DEVELOPMENT OF HYDROLOGIC AND VADOSE MODELS TO IMPROVE GROUNDWATER MANAGEMENT IN THE OWENS VALLEY

Addendum to Final Report Prepared by The County of Inyo Water Department for the State of California, Department of Water Resources, Grant Agreement No. 460001827 under the Local Groundwater Management Assistance Act

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Executive Summary

The County of Inyo and the City of Los Angeles and its Department of Water and Power have adopted a Long Term Groundwater Management Plan (Plan) to manage groundwater and surface water in the Owens Valley to avoid adverse changes to phreatophytic vegetation while continuing to supply water to Los Angeles. Experience gained through monitoring and research during the last decade revealed the ineffectiveness of existing monitoring and management procedures. The purpose of this research project was to improve prediction tools used to evaluate the potential effects of proposed groundwater pumping. Specifically, this project focused on revision and testing of existing groundwater and vadose zone models and collection of field measurements to study the conceptualization of the models.

A post-audit for the period 1989-2002 was completed for a regional groundwater model of the Owens Valley originally prepared by Danskin (1998). In addition, the model was revised to separate the water balance components into custom MODFLOW packages to facilitate evaluation of each component. The model now simulates the period 1963-2002. It successfully simulated the drawdown due to the high pumping of 1987 through 1990 and the subsequent period of low pumping to allow water table recovery. Significant modifications completed in 2003 expanded our capability to utilize the model to evaluate LADWP annual pumping proposals and our capability to efficiently export and present the results to decision makers.

Evapotranspiration is a primary component of the soil water and groundwater balance in the vadose zone and groundwater models, but the variable is poorly quantified. A field investigation begun in 2000 was continued in 2003 to measure ET using micrometeorological methods to

compare with vegetation based Kc methods like those used to estimate irrigation needs for agricultural pastures. Along with the ET and vegetation measurements, soil water and water table measurements were collected to account for sources and locations of plant uptake to compute the water balance of the vadose zone. Turbulent fluxes of heat and water measured by the eddy covariance ET systems did not account for approximately one-third of the available energy in 2003 similar to that observed in preceding years. Estimates derived from Kc models and LAI measurements agreed well with measured seasonal ET in 2003 at one site but underestimated measured ET at two sites. Additionally, the sensitivity of the Kc models to correctly sampling the peak leaf area suggested the practice of obtaining a single vegetation measurement is potentially error prone.

The portion of ET derived from the water table was estimated from the water balance as the difference between measured ET, soil water depletion, precipitation, and evaporation. Total ET following the much wetter winter in 2003 was greater than previous years, but the absolute quantity of groundwater used was approximately the same. Direct uptake accounted for greater than 60% of ET during the summer for sites with water table depths of 1 to 3 m except for one site in 2003 which relied more heavily on winter precipitation stored in the soil. Vegetation with deeper water tables relied less on groundwater in all years. The field results suggest that a general relationship may exist that relates the partitioning of plant uptake (ET) to depth to water table although results in 2003 from one site suggested varying precipitation could cause groundwater uptake to deviate from the function.

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I. Introduction

The Owens Valley is a long, narrow valley on the eastern slope of the Sierra Nevada in Inyo County, California. Since the early 1900's, the water resources of the Owens Valley have been managed by the Los Angeles Department of Water and Power (LADWP) as the primary water supply for the city. In 1991, the County of Inyo and the City of Los Angeles and its Department of Water and Power adopted a Long Term Groundwater Management Plan (Plan) to settle two decades of litigation over the effects of Los Angeles' export of groundwater from the Owens Valley. The Plan requires management of groundwater and surface water in the Owens Valley to avoid adverse changes to phreatophytic vegetation while continuing to supply water to Los Angeles. Monitoring and management provisions of the Plan were initiated during 1989, but field observations and research during the 1990s have demonstrated the need to evaluate the effectiveness of existing monitoring and management procedures and to improve prediction tools to evaluate the potential effects of proposed groundwater pumping. The purpose of this project was to improve existing groundwater and vadose zone groundwater models that can be used to evaluate the impact of groundwater pumping on groundwater levels and water availability for native vegetation.

This project officially terminated July 1, 2003, midway through the growing season when field measurement were still being collected. A final report was prepared in 2003 (Harrington and Steinwand, 2003) that excluded the 2003 field data. After the final report was completed, an extension of the original contract was granted to complete the analysis of the field data. This addendum to the final report presents the analysis of field data collected during the 2003 growing season and describes additional revisions to the groundwater model completed since November, 2003.

II. Task 1: Groundwater model

Introduction

Research examining the relationship between groundwater pumping and environmental change was conducted in the 1980's by Inyo County and LADWP with assistance from the U.S. Geological Survey and others. From that effort, the USGS produced a basin-wide MODFLOW application which spanned the period 1963-1988 (Danskin, 1998). This model was the starting point for further development of numerical groundwater modeling completed as part of the original project. Under this grant, a post-audit of the Danskin (1998) model was completed, and the model was updated through 2002. The model also now has the capability of simulating future scenarios through 2020, an arrangement which serves both to test the performance of the model in simulating the period 1989-2002 and to provide Inyo County and LADWP a tool with which to evaluate future scenarios. This report describes the additional refinements completed since November, 2003 to develop the model into a useable management tool.

Methods

Updates to the USGS groundwater model were: (1) separation of flowing and pumped water for the period 1963-1972, (2) conversion of model from water-year to runoff-year, (3) refinement of well locations within model grid, and (4) refinement of export/import procedures for feeding model output into the Arcview GIS. All pre-processing and post-processing programs and categories of fluxes for the post-audit were maintained as before except for as described below.

Results

The post-audit separated pumped and flowing well discharge for water years 1971 through 2002. Previously, flowing and pumped water had been lumped into a single groundwater extraction component because no discrimination was made between pumped and artesian wells in LADWP's pre-1972 well records. The pre-processing program for pumpage was modified to separate pumped and flowing well discharge.

Conversion of the model from water-year (October 1 through September 30) to runoff-year (April 1 through March 31) was desirable because many of the management decisions and deadlines incorporated in the Inyo-Los Angeles Water Agreement were based on the start of the runoff-year. This task was accomplished by recasting pumped water, artesian wells, and runoff in terms of runoff-year, and regenerating model input files with the recast data.

Well locations were originally input into the model by locating wells on 15-minute quadrangles and converting those locations into model grid coordinates. Since then, all LADWP wells have been precisely located using GPS, and those coordinates were checked against the locations determined from quadrangles. The quadrangle-derived locations were generally accurate, however the additional precision of the GPS locations required that several wells be relocated into an adjacent model cell. Model input files were modified to reflect the new model grid locations of the wells.

In order to present model results to decision makers and the public, it is necessary to export model results from the raw MODFLOW output files into a more concise and intuitive form. Importing selected model output into the Arcview GIS or other graphics programs enables us to generate maps and hydrographs to present model results in a way that is meaningful for the intended audience. We accomplished this by developing UNIX shell-scripts for extracting the desired results from MODFLOW output files and reformatting the information as either Arcview ASCII grids or time-series hydrographs.

Field ET investigation

Introduction

The eddy covariance (EC) micrometeorological method to measure ET continued to be used in 2003. Because of the similar study design, data from LADWP funded equipment (one site) are included in this addendum.

Materials and Methods

Data were collected at three sites in 2003; BLK100, PLC074 and PLC185, all of which also were monitored in 2002 (Figures 1 to 3). Each EC tower was fenced to prevent range cattle from damaging the instruments. Part of the rationale to continue monitoring at the same sites in 2003 was to determine if ET and the soil water balance differed after a much wetter winter. Precipitation preceding the growing seasons each year 2000-2002 consisted of small events, and total precipitation was below normal (about 130 mm) in all years. Precipitation preceding the 2003 growing season was 3 to 5 times that in previous years (Table 1). As in previous years, EC measurements were nearly a continuous record for the majority of the growing season, approximately March 25 to October 15 (Table 2).

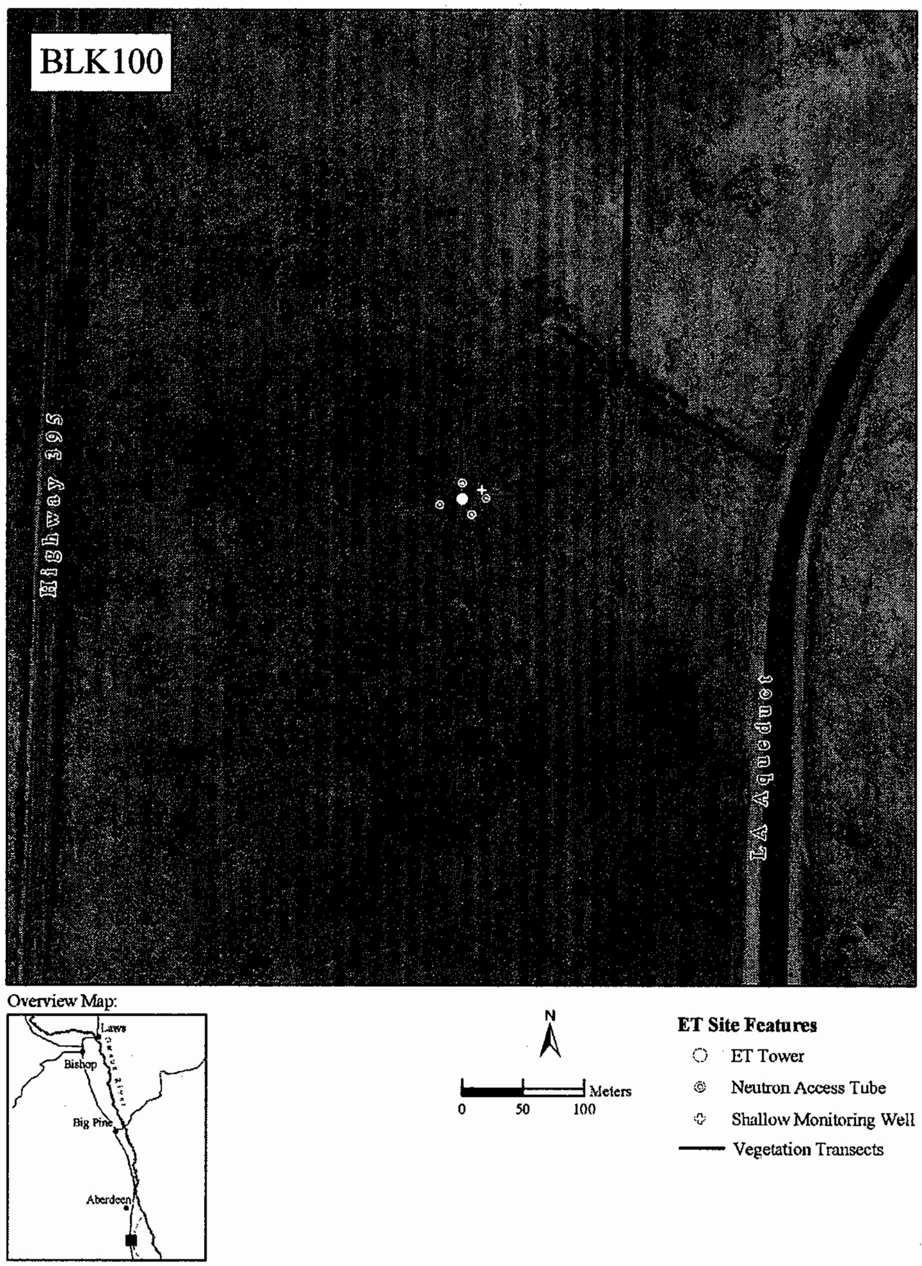

Figure 1. Aerial photograph and measurement locations for ET, soil water, and LAI at BLK100.

