdss/gwm/tm/SPDSSTask65_20080314.pdf (accessed July, 2011)

Appendix C

Subirrigated Meadows Documentation

Reference: Sanderson, John, S., and David J. Cooper, 2008, *Ground Water Discharge by Evapotranspiration in Wetlands of an Arid Intermountain Basin*, Journal of Hydrology, pages 344-359.

Journal of Hydrology (2008) **351**, 344–359

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Ground water discharge by evapotranspiration in wetlands of an arid intermountain basin

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KEYWORDS
Evapotranspiration;
Ground water;
Wetland;
Wet meadow;
Playa

Summary To improve basin-scale modeling of ground water discharge by evapotranspiration (ET) in relation to water table depth, daily ET was measured using the Bowen ratio energy balance method during 1999–2005 in five herbaceous plant dominated wetlands in an arid intermountain basin in Colorado, USA. Three wetlands were wet meadows supplied primarily by regional ground water flow and two were playas supplied primarily by local stream flow. In wet meadows, mean daily water table depth (WTD) ranged from 0.00 m (ground surface) to 1.2 m, with low inter-annual variability. In wet meadows, annual actual ET (ET_a) was 751–994 mm, and ground water discharge from the shallow aquifer (ET_g) was 75–88% of ET_a. In playas, mean daily WTD ranged from −0.65 to 1.89 m, with high inter-annual variability. In playas, annual ET_a was 352–892 mm, and ET_g was 0–77% of ET_a. The relationship of annual ET_g to WTD was compared to existing ET_g–WTD models. For wet meadows, ET_g decreased exponentially as WTD increased from 0.13 to 0.95 m ($r^2 = 0.83$, CV = 5%, $p < 0.001$). In comparison with our findings, existing models under- and over-estimate ET_g by −30% to 47% at WTD of 0.13 m, and they under-estimate ET_g by −12% to −42% at WTD of 0.95 m. This study found that as the water table declined from near the soil surface to 0.95 m, ET_g decreased only ~26% versus 39–55% estimated by existing models. The magnitude of ET_g decrease was 220 mm, whereas existing models predicted decreases up to 700 mm (218% greater). In playas, there was no clear ET_g–WTD relationship. Instead, ET_g was strongly dependent on the surface water supply. When sufficient surface water inputs occurred to meet ET demand, ET_g was ≈0 mm/yr and independent of WTD. When inputs did not meet ET demand, ET_g was positive though highly variable at WTD up to 1.68 m.

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Introduction

In arid region intermountain basins, evapotranspiration (ET) is often the primary mechanism of water loss from shallow aquifers (Emery, 1970; Nichols, 1994, 2000; Laczniak et al., 1999, 2001; Reiner et al., 2002; DeMeo et al., 2003; Cooper et al., 2006; Groeneveld et al., 2007; Moreo et al., 2007). In hydrologically closed basins (Snyder, 1962) virtually all water loss is through ET (Huntley, 1979), and a large proportion of this may be ground water from the shallow aquifer. In parts of the Great Basin of the western US, for example, 73–100% of actual evapotranspiration (ET_a) is ground water (Laczniak et al., 1999).

The ground water fraction of ET_a, termed ET_g, is a critical component of hydrologic models used to estimate water fluxes and storage in shallow aquifers. Since ground water models such as MODFLOW (Harbaugh et al., 2000; McDonald and Harbaugh, 2003) estimate WTD, relationships between ET_g and WTD are valuable for estimating ET_g across large landscapes. Several models have been proposed relating ET_g to WTD (Emery, 1970, 1991; Nichols, 2000). However, these models are based on relatively few studies and vegetation types (Emery et al., 1973).

ET data are particularly lacking for wetlands in arid regions (Laczniak et al., 1999, 2001; DeMeo et al., 2003). Despite extremely low mean annual precipitation on the floor of intermountain basins, abundant surface and ground water may flow into basins from adjacent high mountains (Walton-Day, 1996; Cooper et al., 2006) and support large wetland complexes with high ET rates (Drexler et al., 2004; Sanderson, 2006; Sanderson et al., in press). Potential ET (ET_p) can exceed mean annual precipitation by up to 10–30 times (Mifflin, 1988) and wetland ET rates can be >10 times greater than that of surrounding uplands (Laczniak et al., 2001) making wetland ET an important component of arid region water budgets. Wetland ET rates are influenced by the short- and long-term presence of surface water, variations in WTD controlled by climate variation, and human alterations of stream flow and ground water pumping (Cooper et al., 2006).

Wet meadows (Gosselink and Turner, 1978; Cooper, 1986; Carsey et al., 2003; Moreo et al., 2007) and playas (Malek et al., 1990; Laczniak et al., 2001; DeMeo et al., 2003; Sanderson, 2006; Sanderson et al., in press) are two major types of wetlands common in arid regions such as the western US. Wet meadows are ground water supported and typically have shallow WTDs throughout the year (Cooper, 1986; Carsey et al., 2003). Ground water storage varies gradually and subsequently inter-annual changes in WTD are typically small. Wet meadows are often seasonally shallowly flooded (Carsey et al., 2003), but surface ponding is only infrequently deep or prolonged. Playas occur in depressions with fine-grained soils and are filled by streams and surface runoff from snow melt or rain events (DeMeo et al., 2003; Kappen, 2004; Sanderson, 2006). In playas, surface runoff and variation in WTDs can be highly variable between years (Sanderson et al., in press). In some years water may pond deeply (up to 0.65 m in this study) for weeks or months, yet in other years there may be no ponding (Laczniak et al., 2001; Sanderson et al., in press).

Accurate estimates of ET rates are required for modeling the water budget of individual wetlands and entire intermountain basins (Poiani and Johnson, 1993; Devitt et al., 2002; CDSS, 2005), and methods and models have been developed for estimating ET_a in wetlands, many based on estimates of potential evapotranspiration (ET_p) (Winter et al., 1995; Rosenberry et al., 2004; Drexler et al., 2004). Models of ET_p have been derived using theoretical principles (Penman, 1948, 1963; Monteith, 1965), empirical relationships (Blaney and Criddle, 1950; Thornthwaite, 1948), and a combination of theory and empiricism (Priestley and Taylor, 1972). Independent measurements of ET_a for calibrating ET_p are performed using a variety of field methods (Drexler et al., 2004), including the Bowen ratio energy balance method (BREB), which is among the most commonly used and robust (Winter et al., 1995; Rosenberry et al., 2004).

Several models of ET_p have been successfully applied to wetlands (Drexler et al., 2004; Rosenberry et al., 2004) after calibration with independent measures of ET_a (Souch et al., 1996; Jacobs et al., 2002). Calibration is required for a variety of reasons. First, ET_a is strongly influenced by vegetation characteristics such as leaf area, plant height and roughness, and total plant cover and albedo (Peacock and Hess, 2004), all of which vary during the year. Second, ET_a is influenced by the presence of surface water, WTD, and soil water content, all of which vary by wetland type and may change during the year (Jacobs et al., 2002).

The objectives of this paper are to present data on ET_a and ET_g for wet meadows and playas in a large intermountain basin region of the western US, and to analyze ET_g as a function of water source and WTD. We specifically address the following questions: (1) What rates of ET_a and ET_g occur in intermountain basin wetlands? (2) How does ET_g vary with WTD? (3) Do ET_g–WTD relationships differ between wet meadows and playas? To address these questions, we measured daily ET_a and related environmental attributes over a period of 7 yr in five wetlands in Colorado's San Luis Valley (SLV).

Study area

Regional setting

The SLV is a high elevation intermountain basin covering ~8400 km^2 in southern Colorado, USA (Fig. 1; Huntley, 1979). The valley floor averages ~2350 m elevation and has little topographic relief. Peaks rise above 4000 m in both the Sangre de Cristo Mountains to the east and the San Juan Mountains to the west. In the SLV, summers are warm (July mean = 17 °C), winters are cold (January mean = −9 °C), and insolation is high all year (Doesken and McKee, 1989; Western Regional Climate Center, 2005).

Orographic effects result in high mountain precipitation and low valley floor precipitation. Mean annual precipitation at Wolf Creek Pass (elevation 3290 m, Fig. 1) is 1153 mm, while at Center on the SLV floor (elevation 2350 m, Fig. 1) it is 177 mm (Western Regional Climate Center, 2005). The SLV is the most arid region in Colorado, and it also supports Colorado's highest concentration of wetlands (Walton-Day, 1996). This results from the abundant mountain snowfall contributing abundant surface and ground water inflows to the relatively flat valley floor.

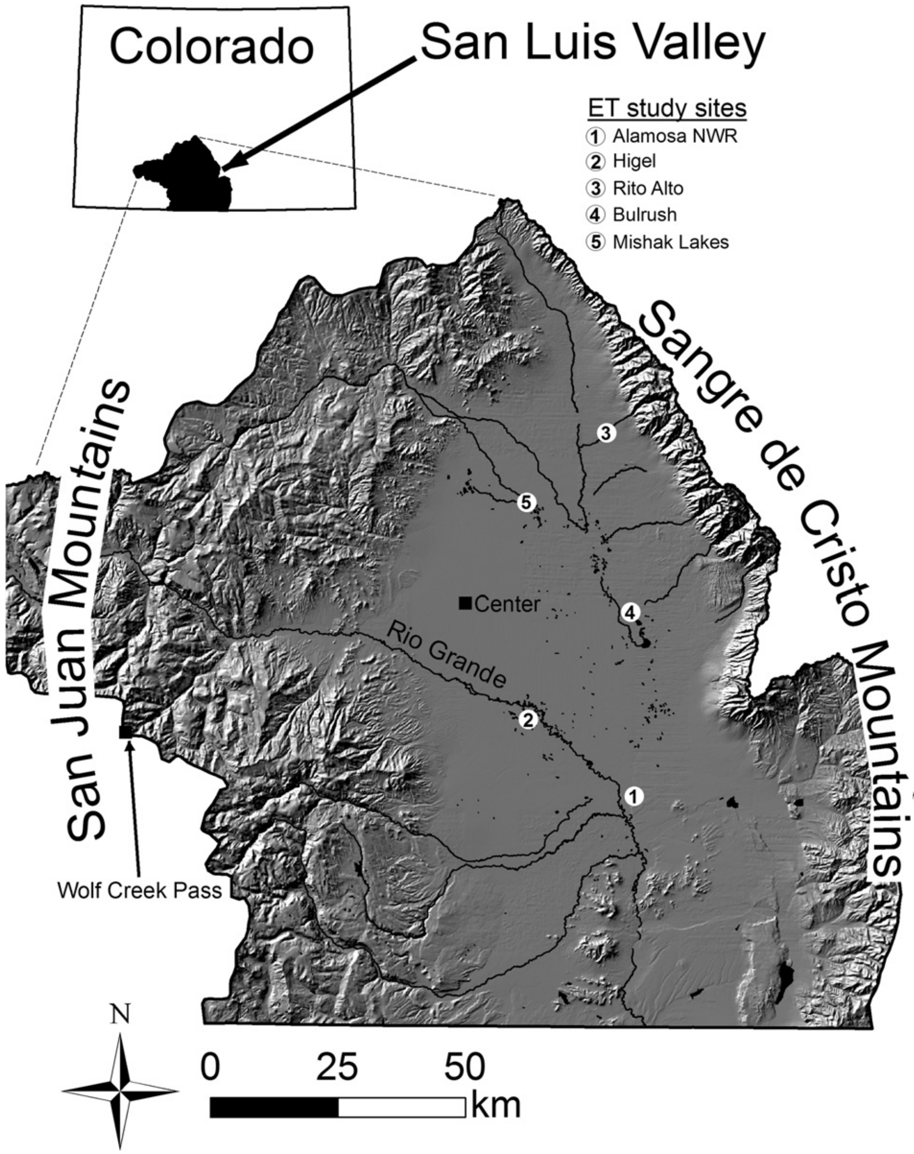

Figure 1 Study area and site locations.

The study years, 1999–2005, spanned a range of climatic conditions. In the late 1990s, the second-longest sustained wet period on record and the most drought-free period since 1890 were ending (McKee et al., 2000). Several months of moderate drought occurred in 2000, followed by a wet period from late 2000 through July of 2001. A severe drought lasted from the second half of 2001 through 2004. High snowmelt runoff and moderate rainfall followed the winter of 2004–2005, but water levels did not return to 2000 levels.

Our five study sites represented two wetland types. Three study sites (Alamosa National Wildlife Refuge, Higel, and Rito Alto; Fig. 2a–c) were wet meadows (Gosselink and Turner, 1978; Cooper, 1986; Carsey et al., 2003) that had no surface water inflow or outflows, were supported by subsurface flows, and had a water table within 1 m of the ground surface. When WTD was near zero, water was present in small (<0.2 m) pockets across the hummocky sites (Alamosa NWR and Higel), but standing water was at no time observed covering more than ~5% of the ground surface. In wet meadows, observed seasonal changes in WTD ranged from 0.40 m (at Higel) to 0.96 m (at Alamosa NWR) (Table 1), and the rate of WTD change was up to 1.6 cm/d (at Alamosa NWR). Patterns of WTD change in wet meadows were similar across years (Fig. 3).

Two study wetlands (Bulrush and Mishak Lakes; Fig. 2d and e) were playas (Laczniak et al., 2001; DeMeo et al., 2003; Kappen, 2004; Sanderson, 2006; Sanderson et al., in press), shallow basins (<1.25 m deep) with distinct stream inlets that had intermittent surface water inflow and outflow. Surface water covered the entire ground surface of both playa wetlands for at least some time during the years of this study to a depth of 0.24 m at Bulrush and 0.65 m at Mishak Lakes (Table 1). Bulrush also experienced 2 yr with no surface water inflow. In the absence of surface water, WTD was >1.0 m. The rate of WTD change in playas was up to 2.6 cm/d (at Bulrush). Patterns of WTD change were highly variable across years (Fig. 3).

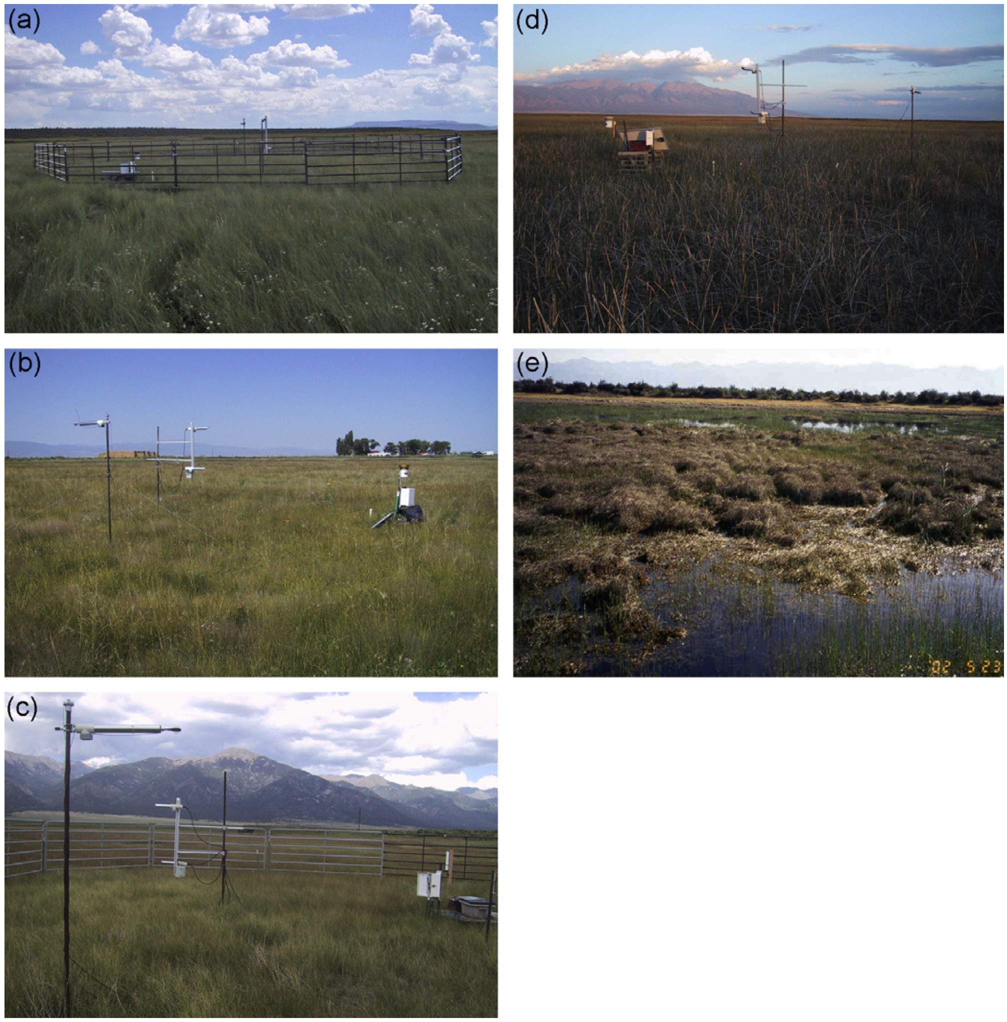

Figure 2 Photos of wetland study sites. Wet meadows are (a) Alamosa NWR, (b) Higel, and (c) Rito Alto. Playas are (d) Bulrush and (e) Mishak Lakes. The sets of equipment shown are the Bowen Ratio Energy Balance stations. The highest pieces of equipment are ~2.5 m above the ground surface.

Table 1 Site characteristics

Wetland	Dominant vegetation	Vegetation height (m)	Daily water table elevation (m)[a]	Site elevation (m above MSL)	Location[b]
Alamosa NWR	*Carex simulata* Mackenzie and *C. aquatilis* Wahlenb.	0.50	0.0 to −0.90	2291	43°37′17″E, 414°04′12″N
Higel	*Carex simulata* Mackenzie and *Juncus balticus* Willd. var. *montanus* Engelm.	0.60	0.0 to −0.40	2310	41°31′22″E, 415°48′50″N
Rito Alto	*Carex simulata* Mackenzie and *Juncus balticus* Willd. var. *montanus* Engelm.	0.50	−0.24 to −1.20	2324	42°85′58″E, 421°02′84″N
Bulrush	*Schoenoplectus tabernaemontani* (K.C. Gmel.) Palla	1.0–2.0[c]	+0.24 to −1.89	2296	43°32′48″E, 417°59′29″N
Mishak Lakes	*Eleocharis palustris* (L.) Roemer & J.A. Schultes	0.50	+0.65 to −1.26	2302	41°32′43″E, 419°70′31″N

[a] Relative to ground surface; positive is above the ground surface, negative is below.
[b] NAD1983 UTM Zone 13N.
[c] Bulrush height varies depending on amount of water supplied to the wetland in any given year.

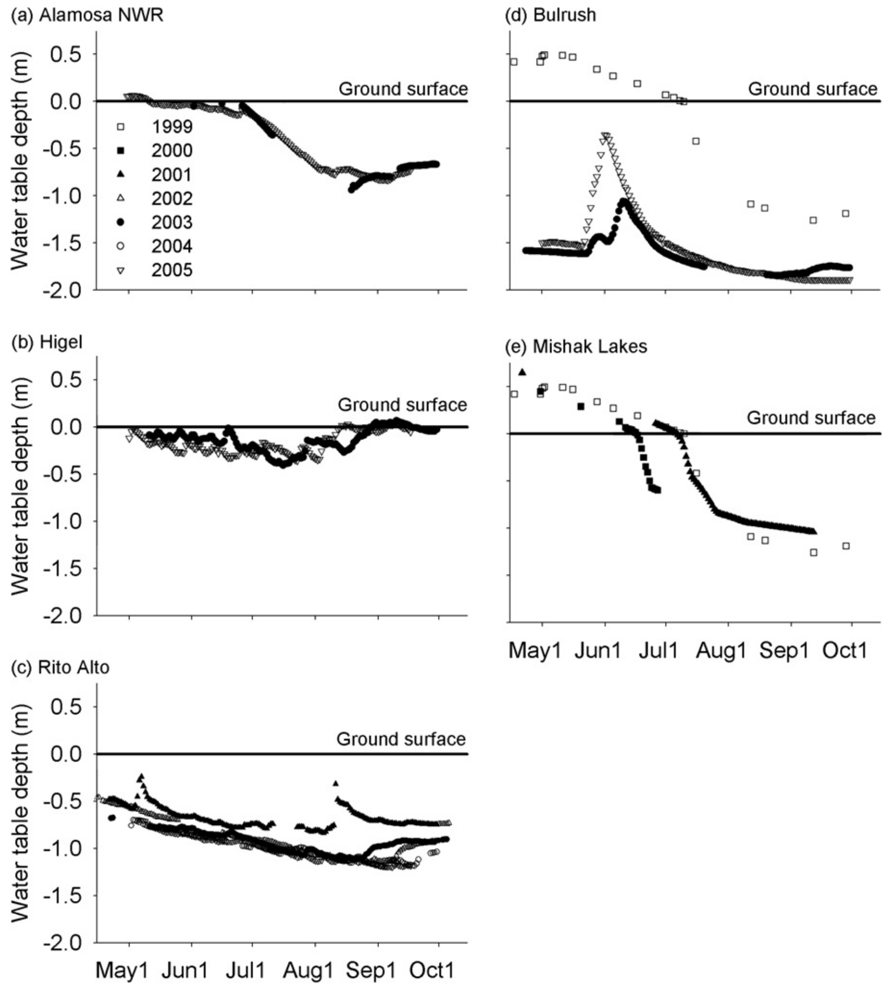

Figure 3 Water table position for wet meadows (a—c) and playas (d and e).

Uplands surrounding all of the sites are dominated by the desert halophytic shrubs greasewood (*Sarcobatus vermiculatus* (Hooker) Torrey) and rabbitbrush (*Ericameria nauseosa* (Pallas ex Pursh) Nesom & Baird), with a grass understory dominated by saltgrass (*Distichlis spicata* (L.) Greene) and alkali sacaton (*Sporobolus airoides* (Torr.) Torr.). Species nomenclature follows the USDA (2005).

Wet meadows

Alamosa National Wildlife Refuge

The Alamosa NWR site (Fig. 2a) is located on the margin of the broad Rio Grande floodplain. The site is a relatively homogeneous 13 ha area densely vegetated by grasses and sedges (Table 1). The wetland is supported by regional ground water flow through sandy alluvium (the Alamosa formation; Siebenthal 1910). During this study, the water table was within 0.3 m of the soil surface for ~85 d at the beginning of each growing season, and after ~July 1 the water table declined to ~0.8 m depth through the fall (Fig. 3a). In early summer, small (<0.2 m across) pools created by ground water discharge were present between hummocks that were up to 0.2 m high. The upper 1.4 m of soil is partially decomposed organic matter (peat).

Higel

The Higel site (Fig. 2b) is located on the edge of the broad Rio Grande floodplain. The site is a relatively homogenous 14 ha area dominated by grasses, sedges, and *Juncus balticus* (a rush) (Table 1). This wet meadow is maintained by ground water flows from the Rio Grande as well as irrigation ditches on the upper floodplain margin. During this study, the WTD was <0.3 m for 2—3 months at the beginning of the growing season, and another 2 months at the end of the growing season. The greatest WTD observed was 0.41 m (Fig. 3b). Hollows between 0.30 m tall hummocks fill with discharging ground water when WTD is near 0, but standing water did not cover more than a small fraction of the site. Soil water content in the silt loam soils remained close to saturation all summer.

Rito Alto

The Rito Alto site (Fig. 2c) is located near the small perennial stream Rito Alto, ~5 km west of the Sangre de Cristo Mountains. The site is a relatively homogenous 3.7 ha wet meadow dominated by sedges and *J. balticus* (Table 1). The water table is supported by ground water flow through the mountain front alluvial fan of Rito Alto, and the water table responds to both high discharges in Rito Alto and local rain events. During most study years, the water table high occurred in March or April, and declined through the summer (Fig. 3c). During July and August the water table elevation increased following summer thunderstorms. WTD was <0.3 m for only 2 d among all years of the study (minimum WTD = 0.24 m). Soils are silt loams, with high organic matter content in the upper 5 cm.