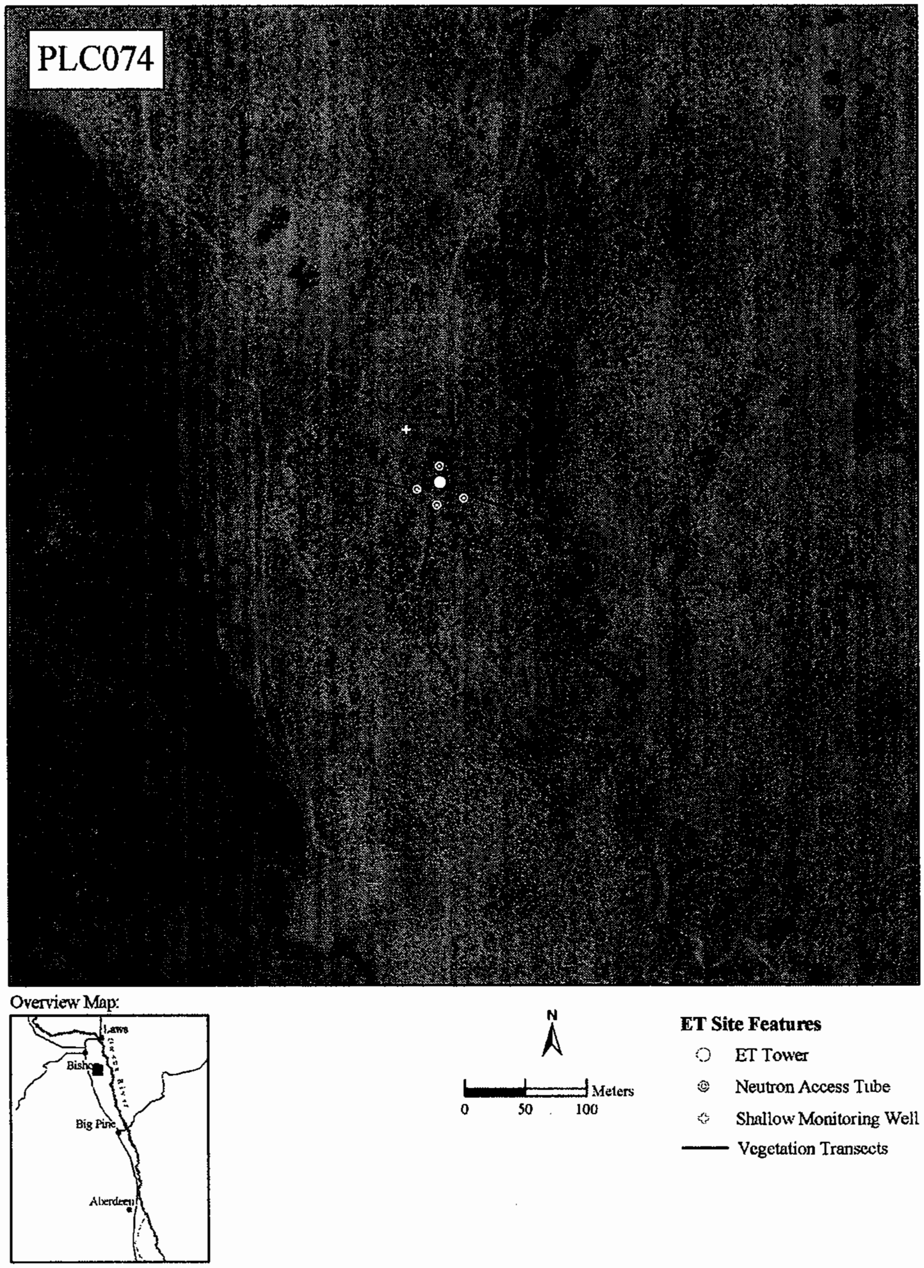

Figure 2. Aerial photograph and measurement locations for ET, soil water, and LAI at PLC074.

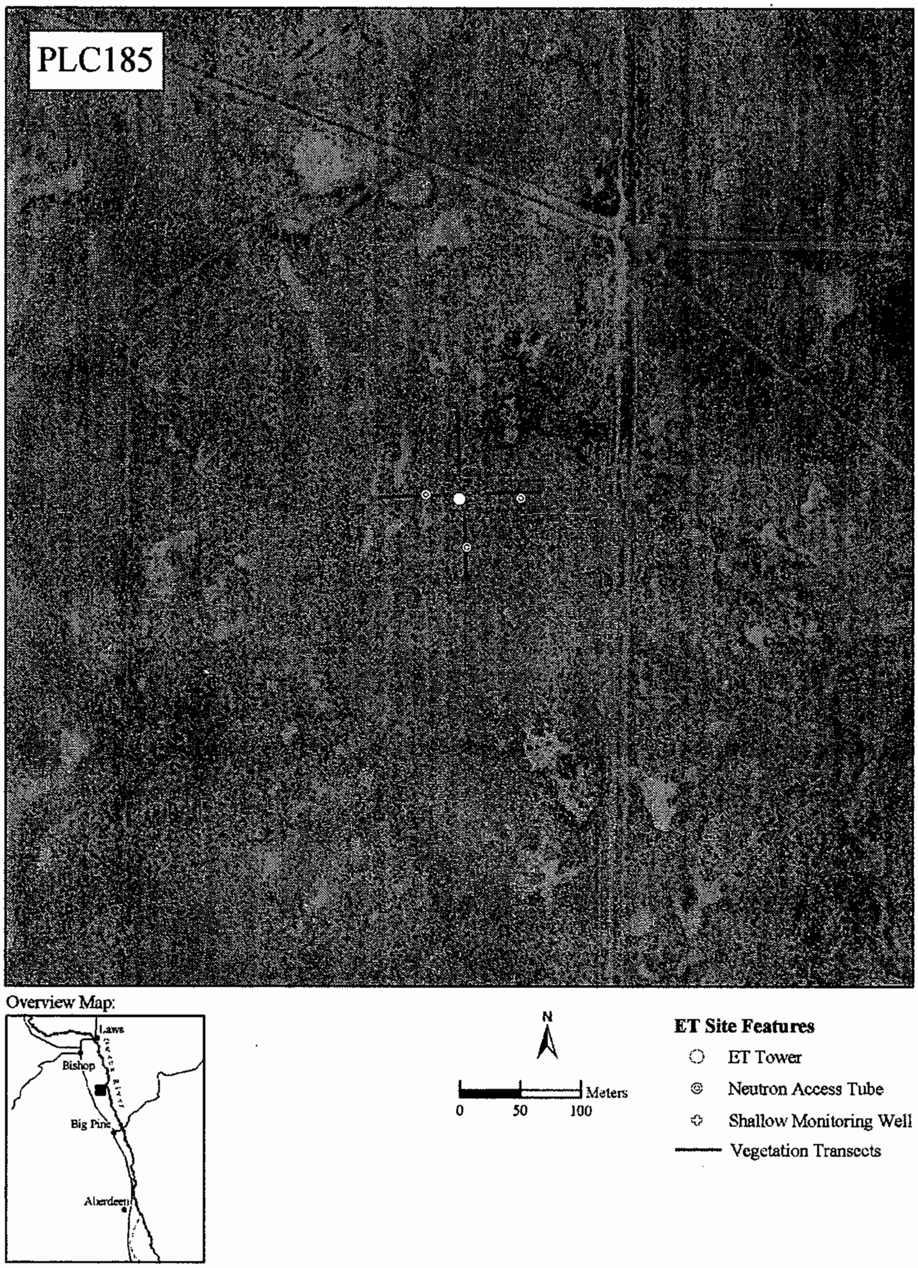

Figure 3. Aerial photograph and EC, soil water and LAI measurement locations at PLC185.

Table 1. Eddy covariance site characteristics. Depth to water are the range of depths experienced during the growing season. Precipitation values are annual totals beginning October 1 the previous year.

Year	Site	Vegetation type	Dominant Species⊥	Depth to water	Precipitation
				(m)	(mm)
2000	BLK 100	alkali meadow	SPAI, DISP2	2.0-2.5	35.6
2001	BLK 100	alkali meadow	SPAI, DISP2	2.2-3.0	71.1
	BLK 9	rabbitbrush meadow	CHNA2, SPAI	2.6-3.2	71.1
	PLC 45	Nev.saltbush scrub	ATTO	3.8-4.1(est.)	105.9
2002	BLK 100	alkali meadow	SPAI, DISP2	2.3-3.1	32.5
	FSL 138	alkali meadow	DISP2, LETR5, SPAI	1.2-2.1	21.8
	PLC 18	rabbitbrush scrub	CHNA2	>5.0	34.5
	PLC 74	Nev. saltbush meadow	SAVE4, ATTO, DISP2	2.1-2.4	31.5
	PLC 185	desert sink scrub	SAVE4	4.0	31.5
2003	BLK 100	alkali meadow	SPAI, DISP2	2.1-3.3	301.8
	PLC 74	Nev. saltbush meadow	SAVE4, ATTO, DISP2	2.1-2.4	91.7
	PLC 185	desert sink scrub	SAVE4, ATCO	>4.0	150.9

⊥grasses: SPAI, *Sporobolus airoides;* DISP2, *Distichlis spicata;* LETR5, *Leymus triticoides.* shrubs*:* CHNA2, *Chysothamnus nauseosus;* ATTO *Atriplex lentiformis* ssp. *torreyi;* SAVE4, *Sarcobatus vermiculatus;* ATCO, *Atriplex confertifolia.*

Eddy covariance instrumentation and theory

The EC methods were unchanged from those described in the final report (Harrington and Steinwand, 2003). The sign convention adopted throughout this report is as follows: net radiation is positive when directed toward the land surface, sensible and latent heat fluxes are positive when directed away from the land surface, and soil heat flux is positive when directed into the soil. Quality control measures were continued in 2003 including: 1) factory recalibration of instruments before the field season, 2) inspection of all data streams for anomalies or signal losses, 3) correction for varying air density and oxygen absorption of the hygrometer beam, and

Table 2. Dates of EC station operation.

Year	Site	Date established	Date removed
2000	BLK 100	April 21	January 8, 2001
2001	BLK 100	March 7	November 27
	BLK 9	April 11	November 27
	PLC 45	April 10	November 27
2002	BLK 100	March 12	October 2
	FSL 138	May 3	September 11
	PLC 18	May 2	October 8
	PLC 74	May 25	October 7
	PLC 185	May 24	October 7
2003	BLK 100	April 23	December 26
	PLC 74	April 24	November 17
	PLC 185	April 24	January 6, 2004

4) routine field maintenance consisting of cleaning, checking instrument level, or cable repair. ET measured by the EC system was corrected for the energy imbalance based on methods developed during the original study.

Soil water and groundwater measurements

Soil water monitoring continued at the three or four access tubes installed in 2002 adjacent to the vegetation transects. The neutron gauge calibration and monitoring procedures were described in Harrington and Steinwand (2003). Depth to water table was measured in adjacent piezometers at BLK100 and PLC074; there was no nearby piezometer for PLC185. Water level loggers were installed in test wells at BLK100 and PLC074 in June and July, 2003 respectively, to replace manual measurements.

Vegetation measurements

Point frame measurements of vegetation cover and leaf area index (LAI) were completed approximately monthly at the same four 50 m transects monitored in 2002. The field methods

Table 3. Day of year for maximum LAI in the Kc models, the LAI sampling DOY used to determine T_{Kc}, and DOY of actual measured maximum LAI for the dominant species at each site.

Year	Site	Dominant species⊥	Kc LAI model maximum DOY	LAI sampling DOY	Measured LAI maximum DOY
2000	BLK 100	SPAI, DISP2	201, 189	189	188, 250
2001	BLK 100	SPAI, DISP2	201, 189	190	253, 220
	BLK 9	CHNA2, SPAI	184, 201	192	135, 165
	PLC 45	ATTO	163	162	162
2002	BLK 100	SPAI, DISP2	201, 189	191	217,154
	FSL 138	DISP2, LETR5,JUBA	189, 201	190	190 (DISP2)
	PLC 18	CHNA2	184	190	154
	PLC 74	SAVE4, ATTO, DISP2	174, 163, 189	156	156,156,186
	PLC 185	SAVE4	174	156	128
2003	BLK 100	SPAI, DISP2	201, 189	195	255, 160
	PLC 74	SAVE4, ATTO, DISP2	174, 163, 189	160	160, 160,160
	PLC 185	SAVE4	174	160	132

⊥: grasses; SPAI, *Sporobolus airoides;* DISP2, *Distichlis spicata;* LETR5, *Leymus triticoides.* shrubs; JUBA, *Juncus Balticus: CHNA2, Chysothamnus nauseosus;* ATTO *Atriplex lentiformis* ssp. *torreyi;* SAVE4, *Sarcobatus vermiculatus.*

and data handling procedures were described in Harrington and Steinwand (2003).