Playas

Bulrush

The Bulrush site (Fig. 2d) is a playa located at the terminus of a distributary of Sand Creek, ~5 km west of the Sangre de Cristo Mountains. The site is a nearly circular, shallow (<1 m deep) basin ~100 ha in size with a relatively homogenous cover of bulrush (*Schoenoplectus tabernaemontani*) (Table 1). During this study, inter- and intra-annual variability of inflowing surface water was very high, creating high variability in WTD (Fig. 3d). In 1999 WTD was <0.30 m for 23 d, with water up to 0.24 m deep ponded on the surface for 18 d. During 2003 and 2005, minimum WTD was >0.3 m. Soils are sandy clay loams.

Mishak Lakes

Mishak Lakes (Fig. 2e) is a complex of shallow (1.25 m depth) interconnected basins supporting a near-monoculture of ~0.5 m tall spikerush (*Eleocharis palustris* (L.) Roemer & J.A. Schultes) in the basin bottoms (Table 1). No basin is larger than ~2.0 ha, but the contiguous area represented by the study site covers ~200 ha. During the years ET was measured at Mishak Lakes, the wetland complex received ~80% of its water as flow in Russell Creek (Sanderson 2006; Sanderson et al. in press). When sufficient surface water entered the Mishak complex, surface water outflow also occurred. Little net infiltration of surface water occurred (Kappen, 2004). Water ponded for 62–86 d in early summer to a depth of 0.4–0.6 m (Fig. 3e). Once surface water disappeared, WTD increased rapidly to >1.0 m. Soils are sandy loams underlain by a 0.12 m thick low-permeability (vertical hydraulic conductivity = 3.6×10^{-10} m/s) clay layer ~0.5 m below ground surface (Kappen, 2004).

Methods

Field measurements

Daily ET_a was measured using the Bowen Ratio Energy Balance (BREB) method (Tanner, 1960; Fritschen and Simpson, 1989; Moncrieff et al., 2000; Drexler et al., 2004). Data were collected using a micrometeorological system from Radiation Energy Balance Systems Inc. (REBS Inc., Bellevue, WA). Platinum resistance elements were used to measure temperature in the atmosphere and in the cavity where humidity was measured. Humidity was measured with a hydroscopic polymer capacitance chip. Humidity and temperature sensor pairs were vertically separated by 1 m. To remove bias between sensors, their positions were exchanged every 15 min using an automated system. Net radiation (R_n) was measured with a REBS, Inc. Q*7.1 net radiometer deployed and leveled ~2.5 m above the ground surface and oriented due south. For settings without surface water, soil heat flux (G) was measured using two heat flow transducers buried 5 cm below the ground surface and two 10 cm-long soil temperature probes buried at an angle to measure heat storage in the top 5 cm of soil. For settings with surface water, temperature sensors were suspended in the water column, and soil heat flux plates were positioned at the soil surface. Measurements were made every 15 s, and averaged and stored on a data logger every 15 min. ET_a was calculated at 30-min intervals and summed over each 24-h period.

Requirements for fetch (the upwind distance to which the uniform vegetation extends) at three sites (Alamosa NWR, Higel, and Bulrush) exceeded the generally accepted minimum fetch to upper sensor ratio of 100:1 (Stannard, 1993; Moncrieff et al., 2000). At Rito Alto and Mishak Lakes, minimum fetch-to-height ratio was met in and near the direction of the prevailing wind, but was less in other directions. The 80% cumulative source area for turbulent flux was ~1.5 ha at all sites except Bulrush, where the source area was ~3.8 ha (Stannard, 1997).

The BREB method failed under specific combinations of available energy, temperature gradient, and vapor pressure gradient (Ohmura, 1982; Perez et al., 1999), and during advective inversions (Verma et al., 1978). These failures typically occurred around sunrise or sunset, when ET_a is low, and they generally lasted for only one or two 30 min intervals, so it is expected that they did not introduce significant error in daily ET_a totals. Failures were identified in the data set, and 30 min ET values were interpolated from temporally proximate values.

WTD was measured using a GE Druck 1–5 psi water level sensor at one location at each site. Precipitation was measured using an unshielded Texas Instruments 20.3 cm tipping-bucket rain gage with a sensitivity of 0.254 mm. Beginning in 2001, soil water content was measured by time domain reflectometery using Campbell Scientific CS615 probes at 0–30 cm. Probes were calibrated in the lab for each specific soil using known soil water contents.

Estimating ET_a and ET_g

For basin-scale studies of ground water discharge, ET_a and ET_g are commonly expressed as annual totals (Emery, 1970, 1991; Huntley, 1979; Hearne and Dewey, 1988; Duell, 1990; Nichols, 1994, 2000; Laczniak et al., 1999, 2001; Reiner et al., 2002; DeMeo et al., 2003; Cooper et al., 2006; Groeneveld et al., 2007; Moreo et al., 2007). We measured ET at five sites during multiple years at each site; we thus estimated annual ET_a and ET_g for a total of 14 site-year combinations.

Total annual ET_a was estimated by summing daily values of ET_a. Measured values were used where available. Growing-season days without a measured value were modeled. Winter ET_a was estimated by calculating monthly means using at least seven daily measurements for each month from the Rito Alto site, and these means were applied to all sites. The approach to winter ET is realistic because winter ET_a rates are similar across sites during that season, when solar radiation is low, plants are leafless, frozen soils inhibit capillary movement of ground water to the surface, and frontal rather than convective weather patterns prevail.

Table 2 Number of days (percent of growing season) from April 15 to October 15 with measured daily ET for each site from 1999 to 2005

Site	1999	2000	2001	2002	2003	2004	2005
Alamosa	0	0	0	0	60 (33%)	0	140 (76%)
Higel	0	0	0	0	144 (78%)	0	140 (76%)
Rito Alto	0	0	151 (82%)	118 (64%)	162 (88%)	144 (78%)	132 (72%)
Bulrush	0	0	0	0	123 (67%)	0	101 (55%)
Mishak	13 (7%)	19 (10%)	55 (29%)	0	0	0	0

Equipment failures caused the loss of measured ET_a values for some growing-season days. Measured daily ET_a was available for 55–88% of the growing season for 10 of 14 study-year combinations, and for 7–33% of the growing season for the remaining four study-year combinations (Table 2). For days lacking ET_a measurements, daily ET_a was modeled by calibrating the Priestly–Taylor ET_p (P–T ET_p) model and using regional weather data as input.

Calibrating the Priestley–Taylor ET_p model

The P–T ET_p model was chosen because it produces a reasonable approximation of ET_a under a variety of well-watered conditions (e.g., Priestley and Taylor, 1972; Jacobs et al., 2002; Rosenberry et al., 2004). P–T ET_p is:

$$ET_p = \alpha[s/(s+\gamma)][(R_n - G)/\lambda] \tag{1}$$

where α is the Priestly–Taylor coefficient (no units), s the slope of the saturated vapor pressure–temperature curve (mb/°C), γ the psychrometric constant (mb/°C), R_n the net radiation (MJ/m^2/d), G the change in heat stored in surface soil or water (MJ/m^2/d), and λ is the latent heat of vaporization (MJ/kg).

Several authors have argued that α has theoretical significance for well-watered surfaces, where it has a value of 1.26 (Priestley and Taylor, 1972; McNaughton, 1976; de Bruin, 1983). For situations where water may be limiting, α has been related to measures of water availability. A relationship to soil moisture has been demonstrated in some settings (Davies and Allen, 1973; Flint and Childs, 1991); however, Stannard (1993) found that α did not relate to soil moisture but instead was related in a non-linear fashion to leaf area and recent rain. Without assuming any particular relationship, we used multiple linear regression analysis to determine the dependence of α on water limiting variables. Using the form of Eq. (1), the regression was modeled as

$$ET_a = f(\text{water limiting variables}) \cdot 1.26 \cdot [s/(s+\gamma)] \cdot [(R_n - G)/\lambda] \tag{2}$$

where f(water limiting variables) was a function of season, WTD, soil water content, recent precipitation, and the year of measurements.

Season represented seasonal changes in leaf area, plant cover, surface roughness, and other plant canopy-related factors that affect ET (Peacock and Hess, 2004). It was expressed as a log-normal function with the form:

$$\text{season} = [1/(x \cdot s \cdot \sqrt{2\pi})]\exp(-0.5[(ln(x) - m)/x]^2) \tag{3}$$

where x is day-of-year, and m and s are constants (5.44 and 0.533, respectively) determined through iteration so that season ranges from 0 (no green leaves) on April 15 and October 15 to 1 (full canopy) on June 22 (summer solstice). Soil water content was volumetric water content (VWC) in the upper 30 cm (cm^3/cm^3). Cumulative precipitation was the sum of weighted daily precipitation for the previous 7 d (7d_ppt) calculated as

$$\text{7d\_ppt} = \sum_{i=1}^{7}(D - i)\exp[(1 - i)/2] \tag{4}$$

where D is the day for which ET is being modeled, so that, for example, $(D - 1)$ is the amount of precipitation on the previous day and $(D - 7)$ is the amount 1 week ago. Using this formula, yesterday's precipitation was weighted more heavily than the day before yesterday, and so on until 7 d previous, beyond which the effect of precipitation was assumed negligible. This assumption is supported by our data collected during a rainy period in the San Luis Valley that shows ET matches or exceeds precipitation over 7-d intervals (Cooper et al., 2006); thus, most precipitation is returned to the atmosphere within days of its falling. In another intermountain basin, Malek et al. (1990) found that the affect of rain on ET_a lasted about 7 d. Any precipitation remaining in the soil after 7 d is likely a small fraction of total soil water content, so it is expected to have a minimal effect on our modeling approach. Cumulative precipitation was square-root transformed before use in model development.

For the analysis, Eq. (2) was re-written as

$$ET_a/ET_p = f(\text{season} + \text{WTD} + \text{VWC} + \text{7d\_ppt} + \text{year}) \tag{5}$$

Using this model, a calibration function was developed for each site using linear regression. Some relationships between ET_a/ET_p and water-limiting variables may be non-linear (Flint and Childs, 1991; Stannard, 1993). As such, linear regression may not be capable of accurately capturing all aspects of these relationships across the range of their possible manifestations on the landscape. However, since the linear model yielded a good fit to the data and the model was only applied within the range of data used to create it, we assumed the error introduced by using a linear model was minimal.

Data collected on site were used to develop the model. Values of ET_a were those measured during the growing season (April 15–October 15). Values of ET_p were calculated using on-site daily means of temperature, net radiation (R_n) and energy storage (G). Available daily values were randomly split into two equal-sized data sets, and one data set was used for model development. The best regression model was selected using a stepwise procedure with α_{entry}

and $\alpha_{exit} = 0.05$ (SAS Institute, 2003). WTD and VWC content in particular were, in some instances, highly correlated. Because WTD was of primary interest, preference was given to WTD during model development when WTD and VWC were equally good predictors.

Model fit was evaluated using a cross-validation approach. Data withheld during the model development step were used to calculate goodness-of-fit statistics. Statistics included a coefficient of determination (r^2) of modeled and measured values of ET_a, a coefficient of variation (CV) calculated as the standard error of the model divided by the mean of the measured values of ET_a (Stannard, 1993), and a mean-bias error defined as the mean difference between modeled and measured values (Kaygusuz, 1999). Also, slopes of best-fit lines through modeled versus measured ET_a were calculated to assess deviation from one; deviation from a slope of one indicates that the error in the modeled value varies as a function of the size of the value, possibly causing systematic under- or over-estimation of daily ET_a.

Modeling available energy (R_n—G)

For days lacking on-site measurements, available energy (R_n—G) for use in the Priestley—Taylor ET_p equation was modeled as a function of variables measured at a regional weather station. Total solar radiation (Q_s) can be used to model R_n—G with reasonable results (Stewart and Rouse, 1976). However, changes in plant cover alter the relationship between Q_s and R_n—G by changing albedo and surface temperatures, so the season function (Eq. (3)) was also used in developing the model for R_n—G. Yesterday's precipitation was also considered for models of R_n—G, because our data suggest that where vegetation is sparse (such as the Bulrush site) rain wets the soil, temporarily making it darker and lowering its albedo relative to dry soil.

Development and validation of the R_n—G model was done using the same cross-validation approach described for the ET_a model. On-site data were used for the dependent variable and weather station data for the independent variables. Weather station data were obtained principally from the CoAgMet Ctr01 station at Center, Colorado (Colorado Climate Center, 2005). Precipitation data from the Alamosa NOAA weather station (NOAA, 2005) and the Blanca, Colorado CoAgMet station were used when they were the nearest stations with available data.