<u>Comparison of EC and of Kc estimates</u>

Estimates of ET based on transpiration coefficients and vegetation measurements (T_{Kc}) were prepared according to,

$$T_{Kc} = \sum_{j=1}^{n} \sum_{i=1}^{m} (Kc_{ij}\ ETr_i\ LAI_j) \tag{1}$$

where: ETr_i is reference ET for day *i*, n is number of species, Kc_{ij} is the transpiration coefficient for species *j* on day *i*, LAI_j is the midsummer LAI for species *j*. Development and application of T_{Kc} was described in Steinwand (1999) and Steinwand et al., (2001). *LAI* measured on the date nearest the maximum *LAI* in the original Kc models was used in Equation 1 (Table 3). Leaf area of minor species for which no Kc models were available was apportioned among the species with Kc values based on their relative proportion of total LAI.

Daily ET measured with the EC system and corrected for the energy imbalance (ET_{corr}) was modeled using a Fourier series with two harmonics using procedures described by Salas et al., (1980) to permit site to site comparisons and year to year comparisons of transpiration between uniform limits for integration. The first two harmonics series is given by,

$$ET_{corr} = < ET_{corr} > + \sum_{j=1}^{2} \left[A(j)\,\mathrm{COS}(\frac{2\pi ij}{365}) + B(j)\,\mathrm{SIN}(\frac{2\pi ij}{365}) \right] \quad (2)$$

where i is the day of year, $<ET_{corr}>$ is mean daily ETr for the entire year, A(1), A(2), B(1), and B(2) are model coefficients. Occasionally the fitted model was poorly constrained and gave negative values during winter when EC data were lacking. When this occurred, daily ET was assumed to be 0.01 mm day^{-1} and the model was revised. This procedure was largely for graphical purposes. The effect on the comparison with Kc models was negligible because only the daily ET or T values during the period with ET_{corr} data or during the growing season were summed.

Results and Discussion

Site characteristics

Depth to water measured at the EC sites is presented in Figures 4 and 5. Typically, the shallowest depth to water occurred in the spring (March or April) and declined to maximum depth at end of the growing season (October). Water tables increased during the winter when vegetation was senescent. Test well 850T was installed at BLK100 in 2001, but based on the comparison with nearby test well 454T, DTW fluctuations in 2000 were similar to those in later

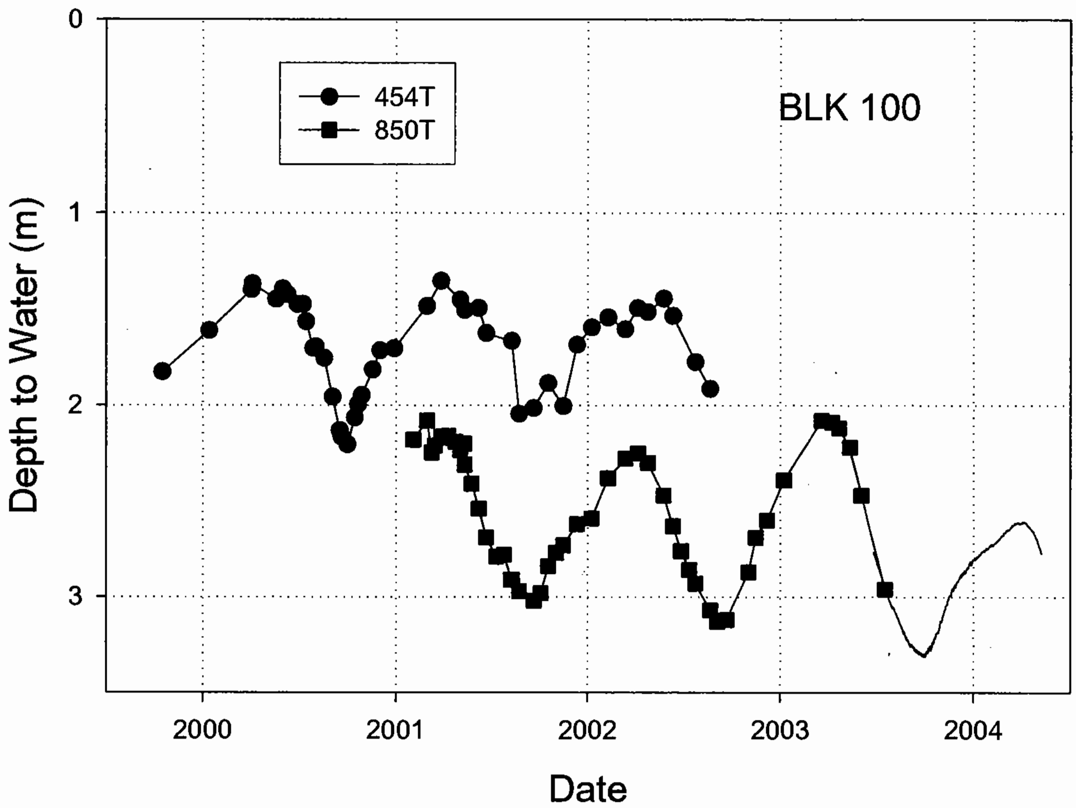

Figure 4. Depth to water in two test well located near BLK100. Test well 850T is adjacent to the EC station; 454T is located southeast of the site, adjacent to the LA Aqueduct.

years. The general declining trend superimposed on the annual cycle at BLK100 (Figure 4) was due to persistent below normal runoff conditions during this study. Additionally, on August 11, 2003 two LADWP production wells sealed below a confining layer and located 2015 meters from 850T were activated. The well operation was part of a test to determine impacts of pumping the deep confined aquifer on the shallow water table in the region. Because the pumping effects must propagate through the confining layer, the drawdown at the EC site was

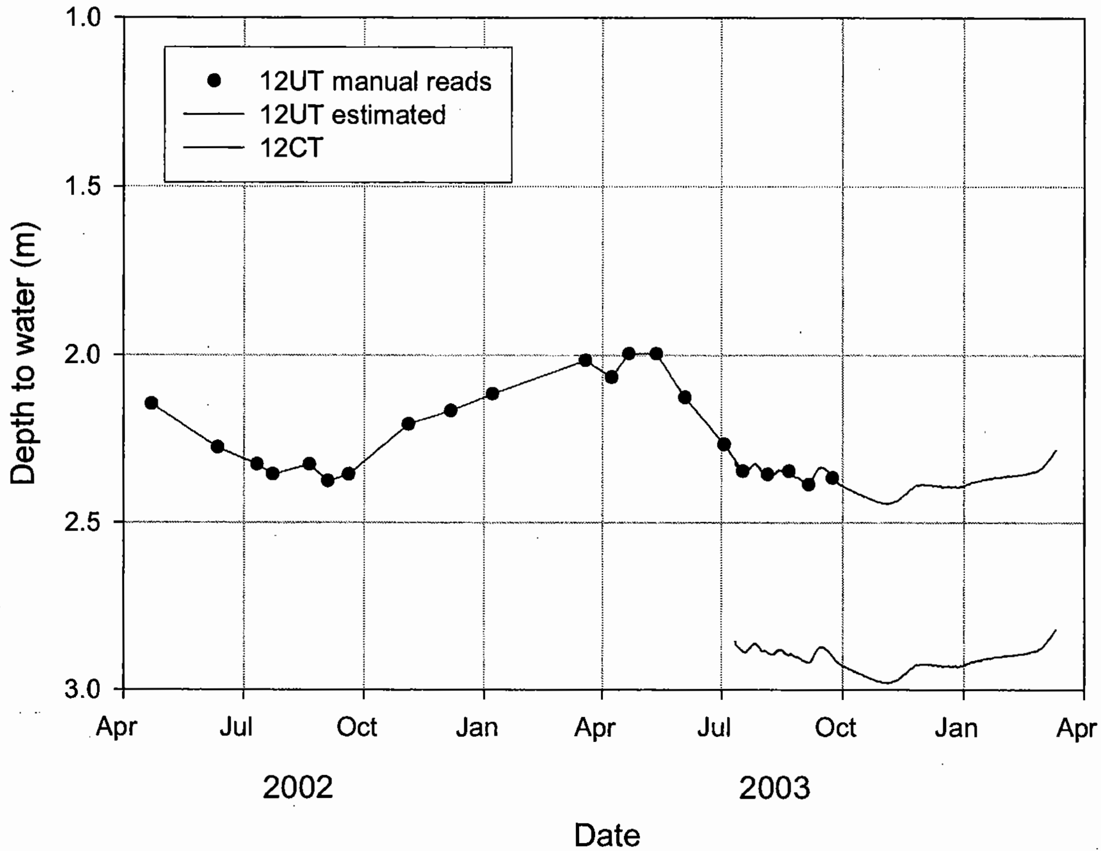

Figure 5. Depth to water at PLC074 in test well 12UT and adjacent test well 12CT. Depth in 12CT measured from reference point; depth in 12UT measured from ground surface. After September, depth in 12UT was estimated from pressure transducer readings in 12CT and the comparison of DTW in both wells from July through September.

gradual and relatively small; approximately 15 cm by May, 2004. The water level at PLC074 declined during the growing season, but small fluctuations observed in July through September probably corresponded with irrigation releases on agricultural pastures west of the site. There was no apparent affect on measured ET during periods of irrigation suggesting the fetch was acceptable. There was no piezometer located at PLC185, but water levels regionally and soil water monitoring suggest conditions at PLC185 were similar in 2002 and 2003. The water table at PLC185 was at approximately 4 m when access tubes for soil water monitoring were installed in the spring of 2002. Piezometers in the area (T842, T480, T479, and V002G) all had equal or slightly shallower (0.06m) DTW in April 2003 than 2002, and soil water measurements did not indicate the water table rose above 4m.

Soil water profiles collected at BLK100, including the shallow TDR measurements are presented in Figure 6. An example of spring, midsummer, and fall conditions in 2003 are presented for each access tube. The soil at the beginning of the growing season was moist throughout the 2.3m profile. Water content at depths greater than approximately 1m was comparable to past years, but shallower depths were wetter due to infiltrating winter precipitation. Soil water contents at BLK100 fluctuated throughout the profile reflecting the coupling with the water table fluctuations (i.e. capillarity and drainage) and plant uptake. The attempt to discriminate between these two processes is described in the vadose zone model section below.

The soil at PLC074 was moist throughout the 2.0 m profile due to recharge from the water table and deep infiltration of winter precipitation (Figure 7). Infiltration reached 1m in all tubes. Depths greater than 1.1m (tubes 742 and 744) to 1.4m (tubes 741 and 743) received recharge during the winter from capillarity above the water table. Water contents declined at all depths during summer due to water table decline and plant uptake.