Estimating ET_g

Annual ET_g was estimated in two ways, depending on the presence or absence of surface inflows: (i) when no surface inflow occurred, ET_g was estimated by subtracting precipitation from ET_a (Nichols, 1994, 2000; Laczniak et al., 1999, 2001; Reiner et al., 2002; Cooper et al., 2006; Groeneveld et al., 2007; Moreo et al., 2007), and (ii) when there was surface inflow, ET_g was estimated by subtracting both precipitation and net surface water fluxes to the site (DeMeo et al., 2003). Situation (i) assumed negligible runoff, a reasonable assumption when the water table was not at the surface, given the limited vertical relief but high surface roughness of the sites, and the infrequent and small magnitude of most precipitation events. When the water table was at the surface and soils were fully saturated, rain events may have resulted in runoff, reducing the precipitation fraction of ET_a. Runoff was not quantified, so ET_g at sites where these conditions occurred (Alamosa NWR and Higel) may be underestimated by as much as ~9%. Situation (ii) required detailed quantification of surface water fluxes so the surface water fraction of ET_a could be estimated. At Mishak Lakes, the only site where this situation occurred, precipitation, surface inflows and outflows, and seepage were quantified in detail (Kappen, 2004; Sanderson, 2006; Sanderson et al., in press).

Calculating water table depth (WTD)

ET data were summed on an annual basis to eliminate the effects of weather and season, which can confound the ET_g—WTD relationship. For example, on July 25 and 26, 2005 at the Higel site, measured ET_a was 2.9 and 6.8 mm, respectively, when insolation was 15.4 and 28.4 MJ/m^2, respectively, yet the WTD depth difference between these two adjacent days was only 0.02 m.

There are many ways to calculate annual WTD for a site, each of which may be suitable for certain watersheds. For sites where the water table varies little between seasons, a simple annual average may be useful. However, where there is considerable seasonal variability in WTDs and ET rates, a weighted average may be most useful. We weighted each month's WTD based on the proportion of annual ET that occurred in that month, calculating weighted annual WTD as

$$\text{weighted WTD}_x = \sum_{i=1}^{12} \text{WTD}_i \cdot \text{ET}_i / (\text{annual ET}_x) \tag{6}$$

where weighted WTD_x is WTD for site x, WTD_i is the mean of daily WTD for month i, ET_i, is the sum of daily ET for month i, and annual ET_x is annual ET_a for site x.

Results

Patterns of daily ET_a

The three ground water wetlands shared a characteristic daily pattern of ET_a during the growing season (Fig. 4a—c), yet during any season anomalously high and low daily ET_a rates occurred, illustrating the variability in ET_a driven by short-term weather patterns. For example, in early May of 2005, Alamosa NWR experienced unusually warm and windy conditions, with daily ET_a rates as high as 8.2 mm/d, near the annual maximum. More typically, in spring and early summer when water tables were highest, daily ET_a increased following leaf emergence in late April and seasonal increases in insolation. ET_g remained high through June and July, with maximum single day ET rates ranging from 8.1 mm/d at Rito Alto to 9.6 mm/d at Higel. Minimum mid-summer (the 2 weeks centered on the summer solstice) rates occurred on cloudy days and ranged from 3.2 mm/d at Alamosa NWR to 3.9 mm/d at Higel. ET_a decreased steadily from August through early October as solar radiation decreased, and water tables and soil water content was declining. Leaf senescence typically occurred by mid-October, and during the leafless period mean daily ET_a was less than 1 mm/d.

In playas, the pattern of daily ET_a differed between Bulrush and Mishak Lakes. At Bulrush, the water table was deep

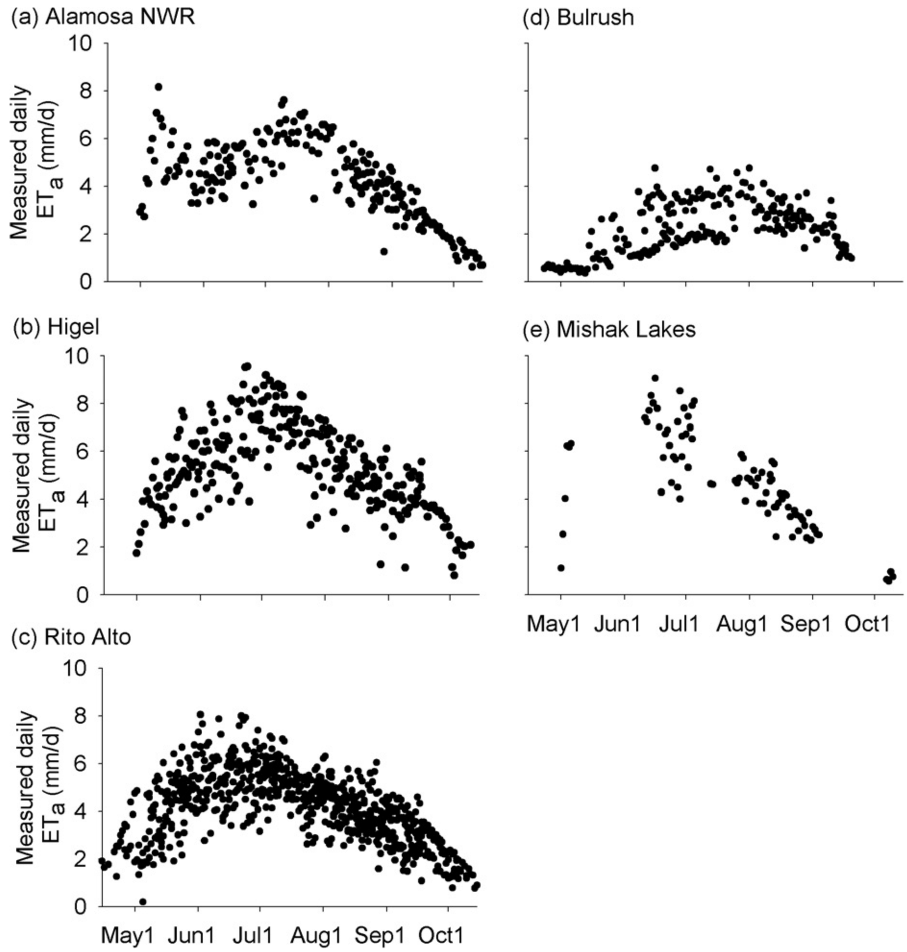

Figure 4 Measured daily actual evapotranspiration (ET_a) in wet meadows (a—c), and in playas (d and e). The number of years of data for each figure is: (a) two, (b) two, (c) five, (d) two, and (e) three. Some daily values are missing in all years for all sites (see Table 2).

through May of both 2003 and 2005, and ET_a rates increased slowly from April 15 through early June (Fig. 4d), reaching a maximum of 4.8 mm/d. In contrast, Mishak Lakes was inundated at the beginning of each growing season, and ET_a increased in spring to a late June maximum of 9.1 mm/d (Fig. 4e), similar to the peak rate at the Higel wet meadow (Fig. 4b). Minimum mid-summer rates ranged from 1.2 mm/d at Bulrush to 4.0 mm/d at Mishak Lakes.

Models of ET_a

For wet meadows, P—T ET_p generally provided good estimates of ET_a (r^2 = 0.73—0.86; coefficient of variation, CV = 14—24%) (Fig. 5a—c, left column). At Alamosa NWR and Rito Alto, P—T ET_p overestimated ET_a across the range of measured values. At Higel, P—T ET_p overestimated ET_a at low values and underestimated at high values. Slopes of P—T ET_p versus measured ET_a were 0.65—0.74.

The use of field ET_a measurements for calibrating ET_p improved estimates for all sites (r^2 = 0.87—0.92; CV = 9—12%) (Fig. 5a—c, right column). Slopes of calibrated ET_p versus measured ET_a were 0.89—0.94. Calibration functions included season and WTD for Alamosa NWR and Rito Alto, but only season for Higel (Table 3).

For playas, P—T ET_p more poorly estimated ET_a than for wet meadows (r^2 = 0.36 and 0.62, for Bulrush and Mishak Lakes, respectively; Fig. 5d and e, left column). For Bulrush, P—T ET_p greatly overestimated daily measured ET_a (CV = 126%; Fig. 5d). Calibrating ET_p for water availability improved the fit for both Bulrush and Mishak Lakes (r^2 = 0.76—0.87; CV = 12—25%; Fig. 5d and e, right column). The calibration function for Mishak Lakes was similar to that for wet meadows, but the function for Bulrush differed substantially and included VWC, precipitation, and year (Table 3). The calibrated ET_p for Bulrush yielded the poorest fit to measured ET_a when compared to other sites.

Modeled daily ET_a using off-site energy flux data from a regional weather station compared well to measured ET_a (r^2 = 0.70—0.84, CV = 15—25%, slopes = 0.81—0.91; Table 4). The model for Bulrush produced the greatest average error in daily estimates (CV = 25% versus 15—18% for the other sites). Mishak Lakes yielded the poorest fit of modeled to measured ET_a (r^2 = 0.70). For all sites modeled daily ET_a underestimated at low measured ET_a and overestimated at high measured ET_a. Slopes of modeled versus measured were 0.78—0.82 for wet meadows versus 0.70—0.71 for playas.

Modeling daily ET_a for days when on-site data were not collected was possible because available energy (R_n-G) at each site was significantly related to solar radiation as measured at Center ($p < 0.001$, Table 5). Thus, ET_p could be calculated even when on-site energy flux data were missing.

Annual ET

In wet meadows, the calculated annual ET_a ranged from 751 mm at Rito Alto in 2005 where WTD was 0.95 m, to 994 mm at Higel in 2003 where WTD was 0.13 m (Table 6). Annual ET_g in wet meadows ranged from 629 mm at Rito Alto in 2004 and 2005 to 866 mm at Higel in 2005.

In playas, annual ET_a ranged from 352 mm at Bulrush in 2003 where WTD was 1.68 m, to 892 mm at Mishak Lakes in 2001 where WTD was 0.18 m. ET_g at these sites ranged from 0 mm at Mishak Lakes in 1999–2001, to 571 mm at Bulrush in 2005 (Table 6). At Mishak Lakes, ET_g was estimated to be ≈0 mm during all years because measured annual stream inflow to the wetland complex in combination with on site precipitation supplied 36% more surface water to the wetland than was consumed by annual ET_a (Sanderson, 2006; Sanderson et al., in press) and there was little net seepage (Kappen, 2004). Of this 36%, most was lost as surface water outflow, although a small amount may have entered the shallow aquifer via ground water recharge

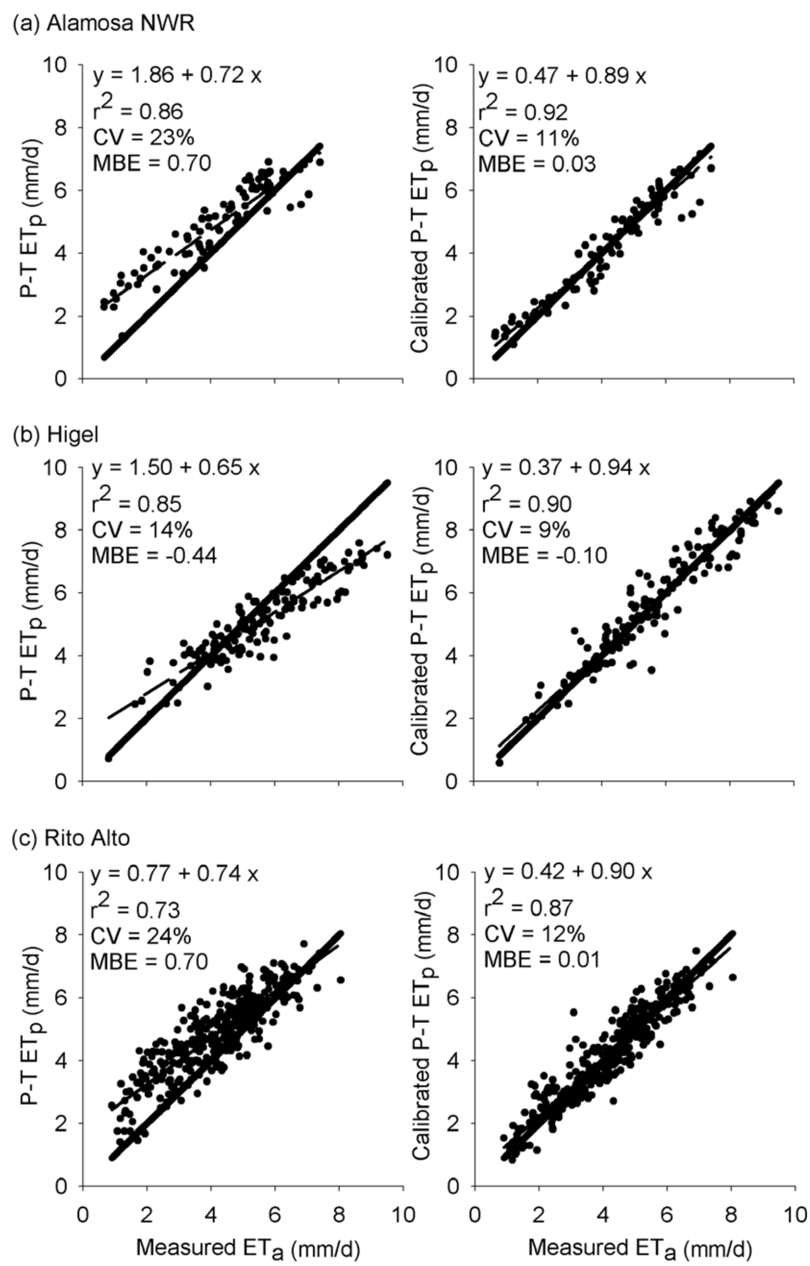

Figure 5 Priestley–Taylor potential evapotranspiration (P–T ET_p) (left) and calibrated P–T ET_p (right) for wet meadows (a–c), and for playas (d and e). r^2 is the coefficient of determination, CV the coefficient of variation, and MBE is the mean bias error. The light line through the data points is the least-squares best fit. The heavy line shows the 1:1 relationship.

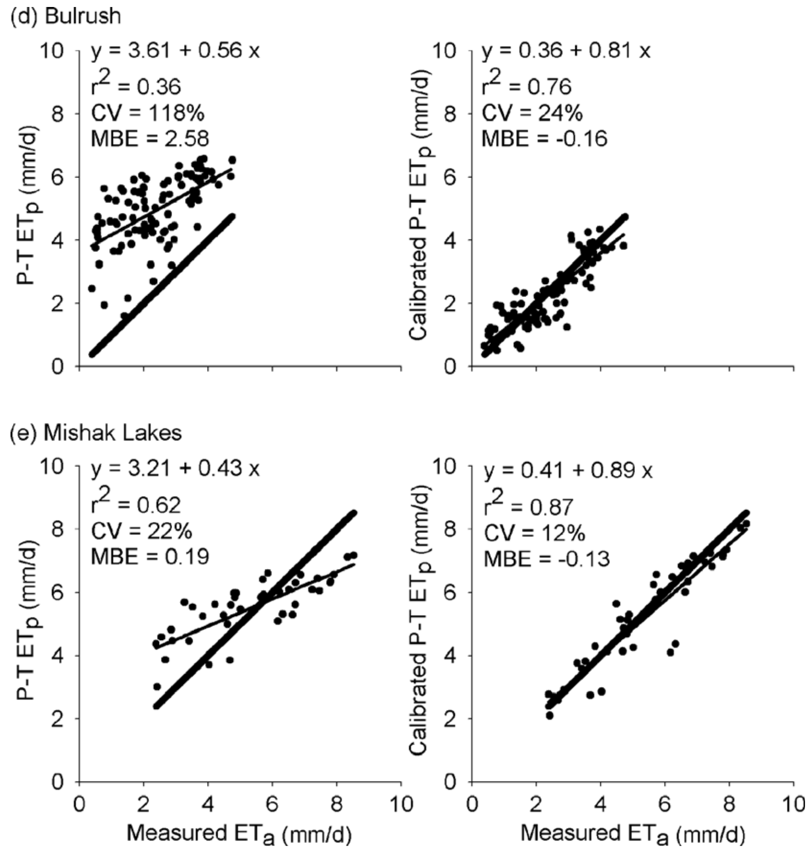

Figure 5 (*continued*)

Table 3 Models used to calibrate Priestly—Taylor potential evapotranspiration (ET_p) to measured actual evapotranspiration (ET_a)

Site	Variables included	Parameter estimate ± 1 s.e.	*p*-Value
Wet meadows			
Alamosa NWR	Intercept	1.14 ± 0.085	
	Season	−0.30 ± 0.100	0.003
	WTD	−1.02 ± 0.13	<0.001
	Season × WTD	1.50 ± 0.18	<0.001
Higel	Intercept	0.75 ± 0.027	
	Season	0.44 ± 0.035	<0.001
Rito Alto	Intercept	0.85 ± 0.042	
	Season	0.38 ± 0.026	<0.001
	WTD	−0.29 ± 0.041	<0.001
Playas			
Bulrush	Intercept	−356.2 ± 40.4	
	Soil water	0.73 ± 0.32	0.023
	7d_ppt	0.054 ± 0.011	<0.001
	Year	0.18 ± 0.020	<0.001
Mishak Lakes	Intercept	0.31 ± 0.069	
	Season	0.83 ± 0.071	<0.001
	WTD	−0.11 ± 0.29	0.001

WTD is water table depth. 7d_ppt is cumulative weighted precipitation over the previous 7 d.

Table 4 Statistics for modeled actual evapotranspiration (ET_a) versus measured ET_a using modeled available energy (R_n-G) and off-site regional weather station data

Site	r^2	CV (%)	MBE	Slope
Alamosa NWA	0.84	16	0.0	0.80
Higel	0.80	15	0.0	0.82
Rito Alto	0.75	17	0.0	0.78
Bulrush	0.76	25	−0.1	0.71
Mishak Lakes	0.70	18	+0.1	0.70

r^2 is the coefficient of determination, CV is the coefficient of variation, and MBE is the mean bias error (in mm).

Table 5 Models of available energy (R_n-G) as a function of off-site data

Site	Variables included	Parameter estimate ± 1 s.e.	*p*-Value	Model r^2	Model MBE
Wet meadows					
Alamosa NWR	Intercept	2.78 ± 0.85		0.79	0.14
	Solar radiation	0.37 ± 0.037	<0.001		
	Season	3.36 ± 0.72	<0.001		
Higel	Intercept	1.76 ± 0.58		0.56	−0.25
	Solar radiation	0.50 ± 0.023	<0.001		
Rito Alto	Intercept	2.57 ± 0.49		0.64	−0.04
	Solar radiation	0.36 ± 0.022	<0.001		
	Season	3.20 ± 0.42	<0.001		
Playas					
Bulrush	Intercept	3.24 ± 0.76		0.64	−0.32
	Solar radiation	0.33 ± 0.031	<0.001		
	Season	2.02 ± 0.65	0.003		
	1d_ppt	0.76 ± 0.24	0.002		
Mishak Lakes	Intercept	2.90 ± 1.01		0.76	−0.23
	Solar radiation	0.49 ± 0.040	<0.001		

1d_ppt is total rainfall on the previous day. See text for complete explanation of independent variables. r^2 is the coefficient of determination of modeled versus measured (R_n-G), and MBE (in $MJ/m^2/d$) is the mean bias error of the model.

Table 6 Annual estimated actual evapotranspiration (ET_a) and the annual estimated ground discharge via evapotranspiration (ET_g) for all sites and all years

Site	Year	WTD (m)	ET_a (mm)	Precipitation (mm)	ET_g (mm)
AL	2003	0.34	882	158	724
AL	2005	0.33	891	131	760
HI	2003	0.13	994	155	839
HI	2005	0.15	987	121	866
RA	2001	0.67	897	221	676
RA	2002	0.83	845	110	735
RA	2003	0.90	804	205	599
RA	2004	0.94	809	180	629
RA	2005	0.95	751	122	629
BU	2003	1.68	352	189	163
BU	2005	1.54	571	128	443
MI	1999	0.21	868	1199[a]	0
MI	2000	0.48	892	1258[a]	0
MI	2001	0.18	872	1232[a]	0

Wet meadows are AL = Alamosa National Wildlife Refuge, HI = Higel, and RA = Rito Alto. Playas are BU = Bulrush and MI = Mishak. WTD = water table depth.

[a] Includes precipitation and surface water inflows per unit area of wetland; the amount in excess of ET_a was lost from wetland primarily as surface water outflow (Sanderson, 2006; Sanderson et al., in press).

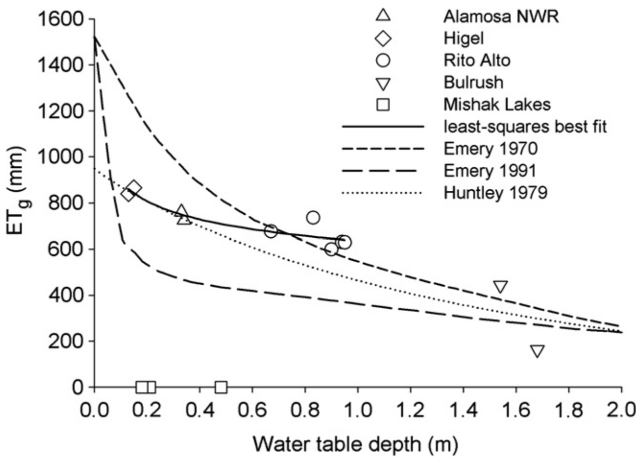

Figure 6 Total annual ground water component of evapotranspiration (ET_g) as a function of water table depth (WTD) for all sites and years, plus three existing models for comparison. The solid line shows the least-squares fit to the nine values for wet meadows.

(Kappen, 2004; Sanderson, 2006; Sanderson et al., in press). At Bulrush, ET_g in 2005 was 466 mm, which was 172% greater than ET_g in 2003, even though the mean annual WTD was only 0.14 m higher in 2005.

Annual ET_g was significantly related to WTD for wet meadows. The best-fit curve for the nine annual values for ET_g from ground water wetlands was

$$ET_g = 635.1\ \mathrm{WTD}^{-0.1488} \quad (r^2 = 0.83,\ p < 0.001) \qquad (7)$$

This curve indicates that ET_g decreased exponentially as WTD increased, comparable to the shape of curves suggested by Emery (1970, 1991) and Huntley (1979) (Fig. 6). However, the magnitude of estimated ET_g differs from existing curves. At WTD = 0.13 m, Eq. (7) yields an annual ET_g of 860 mm, while ET_g from existing models ranges from 605 mm (−30%, Emery, 1991) to 1265 mm (+47%, Emery, 1970). At WTD = 0.95 m, Eq. (7) yields an annual ET_g of 640 mm, while ET_g from existing models ranges from 370 mm (−42%, Emery, 1991) to 565 mm (−12%, Emery, 1970).

The percentage and magnitude of decrease in ET_g with increasing WTD also differ substantially between this study and existing models (Emery, 1970, 1991; Huntley, 1979). We found that in wet meadows ET_g decreased by 26% (220 mm) as the WTD dropped from 0.13 to 0.95 m, versus a 39–55% decrease estimated by existing models (Table 7). The magnitude of ET_g decrease estimated by two existing models (Emery, 1970; Huntley, 1979) was 69–218% greater than estimated by our model. Emery (1991) estimated a decrease in ET_g of 235 mm, only 7% greater than our model's estimate; however, Emery (1991) underestimated the magnitude of ET_g across the range of WTDs studied by up to 42% (Table 7).

Discussion

Annual ET_g versus WTD

This study illustrates that the relationship between ET_g and WTD is not a simple curve with lower ET rates when the water table is deeper, as proposed by other researchers (Emery, 1970, 1991; Huntley, 1979). The ET_g to WTD relationship is significantly different between wet meadows and playas, indicating that models must consider water source. Among wet meadows, ET_g has a consistent relationship with WTD, while for playas it does not.

ET_g versus WTD for wet meadows

For wet meadows, our results corroborate the general relationship that ET_g decreases as WTD increases. However, the magnitude of ET_g estimated by existing models when compared to results from this study is from 30% too low to 47% too high at WTD = 0.13 m and 12–42% too low at WTD = 0.95 m (Fig. 6). Over- and under-estimates of ET_g result in two significant problems for a basin-scale ground water model: (i) substantial over- and under-estimates of water flux from a shallow aquifer to the atmosphere via ET in a given cover type, and (ii) substantially larger estimates of the decrease in ET_g as the water table declines. Thus, existing models would estimate ET ''salvage'', i.e. a reduction in ET_g due to water table drawdown, that may be several times higher than is actually occurring as WTD changes from 0.13 to 0.95 m.