The soil at PLC185 can be divided into three zones based on observed soil water fluctuations. At the start of the 2003 growing season, the soil was moist above 1 to 1.4m (tube 1852) due to precipitation inputs. Recharge from capillarity above the water table only occurred

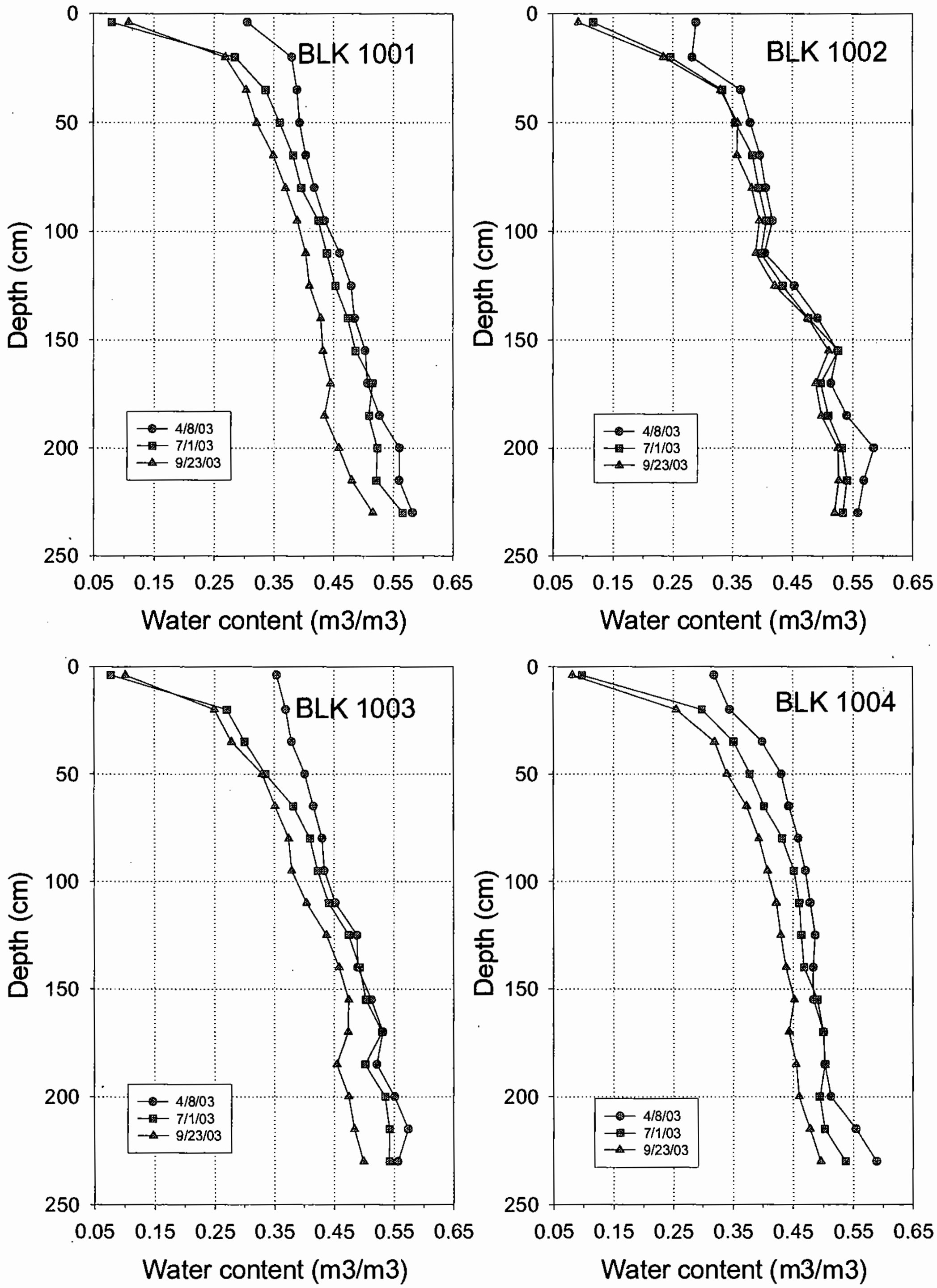

Figure 6. Soil water content θ profiles for spring, summer, and fall conditions in four access tubes at BLK100 in 2003.

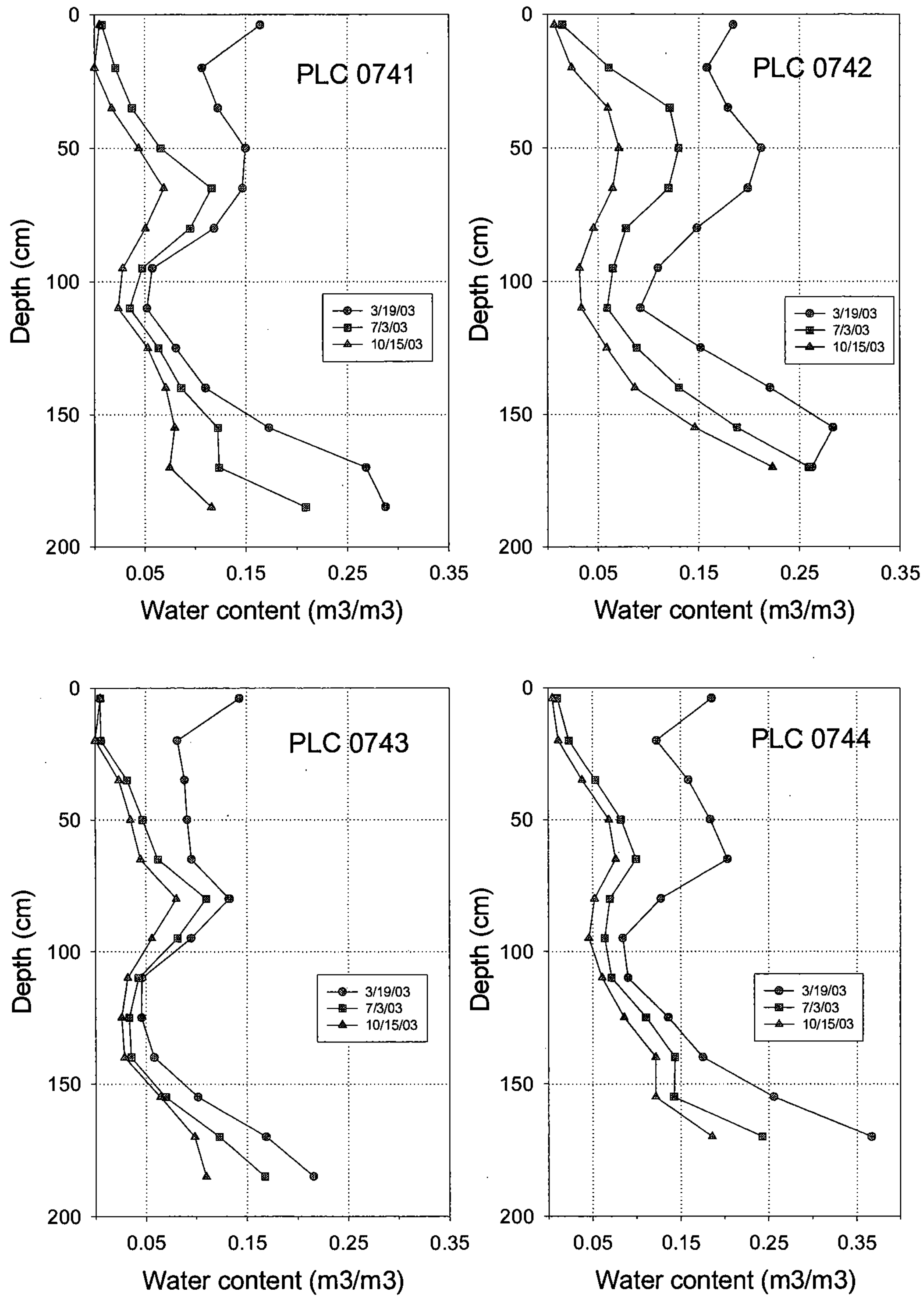

Figure 7. Soil water content 2 profiles for spring, summer, and fall conditions in four access tubes at PLC074 in 2003.

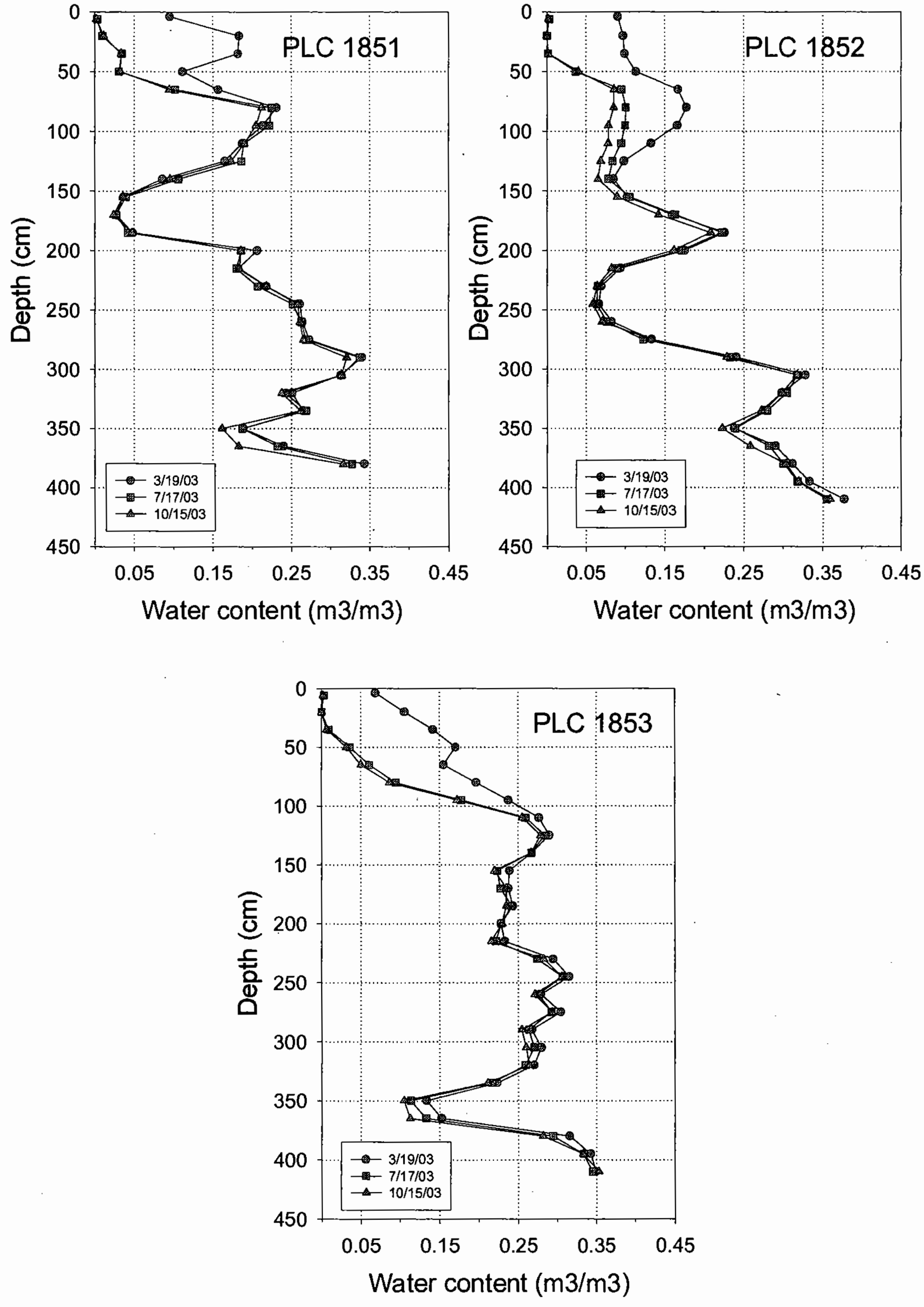

Figure 8. Soil water content θ profiles for spring, summer, and fall conditions in three access tubes at PLC185 in 2003.