The existing ET_g–WTD models (Emery 1970, 1991; Huntley 1979; Hearne and Dewey 1988) are based on limited wetland ET and hydrology data, and studies such as ours that use local data and rigorous techniques result in more accurate quantification of ET rates and processes (Laczniak et al., 1999). For example, existing models that predict steep decreases in ET_g along a WTD gradient are based on ET from open water bodies and ET_g from a single vegetation type (saltgrass, *D. spicata* (L.) Greene) (White, 1932; Blaney

Table 7 Estimates from existing models and the current study of the ground water component of evapotranspiration (ET_g) in the San Luis Valley with water table depth (WTD) = 0.13 and 0.95 m, the range encountered during this study

	Estimated ET_g		Decrease in ET_g
	WTD = 0.13 m	WTD = 0.95 m	
This study	860	640	220 (26%)
Emery (1970)	1265 (+47%)	565 (−12%)	700 (55%)
Emery (1991)	605 (−30%)	370 (−42%)	235 (39%)
Huntley (1979)	851 (+1%)	479 (−25%)	372 (44%)
Hearne and Dewey (1988)	945[a] (+10%)	n/a	

ET_g values are in mm. Percentages show the difference from this study. Estimates from this study are for wet meadows only.
[a] For WTD <0.60 m.

et al., 1938; Blaney and Criddle, 1962; Robinson and Waananen, 1970; Dylla et al., 1972). However, saltgrass is not a typical wetland plant and often grows in alkaline soils where, despite a shallow water table, surface soil water content and plant productivity can remain low. It differs in many ways from highly productive sedges such as *Carex simulata*, *Carex aquatilis* and *Carex utriculata*, the rush *J. balticus*, and other emergent plants that dominate wetlands in mountain and intermountain basins throughout the western US. ET_g estimates from this study, which are based on ET_a measurements in a variety of wetland types, suggest that saltgrass poorly represents ET relationships of wetland vegetation in the western US.

The reduction in ET_g due to water table decline is lower than previous estimates because soil water content does not limit ET when the water table is within $\sim$1.0 m of the ground surface. Soil water content in the upper 0.3 m remained above 0.22 cm^3/cm^3 even at a WTD of 1.20 m, indicating that capillary water moved from the water table into upper soil horizons to support ET_g. This is consistent with other studies that documented significant capillary movement of water through fine textured soils into the root zone (Andersen, 2005), even on sites with a WTD of 2.5 m (Chimner and Cooper, 2004). It also suggests that wetland plants in the study area have well developed root systems that can utilize ground water and ground water recharged soils, even when WTD is 1.0 m.

ET_g versus WTD in playas

Unlike wet meadows, ET_g is highly variable in playas, and lacks a consistent relationship with WTD. For example, ET_g at Bulrush was 172% greater in 2005 than in 2003, despite a difference in WTD of only 0.14 m. The increase in 2005 over 2003 occurred because the water table rose abruptly to within 0.35 m of the ground surface, saturating the soil within the root zone of the plants that dominate the site, and then the water table dropped abruptly so that mean annual WTD did not vary substantially. The variability in WTD and subsequently ET_g arises from the variability in water supply to playas, which is driven by watershed scale precipitation patterns, especially winter snow in the adjacent high mountains. Inter-annual surface water inflows to intermountain basin wetlands may vary by >300% (Sanderson, 2006; Sanderson et al., in press).

In contrast to existing models (Emery, 1970, 1991; Huntley, 1979; Hearne and Dewey, 1988), our estimated ET_g rates in playas were $\approx$0 mm when WTD was <0.50 m (at Mishak Lakes) and were >0 mm when WTD was 1.54 and 1.68 m (at Bulrush). This counter-intuitive result occurred because surface water inflows to the wetland complex combined with precipitation were substantially greater than ET_a demand, eliminating the ground water fraction of ET_a (Sanderson, 2006; Sanderson et al., in press). This result is consistent with the work of DeMeo et al. (2003), who determined that when inflows are in excess of ET_a, calculated ET_g is <0 mm, indicating ground water recharge.

When drought prevails and snowmelt provides insufficient inflows to wetlands yet water tables are near the ground surface (e.g., at Bulrush), ET_a may be satisfied by ground water, thus ET_g is >0 mm. At the Bulrush site, which was not inundated in 2003 and 2005, ET_g was >0 mm despite a mean annual water table up to 1.68 m below ground surface. In playas, ET_g can also vary considerably for a given WTD.

The relationship between hydrologic variability and ET_g of playas is difficult to predict with the current state of knowledge. During long drought periods water tables drop, seepages losses from streams may be great, and playas may remain dry despite high runoff (Wurster et al., 2003), as occurred in 2005 at the Bulrush site. ET_g in this case would be >0 mm. Consecutive years of moderate runoff could also occur, possibly resulting in extensive flooding and causing ET_g to be $\leqslant$0 mm.

Role of vegetation in ET_g

This study could improve existing models of ET_g for wetland ecosystems with shallow WTDs because common wetland types were analyzed. Many previous researchers applied a single ET_g—WTD relationship to all vegetation types, irrespective of hydrologic dynamics and variability in vegetation type, growth, and physiology. We suggest that at any WTD, freshwater wetlands have higher ET_g rates than the saline wetlands and upland vegetation types used to develop existing ET_g—WTD relationships (White, 1932; Blaney et al., 1938; Eakin, 1960; Blaney and Criddle, 1962; Robinson and Waananen, 1970; Dylla et al., 1972; Nichols, 1994).

Water availability is a critical determinant of vegetation composition, and vegetation strongly influences rates of ET_g. As the patterns and rates of water use continue to change in intermountain basins of the western US, vegetation will also continue to respond dynamically, in both the short- and long-term. In the short-term, species dominance, leaf area, and stomatal conductance can respond to a changing water table, thus changing within-season ET rates. In the long-term, changes in water availability may trigger changes in site vegetation composition, cover, and rooting characteristics. For example, Cooper et al. (2006) documented flood-intolerant shrubs invading playas formerly dominated by wetland grasses and other non-woody species after a water table decline of 1.6 m. These upland shrubs have different water acquisition and use patterns than the wetland plants they replaced. These shrubs are deeply rooted and can access deep water tables, yet they have low productivity and low leaf area (Cooper et al., 2006). ET, water table position, and vegetation type are critically inter-related (Ridolfi et al., 2006), and efforts to predict changes in ET_g must consider both short- and long-term changes in these factors.

Acknowledgements

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References

Andersen, H.E., 2005. Evapotranspiration from a riparian fen wetland. Nordic Hydrology 36, 121–135.

Blaney, H.F., Ewing, P.A., Israelson, O.W., Rohwer, C., Scobey, F.C., 1938. Water Utilization, Part III. US National Resources Planning Committee, Upper Rio Grande, Washington, DC.

Blaney, H.F., Criddle, W.D., 1950. Determining water requirements in irrigated area from climatological irrigation data. Technical Paper No. 96. Soil Conservation Service, US Department of Agriculture.

Blaney, H.F., Criddle, W.D., 1962. Determining consumptive use and irrigation water requirements. Technical Bulletin 1275. USDA Agricultural Research Services.

Carsey, K., Kittel, G., Decker, K., Cooper, D.J., Culver, D., 2003. Field guide to the wetland and riparian plant associations of Colorado. Colorado Natural Heritage Program, Fort Collins, CO.

Colorado's Decision Support Systems (CDSS), 2005. CDSS Ground Water Products. <http://cdss.state.co.us/ftp/gw.asp> (last accessed 28-08-2005).

Chimner, R.A., Cooper, D.J., 2004. Using stable oxygen isotopes to quantify the water source used for transpiration by native shrubs in the San Luis Valley, Colorado, USA. Plant and Soil 260, 225–236.

Colorado Climate Center, 2005. CoAgMet Homepage. <http://ccc.atmos.colostate.edu/~coagmet> (last accessed 23-08-2005).

Cooper, D.J., 1986. Community structure and classification of Rocky Mountain wetland ecosystems. In: Windell, J.T., Willard, B.E., Cooper, D.J., Foster, S.Q., Knud-Hansen, C.F., Rink, L.P., Kiladis G.N., (Eds.), An Ecological Characterization of Rocky Mountain Montane and Subalpine Wetlands. USDI Fish & Wildlife Service Biological Report 86 (11), pp. 66–147.

Cooper, D.J., Sanderson, J.S., Stannard, D.I., Groeneveld, D., 2006. Effects of long-term water table drawdown on evapotranspiration and vegetation in an arid region phreatophyte community. Journal of Hydrology 325, 21–34.

Davies, J.A., Allen, C.D., 1973. Equilibrium, potential, and actual evaporation from cropped surfaces in southern Ontario. Journal of Applied Meteorology 12, 649–657.

De Bruin, H.A.R., 1983. A model for the Priestley–Taylor parameter α. Journal of Applied Meteorology 22, 572–578.

DeMeo, G.A., Laczniak, R.J., Boyd, R.A., Smith, J.L., Nylund, W.E., 2003. Estimated ground-water discharge by evapotranspiration from Death Valley, California, 1997–2001. US Geological Survey Water-Resources Investigations Report 03-4254.

Devitt, D.A., Donovan, D.J., Katzer, T., Johnson, M., 2002. A reevaluation of the ground water budget for Las Vegas Valley, Nevada, with emphasis on ground water discharge. Journal of the American Water Resources Association 38, 1735–1751.

Doesken, N.J., McKee, T.B., 1989. The incredible climate of the San Luis Valley. In: Harmon, E.J. (Ed.), Water in the Valley: A 1989 Perspective on Water Supplies, Issues, and Solutions in the San Luis Valley. Colorado Groundwater Association, Colorado, pp. 79–98.

Drexler, J.Z., Snyder, R.L., Spano, D., Paw, K.T.U., 2004. A review of models and micrometeorological methods used to estimate wetland evapotranspiration. Hydrological Processes 18, 2071–2101.

Duell Jr., L.F.W., 1990. Estimates of evapotranspiration in alkaline scrub and meadow communities of Owens Valley, California, using the Bowen-ratio, eddy-correlation, and Penman-combination methods. US Geological Survey Water-Supply Paper 2370-E.

Dylla, A.S., Stuart, D.M., Michener, D.W., 1972. Water use studies on forage grasses in northern Nevada. Technical Series Number T-10. Nevada Agricultural Experiment Station.

Eakin, T.E., 1960. Ground-water appraisal of Newark Valley, White Pine County, Nevada. Ground Water Resources Reconnaissance Report 1. Nevada Department of Conservation and Natural Resources, Carson City, NV.

Emery, P.A., 1970. Electric Analog Model Evaluation of a Water-Salvage Plan, San Luis Valley, South-Central, Colorado. Colorado Water Conservation Board, Denver.

Emery, P.A., 1991. Testimony in Case No. 86CW46, District Court, Water Division No. 3, State of Colorado. November 19, 1991, Transcript page 5741.

Emery, P.A., Snipes, R.J., Dumeyer, J.M., Klein, J.M., 1973. Water in the San Luis Valley, South-Central Colorado. Water Resources Circular 18. Colorado Water Conservation Board, Denver, Colorado.

Flint, A.L., Childs, S.W., 1991. Use of the Priestley–Taylor evaporation equation for soil water limited conditions in a small forest clearcut. Agricultural and Forest Meteorology 56, 247–260.

Fritschen, L.J., Simpson, J.R., 1989. Surface energy and radiation balance systems: general descriptions and improvements. Journal of Applied Meteorology 28, 680–689.

Gosselink, J.G., Turner, R.E., 1978. The role of hydrology in freshwater wetland ecosystems. In: Good, R.E., Whigham, D.F., Simpson, R.L. (Eds.), Freshwater Wetlands: Ecological Processes and Management Potential. Academic Press, New York, pp. 63–78.

Groeneveld, D.P., Baugh, W.M., Sanderson, J.S., Cooper, D.J., 2007. Annual groundwater evapotranspiration mapped from single satellite scenes. Journal of Hydrology 344, 146–156.

Harbaugh, A.W., Banta, E.R., Hill, M.C., McDonald, M.G., 2000. MODFLOW-2000, the US Geological Survey modular ground-water model – user guide to modularization concepts and the ground-water flow process. US Geological Survey Open-File Report 00-92.

Hearne, G.A., Dewey, J.D., 1988. Hydrologic analysis of the Rio Grande Basin north of Embudo, New Mexico, Colorado, and New Mexico. US Geological Survey Water-Resources Investigations Report 86-4113.

Huntley, D., 1979. Ground-water recharge to the aquifers of northern San Luis Valley. Geological Society of America Bulletin, Part II 90, 1196–1281.

Jacobs, J.M., Mergelsberg, S.L., Lopera, A.F., Myers, D.A., 2002. Evapotranspiration from a wet prairie wetland under drought conditions: Paynes Prairie Preserve, FL, USA. Wetlands 22, 374–385.

Kappen, B.J., 2004. Ground and surface water interaction in ephemeral wetlands, San Luis Valley, Colorado. M.S. Thesis. Colorado State University, Fort Collins.

Kaygusuz, K., 1999. The comparison of measured and calculated solar radiations in Trabzon, Turkey. Energy Sources 21, 347–353.

Laczniak, R.J., DeMeo, G.A., Reiner, S.R., Smith, J.L., Nylund, W.E., 1999. Estimates of ground-water discharge as determined from measurements of evapotranspiration, Ash Meadows Area, Nye County, Nevada. US Geological Survey Water-Resources Investigations Report 99-4079.

Laczniak, R.J., Smith, J.L., Elliott, P.E., DeMeo, G.A., Chatigny, M., 2001. Ground-water discharge determined from estimates of evapotranspiration, Death Valley regional flow system, Nevada and California. US Geological Survey Water-Resources Investigations Report 01-4195.

Malek, E., Bingham, G.E., McCurdy, G.D., 1990. Evapotranspiration from the margin and moist playa of a closed desert valley. Journal of Hydrology 120, 15–34.

McDonald, M.G., Harbaugh, A.W., 2003. The history of MODFLOW. Ground Water 41, 280–283.

McKee, T.B., Doesken, N.J., Kleist, J., Shrier, C., Stanton, W.P., 2000. A History of Drought in Colorado: Lessons Learned and What Lies Ahead. Colorado Water Resources Institute, Colorado State University, Fort Collins, CO.

McNaughton, K.G., 1976. Evaporation and advection. I: Evaporation from extensive homogeneous surfaces. Quarterly Journal of the Royal Meteorological Society 102, 181–191.

Mifflin, M.D., 1988. Region 5, Great Basin. In: Back, W., Rosenshein, J.S., Seaber, P.R. (Eds.), The Geology of North America, Hydrogeology, O-2. The Geological Society of America, Boulder, Colorado, pp. 69–78.

Moncrieff, J., Jarvis, P., Valentini, R., 2000. Canopy fluxes. In: Sala, O.E., Jackson, R.B., Mooney, H.A. (Eds.), Methods in Ecosystem Science. Springer-Verlag, New York, pp. 161–180.

Monteith, J.L., 1965. Evaporation and environment. In: Fogg, G.E. (Ed.), The State and Movement of Water in Living Organisms, Proceedings of the 19th Symposium of the Society of Experimental Biology. Cambridge University Press, New York, pp. 205–233.

Moreo, M.T., Laczniak, R.J., Stannard, D.I., 2007. Evapotranspiration rate measurements of vegetation typical of ground-water discharge areas in the Basin and Range carbonate-rock aquifer system, Nevada and Utah, September 2005–August 2006. US Geological Survey Scientific-Investigations Report 2007-5078.

Nichols, W.D., 1994. Groundwater discharge by phreatophyte shrubs in the Great Basin as related to depth to groundwater. Water Resources Research 30, 3265–3274.

Nichols, W.D., 2000. Regional ground-water evapotranspiration and ground-water budgets, Great Basin, Nevada. US Geological Survey Professional Paper 1628.

NOAA, 2005. Satellite and information service. <http://lwf.ncdc.noaa.gov/oa/climate/climatedata.html> (last accessed 1-09-2005).

Ohmura, A., 1982. Objective criteria for rejection of data for Bowen ratio flux calculations. Journal of Applied Meteorology 21, 595–598.

Peacock, C.E., Hess, T.M., 2004. Estimating evapotranspiration from a reed bed using the Bowen ratio energy balance method. Hydrological Processes 18, 247–260.

Penman, H.L., 1948. Natural evaporation from open water, bare soil and grass. Proceedings of the Royal Society, London 193, 120–146.

Penman, H.L., 1963. Vegetation and Hydrology. Commonwealth Bureau of Soils, Harpenden.

Perez, P.J., Castellvi, F., Ibáñez, M., Rosell, J.I., 1999. Assessment of reliability of Bowen ratio method for partitioning fluxes. Agricultural and Forest Meteorology 97, 141–150.

Poiani, K.A., Johnson, W.C., 1993. A spatial simulation model of hydrology and vegetation dynamics in semi-permanent prairie wetlands. Ecological Applications 3, 279–293.

Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Monthly Weather Review 100, 81–92.

Reiner, S.R., Laczniak, R.J., DeMeo, G.A., Smith, J.L., Elliott, P.E., Nylund, W.E., Fridrich, C.J., 2002. Ground-water discharge determined from measurements of evapotranspiration, other available hydrologic components, and shallow water-level changes, Oasis Valley, Nye County, Nevada. US Geological Survey Water-Resources Investigations Report 01-4239.

Ridolfi, L., D'Odorico, P., Laio, F., 2006. Effect of vegetation–water table feedbacks on the stability and resilience of plant ecosystems. Water Resources Research 42, W01201, doi:10.1029/2005WR004444.

Robinson, T.W., Waananen, A.O., 1970. Evapotranspiration by woody phreatophytes in the Humboldt River Valley near Winnemucca, Nevada. US Geological Survey Professional Paper 491-D.

Rosenberry, D.O., Stannard, D.I., Winter, T.C., Martinez, M.L., 2004. Comparison of 13 equations for determining evapotranspiration from a prairie wetland, Cottonwood Lake area, North Dakota, USA. Wetlands 24, 483–497.

Sanderson, J.S., 2006. Hydrology and conservation of intermountain wetlands. Ph.D. Dissertation. Colorado State University, Fort Collins, CO.

Sanderson, J.S., Kotliar, N.T., Steingraeber, D., Browne, C., in press. The simulated natural hydrologic regime of an intermountain playa conservation site. Wetlands.

SAS Institute, 2003. SAS for Windows, Release 9.1. The SAS Institute Inc., Cary, NC.

Siebenthal, C.E., 1910. Geology and water resources of the San Luis Valley, Colorado. US Geological Survey Water Supply Paper 240.

Snyder, C.T., 1962. A hydrologic classification of valleys in the Great Basin, western United States. Bulletin of the International Association of Scientific Hydrology 7, 53–59.

Souch, C., Wolfe, C.P., Grimmond, C.S.B., 1996. Wetland evaporation and energy partitioning: Indiana Dunes National Lakeshore. Journal of Hydrology 184, 189–208.

Stannard, D.I., 1993. Comparison of Penman–Monteith, Shuttleworth–Wallace, and modified Priestly–Taylor evapotranspiration models for wildland vegetation in semiarid rangeland. Water Resources Research 29, 1379–1392.

Stannard, D.I., 1997. A theoretically based determination of Bowen-ratio fetch requirements. Boundary-Layer Meteorology 83, 375–406.

Stewart, R.B., Rouse, W.R., 1976. A simple method for determining the evaporation from shallow lakes and ponds. Water Resources Research 12, 623–628.

Tanner, C.B., 1960. Energy balance approach to evapotranspiration from crops. Soil Science Society of America Proceedings 24, 1–9.

Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geography Review 33, 55–94.

USDA, 2005. Plants database. <http://plants.usda.gov> (last accessed 12-10-2005).

Verma, S.B., Rosenberg, N.J., Blad, B.L., 1978. Turbulent exchange coefficients for sensible heat and water vapor under advective conditions. Journal of Applied Meteorology 17, 330–338.

Walton-Day, K., 1996. Colorado wetland resources. In: Fretwell, J.D., Williams, J.S., Redman, P.J. (Eds.), National Water Summary 1992–1993 – Hydrologic Events and Wetland Resources. US Geological Survey Water-Supply Paper 2425, pp. 135–140.

Western Regional Climate Center, 2005. <http://www.wrcc.dri.edu/index.html> (last accessed 12-06-2005).

White, W.N., 1932. A method of estimating ground-water supplies based on discharge by plants and evaporation from soil. US Geological Survey Water-Supply Paper 659-A.

Winter, T.C., Rosenberry, D.O., Sturrock, A.M., 1995. Evaluation of 11 equations for determining evaporation for a small lake in the north central United-States. Water Resources Research 31, 983–993.

Wurster, F.C., Cooper, D.J., Sanford, W.E., 2003. Stream/aquifer interactions at Great Sand Dunes National Monument, Colorado: influences on interdunal wetland disappearance. Journal of Hydrology 271, 77–100.

Appendix D

Subirrigated Other Crop Documentation

Reference: Thompson, Kelley, and Kirk Thompson, November 22, 2011, Memorandum to Mike Sullivan, Mary Halstead, and James Heath with Colorado Division of Water Resources, *RGDSS Groundwater ET Curves for "Other" Crops.*

TO: Mike Sullivan, Deputy State Engineer
Mary Halstead, Chief of Modeling & DSS
James Heath, Lead Modeler
Colorado Division of Water Resources

FROM: Kelley Thompson, Kirk Thompson
Agro Engineering Inc.

SUBJECT: RGDSS Groundwater ET Curves for "Other" Crops
DATE: 11/22/2011

INTRODUCTION

Agro Engineering was asked to develop one curve that estimates evapo-transpiration (ET) from groundwater based on a depth to groundwater for crops other than established alfalfa and grass-pasture that have been referred to as "other" crops in the RGDSS modeling process.

In the RGDSS groundwater model, shortages in crop irrigation water requirements can be supplied when the model indicates high groundwater tables. These shortages are calculated in StateCU by structure and supplied to the groundwater model package. Currently, StateCU can only provide shortages for three crop classes; alfalfa, grass pasture, and "other" crops. The "other" crops include all other crop classifications considered in the model; small grains, potatoes, vegetables, fall wheat, new alfalfa, and cover crops.

The groundwater model can supply a shortage in crop irrigation water requirement (IWR) given a depth to groundwater from the ground surface. For consistency with other documents, this is referred to here as the amount of crop ET that can be supplied by groundwater - ETg.

HISTORIC PRACTICES

The irrigation practice commonly known as "sub-irrigation" was prevalent for irrigation of crops such as grain, potatoes, alfalfa, peas, and other vegetables for some time in the San Luis Valley.

The groundwater table in some areas of the valley had been raised through importation of surface waters and was naturally high in other areas. With these high groundwater levels, the practice of "sub-irrigation" involved intentionally manipulating the groundwater table to the root zone of crops using on-farm ditch laterals supplied by surface water and wells. Reportedly, ground-water tables were generally maintained to approximately two feet of ground surface to supply crop-water needs. Due to topographic changes throughout fields and proximity to ditches, it is expected that ground water levels varied throughout a field. However, in a very anecdotal sense, this would suggest that ground water at a depth of about two feet may be sufficient to meet the water needs of many "other crops".

For non-hay crops, the intentional use of "sub-irrigation" was generally phased out by the time that center pivot irrigation sprinklers were widely installed and used throughout areas of the valley. It is not expected that intentional "sub-irrigation" would be widely used again in the valley, but high groundwater levels in some areas may contribute to crop water needs.

ANALYSIS

There has been little documented quantitative study of sub-irrigation in crops such as grains, potatoes, and other vegetables; particularly in the San Luis Valley or similar areas. However, a common conclusion in available crop water supply literature is that the majority of water extraction for a crop occurs in the top half of the rooting depth (see references). Therefore, this suggests that the amount of crop ET that could be supplied by ground water (ETg) should be close to the maximum crop irrigation requirement from a depth equal to roughly one-half of the crop rooting depth to near to the ground surface. Additionally, the ETg that can be supplied decreases from near the maximum crop irrigation requirement at about one-half the crop rooting depth to zero at an extinction depth equal to the maximum crop rooting depth. As no more detailed evaluations were found in the literature, it appears reasonable that a linear function can represent water use between one-half of rooting depth and the maximum rooting depth.