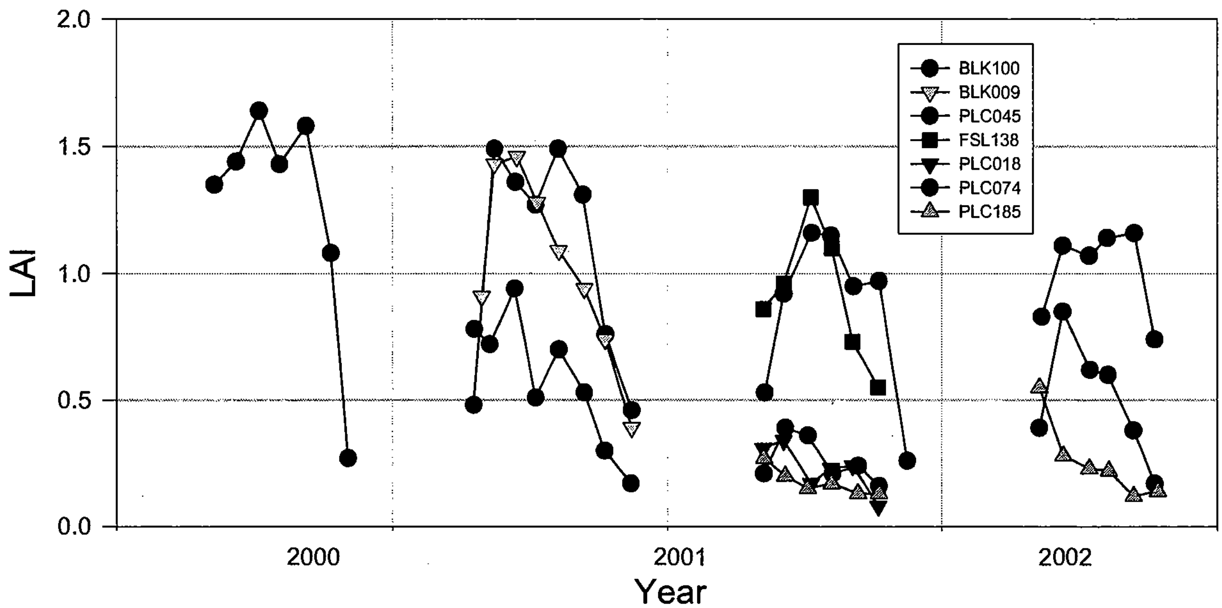

Figure 9. LAI for all sites. Values are the average of four transects.

below 3.5m. Intermediate depths from 1 m to approximately 3.5 m, had nearly constant water content during the winter (i.e. no recharge). Vertical variation in water content in this zone corresponded with changes in soil texture (Steinwand and Harrington, 2003). The primary plant uptake occurred in soil above 1m and below 3.5m. Unlike 2002, a small amount of plant uptake was observed in the intermediate zone in 2003 (e.g. tube 1853, Figure 8).

Leaf area index of all species was similar in 2002 and 2003 at BLK100 and PLC185 (Figure 9). BLK100 continued to maintain a high leaf area through June, July, and August before declining in September to October. Like 2002, LAI at PLC185 peaked in May and maintained relatively low cover throughout the summer. The increased LAI in May 2003 compared to 2002 was largely due to short-lived annuals although SAVE4 and ATCO LAI were also slightly greater as well. LAI increased markedly at PLC074 in 2003 probably due to

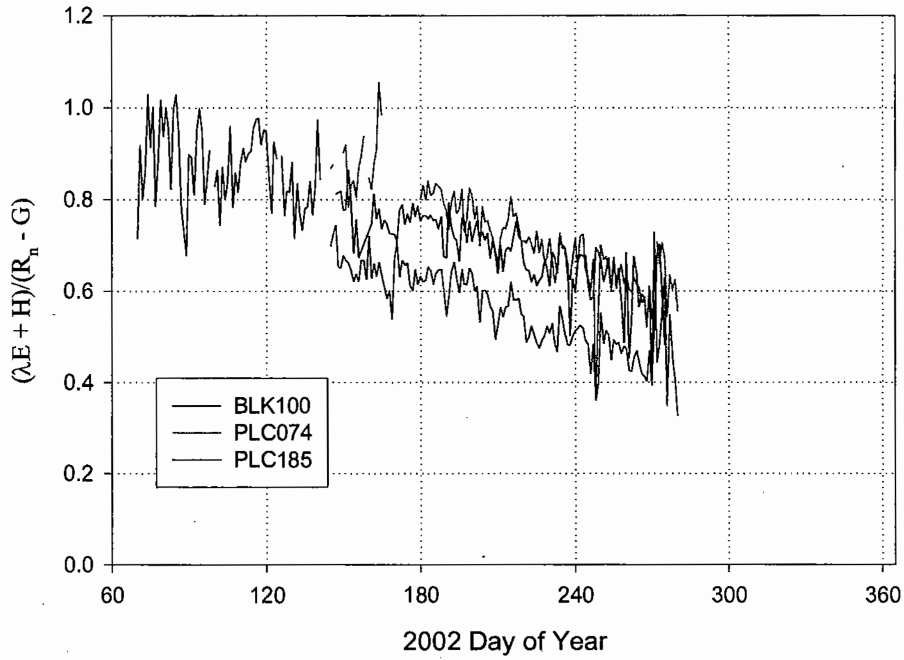

Figure 10. EB for PLC185, PLC074 and BLK100 in 2002.

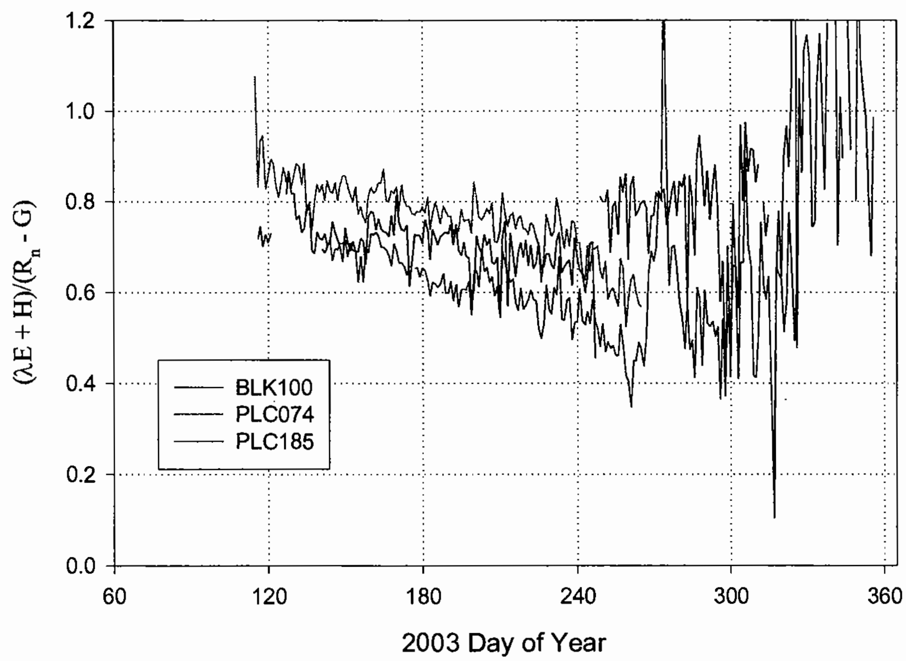

Figure 11. EB for PLC185, PLC074 and BLK100 in 2003.

Table 4. ET_{corr} Fourier model coefficients and r^2 for each site-year.

Year	Site	mean	A(1)	A(2)	B(1)	B(2)	r^2
		mm day^{-1}					
2000	BLK 100	1.37	-1.62	0.26	-0.12	0.06	0.93
2001	BLK 100	1.33	-1.56	0.27	-0.13	-0.12	0.90
	BLK 9	1.43	-1.65	0.31	-0.14	-0.17	0.95
	PLC 45	0.50	-0.50	0.12	0.15	-0.08	0.85
2002	BLK 100	1.12	-1.33	0.30	-0.27	0.03	0.98
	FSL 138	1.94	-2.28	0.50	0.10	-0.20	0.70
	PLC 18	0.18	-0.14	0.01	-0.03	-0.02	0.54
	PLC 74	0.60	-0.49	0.02	0.06	-0.004	0.63
	PLC 185	0.35	-0.33	0.05	0.05	-0.05	0.57
2003	BLK 100	1.53	-1.92	0.33	-0.14	-0.17	0.91
	PLC 74	0.81	-1.07	0.27	0.01	-0.16	0.91
	PLC 185	0.68	-0.57	-0.04	0.14	-0.05	0.71

increased soil water and nutrient availability provided by increased winter precipitation. All species except SAVE4 increased in leaf area in 2003.

<u>EC energy balance (EB)</u>

The mean EB calculated on a daily basis ranged from 47 to 94% during the growing season and was similar in 2002 and 2003 for each site suggesting the EB was primarily a function of site characteristics or instrument configuration rather than calibration drift (Figures 10 and 11). Highly erratic values of EB occurred before and after the growing season (84>DOY>288) when all the fluxes were relatively small. Generally, the closure error was least early in the growing season and increased approximately 20% by the end of the season.

<u>Eddy covariance results</u>

ET seasonal trends corresponded with the expected trends in evaporative demand throughout the summer and usually were greatest in late June or early July. Fourier model coefficients and fitting statistics are given in Table 4 . The lower r^2 for PLC185 (Table 4) was

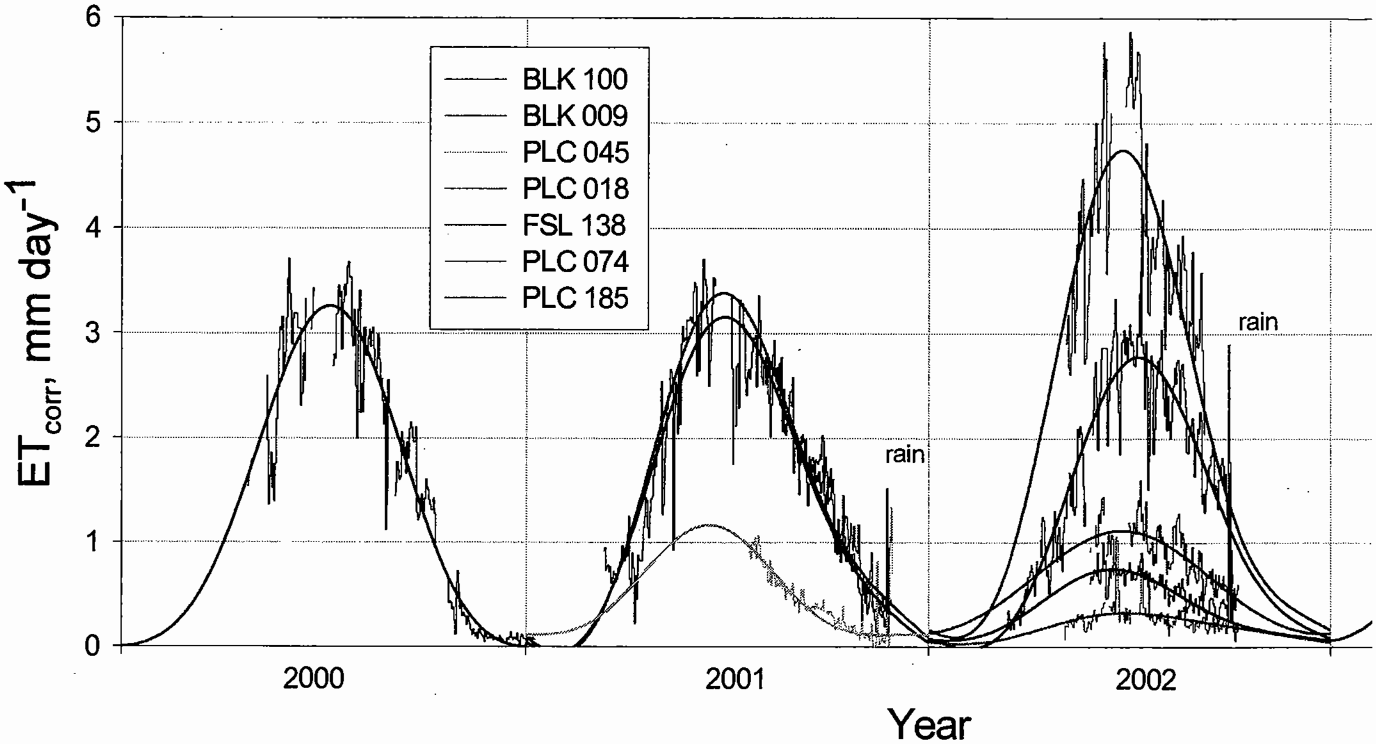

Figure 12. ET_{corr} and fitted Fourier models. for all sites and years See Table 4 for model statistics..

due in large part to the lower and relatively flatter seasonal ET trend (smaller variance). Inspection of Figure 12 suggests the agreement between the data and Fourier models was acceptable for the purpose of integration. ET_{corr} during the 2003 growing season ranged between 174 and 479 mm, and was substantially greater than measured in previous years at the same sites. As described above, water table depths were comparable in 2002 and 2003. Judging from reference ET (ET_r) as an indicator of the atmospheric demand, weather conditions were similar in 2002 and 2003 growing seasons. Cumulative ET_r was 1225 and 1160 mm suggesting that the higher ET_{corr} was not due to hotter or drier conditions and was probably caused by wetter soil conditions from greater winter precipitation. Interestingly, only PLC074 had substantially increased vegetation growth suggesting that at the other sites, the increase in ET_{corr} was through greater soil evaporation and/or increased stomatal conductance (transpiration per leaf area).

Comparison of EC and T_{Kc} results

Performance of the Kc models and vegetation measurements was evaluated to address three questions: 1) Did T_{Kc} approximate seasonal trends in ET measured by the EC stations? 2) Did the seasonal estimates of T_{Kc} compare favorably with measured seasonal totals? and 3) Did the LAI models for dominant species used to construct the Kc models agree with field measurements?

Daily values of ET measured by EC methods and corrected for the energy imbalance are presented in Figures 13 to 15 along with the daily T_{Kc} estimated using transpiration coefficients and LAI measurements. T_{Kc} underestimated measured growing season ET in 2003 at BLK100 and PLC185, but the two values agreed well at PLC074 (Table 5). Unlike BLK100, the correspondence between measured ET and T_{Kc} at PLC185 was fairly good for most of the year.

2/3 of data occurs within 6 mos

2/3x = 460 → 690 total ET for year 2000

Table 5. Eddy covariance ET corrected for energy balance closure and T estimated from Kc models and measured *LAI* and ETr_i. Vegetation measurements taken nearest the date of maximum LAI for the dominant species in Kc models were used (Table 9). ETcorr is the fitted Fourier model integrated for the growing season (March 25-October 15). 204 days

Year	Site	ET_{corr}	T_{Kc}	RMSE ⊥
		mm	mm	mm day^{-1}
2000	BLK 100	460	472	0.80
2001	BLK 100	446	384	0.66
	BLK 9	471	593	0.78
	PLC 45	165	266	0.53
2002	BLK 100	377	362	0.54
	FSL 138	646	414	1.27
	PLC 18	53	107	0.31
	PLC 74	177	147	0.42
	PLC 185	108	82	0.20
2003	BLK 100	526	313	0.93
	PLC 74	282	292	0.45
	PLC 185	205	121	0.47

⊥: RMSE calculated for daily measured ET_{corr} and T_{Kc}. RMSE = $[3(ET_{corr}\text{-model})^2/n]^{0.5}$

The poorest agreement was early in the growing season before about DOY 150 when E from moist soil near the surface and/or transpiration by the flush of short lived annuals probably contributed to ET that the Kc model ignores. The Kc model agreement with daily ET_{corr} was evaluated by calculating the root mean squared error (RMSE) between T_{Kc} and measured daily ET_{corr}. The root mean squared error (RMSE) of T_{Kc} model and measured daily ET ranged from 0.45 to 0.93 mm d^{-1} (Table 5) and was larger than in past years indicating relatively poorer performance of the Kc models in 2003.

A potential large source of error in the application of the Kc models is whether the trend in leaf area incorporated into the model adequately reproduces the field measurements. The LAI models for individual species in the Kc were extracted and compared with measured LAI.

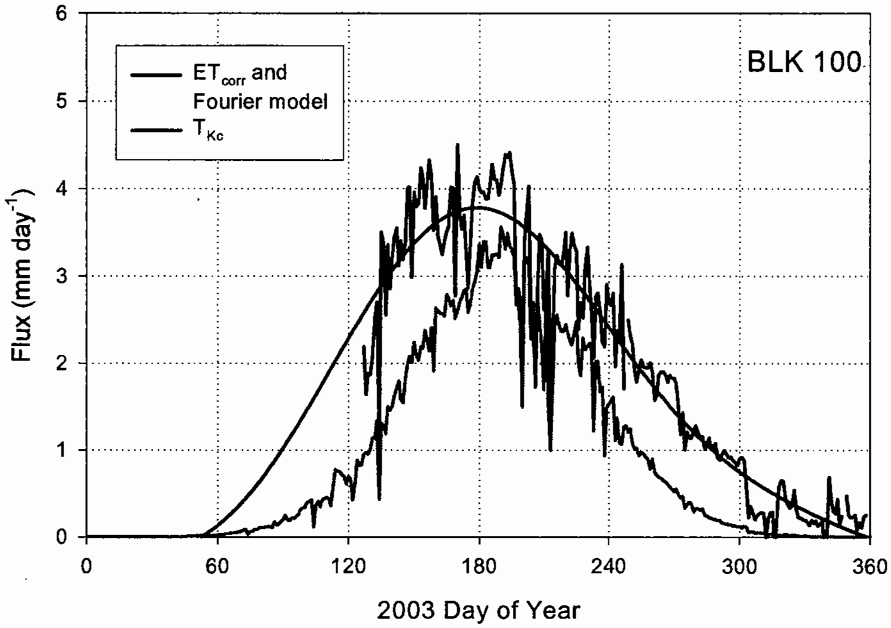

Figure 13. ET at BLK100 in 2003 measured with the EC system and estimated using field measurements and transpiration coefficients.

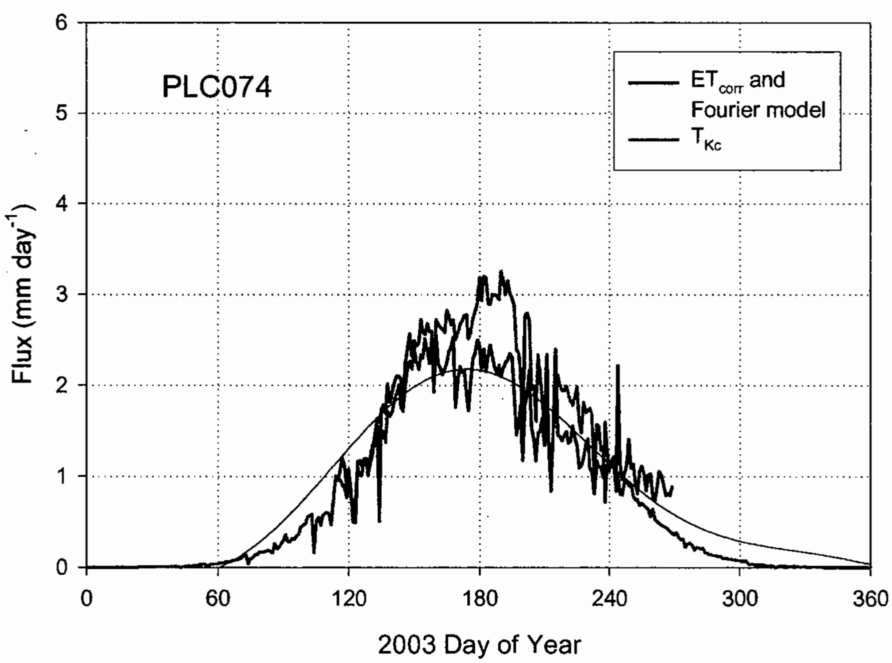

Figure 14. ET at PLC074 in 2003 measured with the EC system and estimated using field measurements and transpiration coefficients.

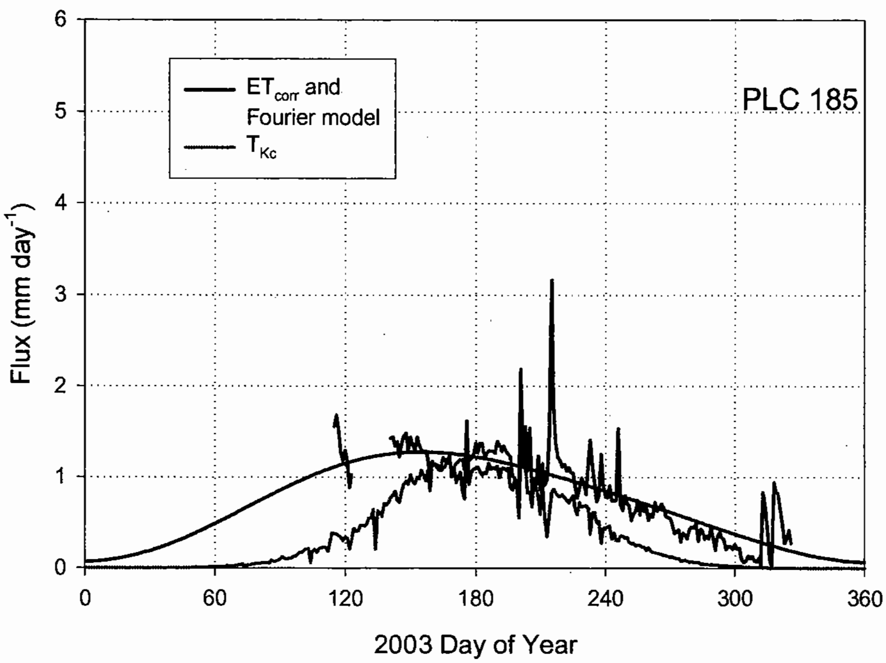

Figure 15. ET at PLC185 in 2003 measured with the EC system and estimated using field measurements and transpiration coefficients.

There was generally good correspondence between the observed and modeled LAI except for DISP2 at BLK100 (Figures 16-19). To be consistent with current management techniques, calculation of T_{Kc} requires a single vegetation measurement which in this case was chosen midway between the individual species peak LAI (DOY 195). The disadvantage of using a single measurement to adjust the LAI models for a mixture of species is most evident in Figure 16. At this site with a mixture of two dominant species with just slightly differing peak LAI on average, the correspondence of the LAI model and data could be improved considerably by relying on vegetation measurements collected on date(s) nearer the maximum for the dominant species.