The majority of the crops represented by the classification of "Other Crops" are small grains and vegetables. Small grains including barley, wheat, oats, and canola tend to root to a maximum depth of about four feet. The vegetable crops typically grown in the San Luis Valley including potatoes, lettuce, spinach, and carrots tend to root to a maximum depth of two to three feet. The rooting depth of new alfalfa and sudan grass, the predominant cover crop, is more similar to small grains. An optimum scenario would be to have two separate curves based on these two general crop types. However, as mentioned, StateCU can currently only provide shortages for one lumped "other" crop. Given both the uncertainties in estimation of groundwater levels and the general cropping pattern in the San Luis Valley, it appears reasonable to estimate ET from groundwater based on a depth to groundwater using one general curve for "other" crops.

Crop sub-irrigation would be limited to areas with high groundwater tables, and these areas may generally have a crop mix that is different from other areas. The state has compiled water level data from wells monitored throughout the San Luis Valley, and this data was used to estimate regional areas with groundwater tables less than 5 feet from the surface. Crop types of parcels within these areas (from the 1998 and 2005 irrigated parcel datasets) are compiled in the following table. As noted, small grain crops are more predominant in areas of high groundwater tables than vegetables. This suggests that the most appropriate single curve to estimate ET of "other crops" from groundwater would be the curve suggested for small grains.

Table 1. Crops Within Areas of High Groundwater Tables (<=5 ft Depth to Water)

Crop Acres	1998 1950-	2005 1950-	1998 1970-	2005 1970-
Potatoes	2566	1459	1879	832
Vegetables	172	276	191	189
Small Grains	14020	9777	12985	8834
Wheat Fall	85	45	85	104
CoverCrop	197	184	197	0
% vegetables	16%	15%	13%	10%
% grains	84%	85%	87%	90%

Note: "1950-" WL contours from state from average of all well data since 1950
"1970-" WL contours from kriging of average of well data since 1970

RESULTS

In the RGDSS groundwater model, tables are used to relate amount of crop ET that can be supplied from groundwater (ETg) to the depth of groundwater below ground surface that is indicated in the model. As discussed, the amount of crop ET that could be filled by ground water should be close to the maximum crop irrigation requirement from ground surface to a depth of one-half the crop rooting depth and decrease linearly to zero at the maximum crop rooting depth. The maximum crop irrigation requirement varies from year to year. The potential to fill up to two feet of shortage in crop IWR appears appropriate and is near the maximum IWR of most “other crops” but would not be set so high so as to inappropriately skew the linear curve for water levels below one-half the rooting depth. If water was actually at the ground surface, water would be consumed at the rate of surface water evaporation rather than crop transpiration and higher rates could extend to a depth of several inches due to upward capillary movement. However, the ability of the groundwater model to predict a water level to within inches given topographic changes in half-mile wide grid cells is questionable, and, reportedly, a very rapid increase in potential consumption over a short difference causes significant model instabilities. Therefore, for modeling purposes, it is appropriate to extend the shortage amount filled at one-half the root depth at the same rate to the ground surface.

The following table and figure represent the proposed relationship between ET for “other crops” that can be supplied from groundwater (ETg) to the depth of water below ground surface using one single curve to represent the variety of “other crops” including small grains, potatoes, vegetables, fall wheat, new alfalfa, and cover crops.

Table 2. ETg as a function of depth to groundwater

Depth to Water (feet)	ETg (feet)
0	2.0
2	2.0
4	0.0

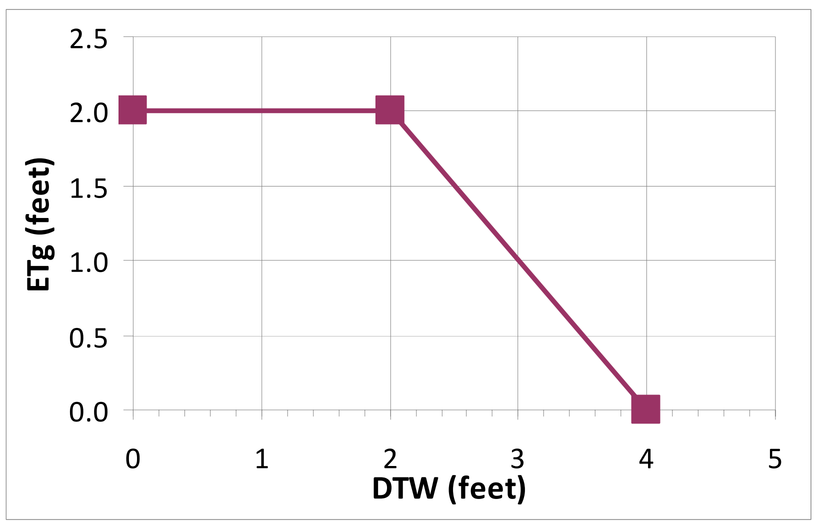

Figure 1. ETg as a function of depth to groundwater

REFERENCES

Agro Engineering, Inc. (2009). "Increased Vegetation ET in Non-Irrigated Areas". Excerpt from unpublished engineering analysis to support water right for Elwes Arroyo; Cunningham Cattle Company.

Ayars, J.E., Shouse, P., and Lesch, S.M. (2009). "In Situ Use of Groundwater by Alfalfa". Agricultural Water Management 96 (2009) 1579-1586. June 12, 2009.

Benz, L.C., E.J. Doering, and G.A. Reichman. (1984). "Water Table Contribution to Alfalfa Evapotranspiration and Yields in Sandy Soils." Transactions for the American Society of Agricultural Engineers.

Benz, L.C., G.A. Reichman, and E.J. Doering. (1983). "Drainage Requirements for Alfalfa Grown on Sandy Soil." Transactions for the American Society of Agricultural Engineers.

Charles, F.L., Morgan, J.A., and W.C. Bausch. (1987). "Evapotranspiration of Native Vegetation in the Closed Basin of the San Luis Valley, Colorado." Colorado State University, Colorado Water Resources Research Institute Completion Report No. 143. June 1987.

Colorado DWR. (2004). "Preliminary Draft. Rio Grande Decision Support System Phase 4 Ground Water Model Documentation." Excerpt section 4.17 Native Evapotranspiration.

Cooper, D.J., Groeneveld, D.P., and R.A. Chimner. (1999). "Evaluation of Evapotranspiration Rates Of Native Non-Wetland Plant Communities in the San Luis Valley, Colorado." unpublished draft research paper submitted to Rio Grande Water Conservation District.

Cooper, D.J., Groeneveld, D.P., Chimner, R.A., and J.S. Sanderson. (2000). "Characterization of Three Functional Ecosystems Based upon Evapotranspiration Relationships in the San Luis Valley, Colorado." unpublished research paper submitted to Rio Grande Water Conservation District.

Cooper, D.J., Sanderson, J.S., Stannard, D.I., and D.P. Groeneveld. (2006). "Effects of Long-Term Water Table Drawdown on Evapotranspiration and Vegetation in an Arid Region Phreatophyte Community." Journal of Hydrology 325 (2006) 21-34

Cooper, D.J. (2005). Opinions as Expert Witness.

Cone, V.M., and A. Kezer. (1915). "Irrigated Agriculture in the San Luis Valley". The Agricultural Experiment Station of the Colorado Agricultural College Bulletin 209. Fort Collins Colorado.

Doty C.W., A. Nassehzadeh-Tabrizi, R.W. Skaggs, and A.W. Badr. (1984). "Stream Water Levels Affect Field Water Tables and Corn Yields." Transactions for the American Society of Agricultural Engineers.

Groeneveld, D.P. (2008). "Remotely-sensed Groundwater Evapotranspiration from Alkali Scrub Affected by Declining Water Table." Journal of Hydrology (2008) 358, 294-303

Groeneveld, D.P. (2011). "Alfalfa Extinction Curve for Use in San Luis Valley Groundwater Modeling". Report submitted to James Heath and Mike Sullivan, Colorado DWR, August 8 2011. Hydrobio, Sante Fe NM.

Groeneveld, D.P. Baugh, W.M., Sanderson, J.S., and Cooper, D.J. (2007). "Annual Groundwater Evapotranspiration Mapped from Single Satellite Scenes." Journal of Hydrology (2007) 344, 146-156.

Harmon, E.J. (2002) "RGDSS Memorandum – Appendix C Native ET." Memorandum from Harmon to Ray Bennett; Subject RGDSS Ground Water, Task 15 – Native ET Data. July 29, 2002

Hiler, E.A., R.N. Clark, and L.J. Glass. (1971). "Effects of Water Table Height on Soil Aeration and Crop Response." Transactions for the American Society of Agricultural Engineers.

Kruse, E.G., R.E. Yoder, D.L. Cuevas, and D.F. Champion. (1986). "Alfalfa Water Use from High, Saline Water Tables." American Society of Agricultural Engineers 1986 Winter Meeting. Chicago, IL.

Kruse, E.G., D.A. Young, and D.F. Champion. (1985). "Effects of Saline Water Tables on Corn Irrigation." Development and Management Aspects of Irrigation and Drainage Systems. American Society of Civil Engineers, Irrigation and Drainage Division, conference proceedings from San Antonio, Texas.

Lockwood – Ames Irrigation Handbook.Gering, Nebraska

Madramootoo, C.A., G.T. Dodds, and A. Papadopoulos. (1993). "Agronomic and Environmental Benefits of Water-Table Management." Journal of Irrigation and Drainage Engineering Vol. 119, No. 6. 1052-1064.

Mueller, L., Behrendt, A., Schalitz, G., and U. Schindler. (2004). "Above Ground Biomass and Water Use Efficiency of Crops at Shallow Water Tables in a Temperate Climate." Agricultural Water Management 75 (2005) 117-136. December 23, 2004.

Nicholson, H.H. (1952). "The Control of Ground Water Level in Crop Production." School of Agriculture, Cambridge. 13th International Horticulture Congress, London.

Parton, W.J., W.K. Lauenroth, and F.M. Smith. (1981). "Water Loss from a Shortgrass Steppe." Agricultural Meteorology 24: 97-109; Amsterdam Netherlands.

Sanderson. J.S., and D.J. Cooper. (2008). "Ground water Discharge by Evapotranspiration in Wetlands of an Arid Intermountain Basin." Journal of Hydrology (2008) 351, 344-359.

SCS National Engineering Handbook, Section 15 Irrigation, Chapter 1 Soil-Plant-Water Relationships. Soil Conservation Service U.S. Dept. of Agriculture.

Shih S.F., and G.S. Rahi. (1984). “Evapotranspiration of Lettuce in Relation to Water Table Depth.” Transactions for the American Society of Agricultural Engineers

Stannard, D.I., and H.L. Weaver. (1995). “Measurements of Evapotranspiration, Surface-Energy Fluxes, Weather Variables, and Water-Table Depths in the Closed Basin of the San Luis Valley, Alamosa County, Colorado, 1985-88” U.S. Geological Survey Open-File Report 93-639. Denver, Colorado.

Tipton R.J., and F.C. Hart (1931). “San Luis Valley - Field Investigations, 1930. Consumptive Use Determination, Evaporation Experiments, and Drainage Measurements” Colorado SEO – Hinderlider, March, 1931.

Tipton R.J., (1930). “San Luis Valley – Present Method of Irrigation. Its Relation toWater Consumption and Waterlogging of Land.” Colorado SEO – Hinderlider, March 1930.

Torres, J.S., and R.J. Hanks. (1989). “Modeling Water Table Contribution to Crop Evapotranspiration”. Irrigation Science 10: 265-279.

Van Hoorn, J.W. (1958). “Results of a Ground Water Level Experimental Field with Arable Crops on Clay Soil.” Netherlands Journal of Agricultural Science. Feb 1958 Vol 6 No. 1 1-76. Wageningen, Holland.

Weaver, John E. (1926). Root Development of Field Crops. New York: McGraw Hill. Downloaded from http://www.soilandhealth.org

Walter, I.A., Siemer, E.G., Quinlan, J.P., Burman, R.D. (1991). “Evapotranspiration and Agronomic Responses in Formerly Irrigated Mountain Meadows, South Park Colorado.” Board of Water Commissioner, City and County of Denver.