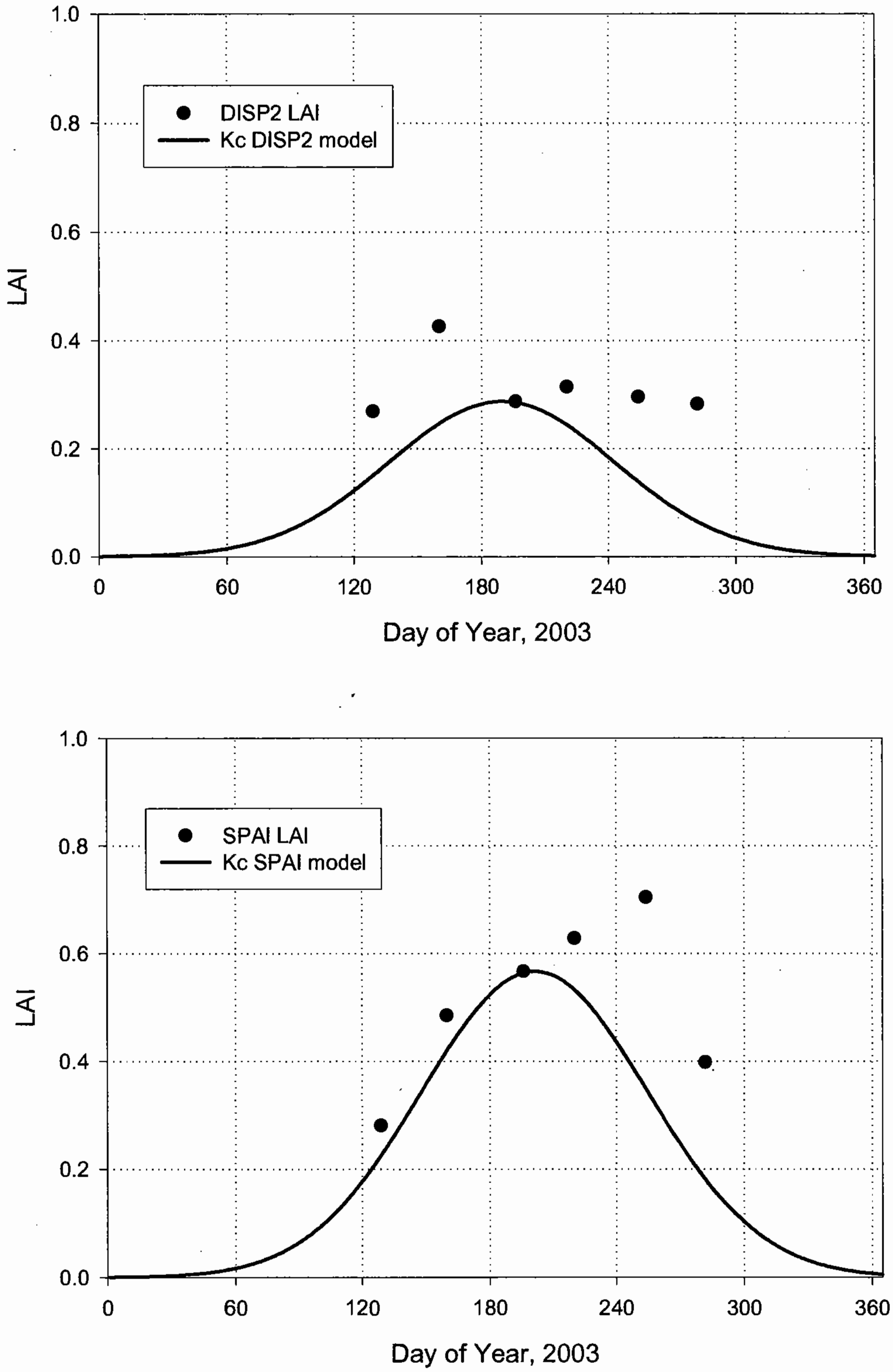

Figure 16. Measured LAI for dominant species at BLK100 in 2003 and LAI model in the Kc model scaled to the LAI used to calculate T_{Kc}. LAI is the mean of the four transects.

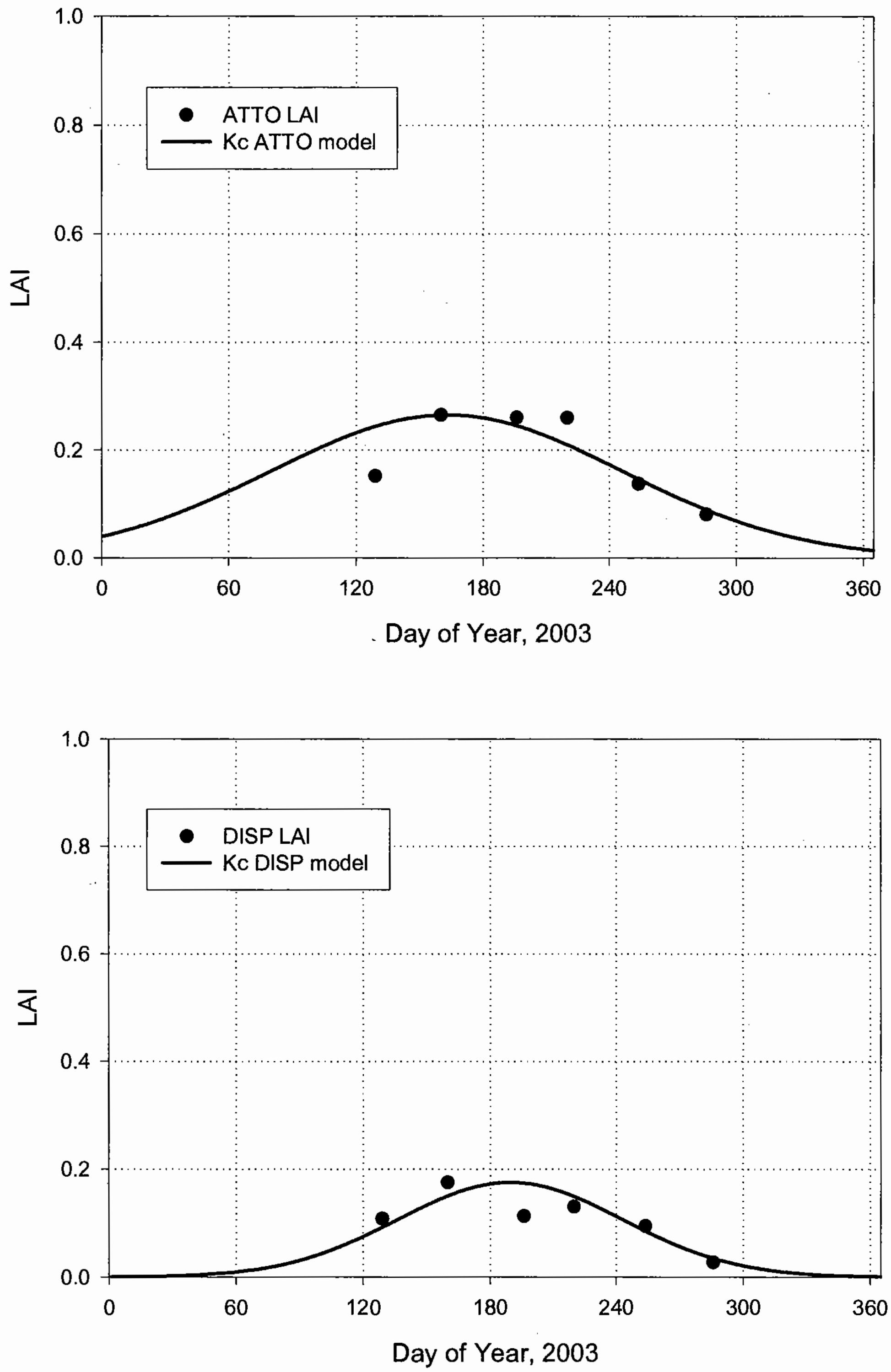

Figure 17. Measured LAI for dominant species at PLC074 in 2003 and LAI model in the Kc model scaled to the LAI used to calculate T_{Kc}. LAI is the mean of the four transects.

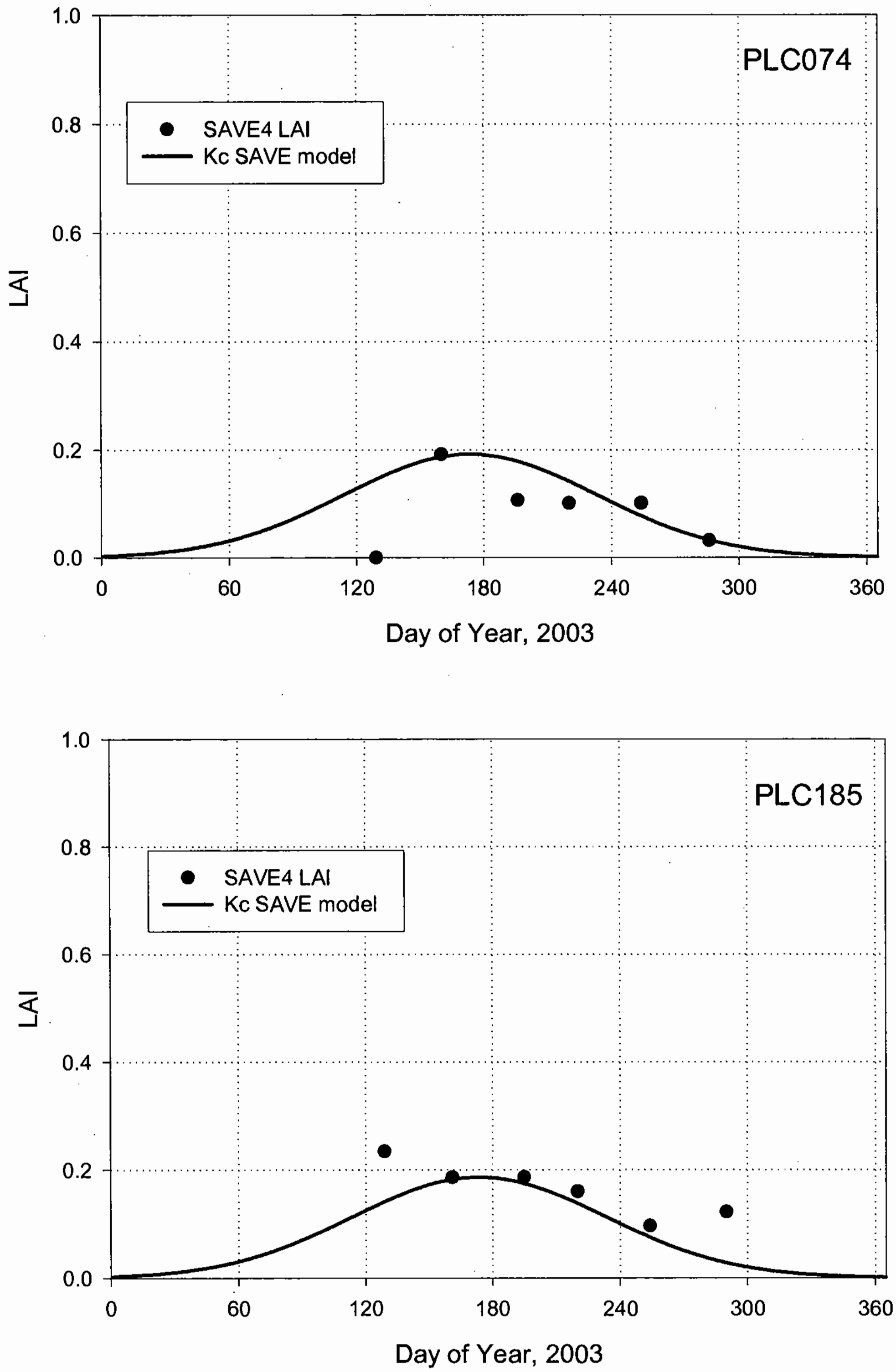

Figure 18. Measured LAI for SAVE4 s at PLC074 and PLC185 in 2003 and LAI model in the Kc model scaled to the LAI used to calculate T_{Kc}. LAI is the mean of the four transects.

Conclusions

ET monitoring at three sites monitored in 2002 continued in 2003. DTW conditions leading into the growing season were approximately the same each year, but the winter precipitation and stored soil water was much greater in 2003. Turbulent fluxes measured by the EC system in 2003 did not account for approximately one-third of the available energy requiring correction of ET flux to close the energy balance. Total ET corrected for the energy balance was measured by eddy covariance at seven sites with growing season totals ranging between 205 and 527 mm (ET_r was greater than 1500mm) exceeding the amounts measured at these sites in 2002 (and for BLK100 during 2000 and 2001). The increased seasonal ET was only accompanied by a sizeable increase in vegetation growth at one site, PLC074. The agreement between measured ET_{corr} and that predicted based on vegetation measurements was very good at this site, but at the two other sites, the agreement was relatively poor. As in past years, the reliance on a single LAI measurement to capture peak LAI for all species for the T_{Kc} determination was problematic.

III. Task 2: Vadose Zone model

Introduction

Phreatophytes are known to utilize groundwater, but quantifying the portion of ET during the growing season drawn from groundwater is difficult. Plant uptake (T) largely drives changes in stored soil water and possibly depth to water table in the absence of hydrologic manipulations. Understanding the partitioning of T between soil water and groundwater sources, therefore, is essential to prepare an accurate model of the vadose zone water balance for phreatophytes. Field experiments were conducted to provide an accounting of the depths and

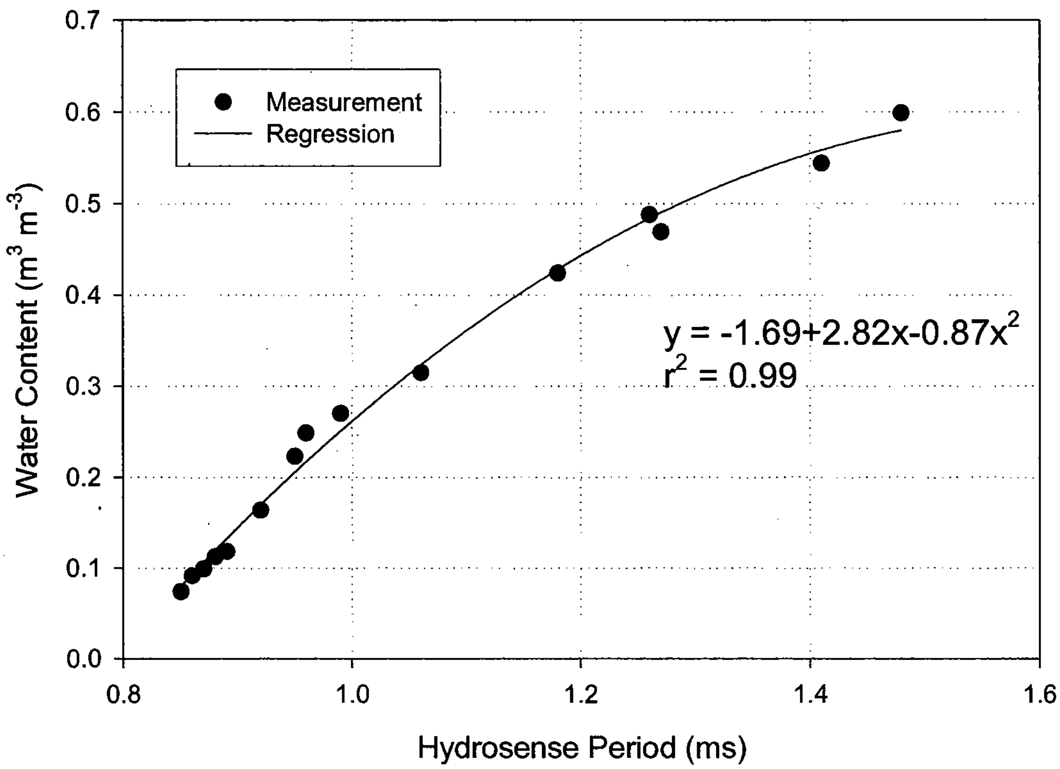

Figure 19. Hydrosense laboratory calibration for surface measurements at BLK100.

magnitudes of water uptake by plant roots at sites instrumented with EC stations. Revision of a previously constructed vadose zone model depended on the completion of the field investigation, but some changes to the model were completed and described in the final report. This section summarizes the additional data collected during the field investigation of the soil water balance components in 2003.

Materials and Methods

Site selection and instrumentation

Detailed measurements of soil water content were conducted using a combination of time

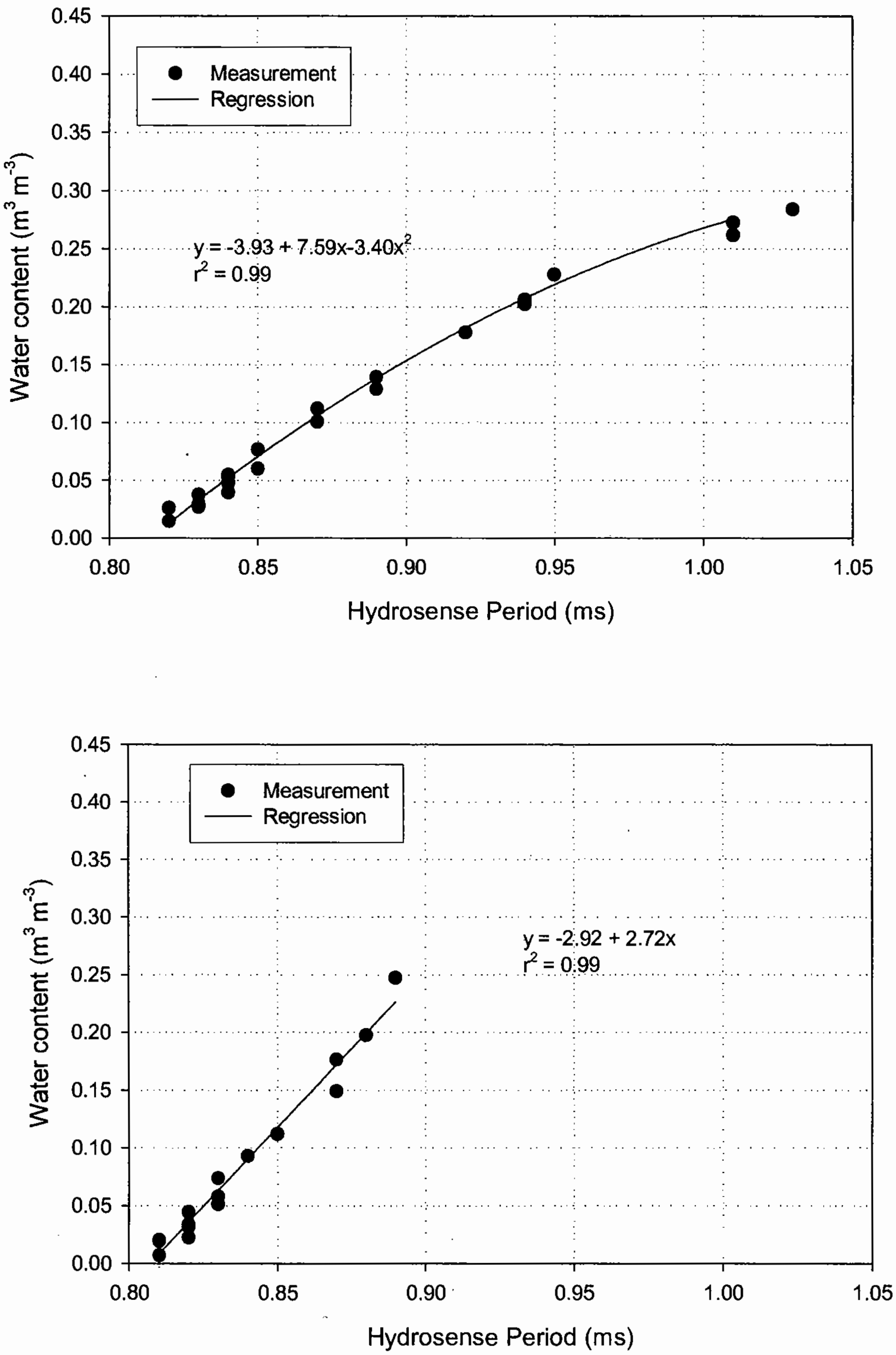

Figure 20. Hydrosense laboratory calibration for surface measurements at PLC074 and PLC185.

domain reflectometry (TDR), neutron probe, and gravimetric sampling. The site selection and instrumentation are described in Steinwand and Harrington (2003).

One change in 2003, was the adoption of TDR measurements of θ of the surface soil layer in conjunction with the gravimetric samples. Surface TDR measurements are less destructive and quicker than the gravimetric samples. Surface (0-12 cm) measurements were collected using a Hydrosense™ TDR system using site-specific calibrations prepared in the laboratory by gradual drying of soil with embedded TDR probes (Steinwand and Olsen, 2003). Linear or quadratic models were fit to data consisting of paired measurements of TDR period and volumetric soil water content (Figures 19 and 20). In the field, the instrument was most reliable at sites with dry sandy soils (PLC074, PLC185) and least reliable at BLK100 when the soil was moist probably due to soil salinity interference with interpretation of the TDR signal. Gravimetric samples were collected when the TDR failed.

Soil Water Balance (SWB) and Partitioning

This study determined the partitioning of ET between groundwater (ET_{gw}) and soil water (ET_{soil}) sources by measuring or estimating the water balance components and closure of the water balance as shown in Equation 3 and Figure 21,

$$\text{(i) } ET_{corr} = ET_{soil} + ET_{gw}, \quad \text{(ii) } ET_{soil} = P + \Delta S, \quad \text{(iii) } ET_{gw} = E_{gw} + T_{gw} \qquad (3)$$

$$\text{(iv) } T_{gw} = ETa - E_{gw} - P - \Delta S$$

where ET_{corr} is the fitted Fourier model integrated between the beginning and end of the growing season , ΔS is change in soil water storage, P is precipitation, and T_{gw} and E_{gw} are transpiration and evaporation derived from groundwater, respectively. Runon, runoff, and deep percolation of

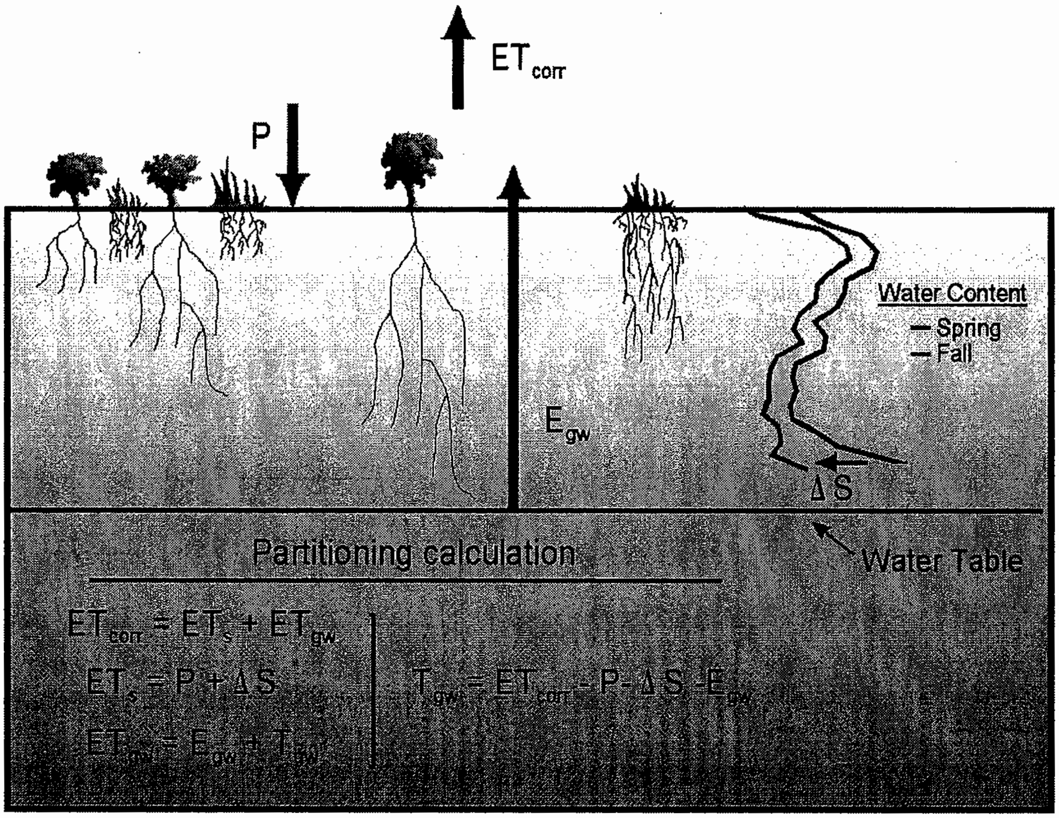

Figure 21: Partitioning of ET_{corr} into soil (s subscript) and groundwater (gw subscript) components. E is evaporation, T is transpiration, P is precipitation, and ΔS is maximum depletion of stored soil water. Red arrows water balance components measured or estimated in this study.

precipitation were negligible. Partitioning calculations were made for the growing season (March 25 to October 15) because of vegetation phenology and availability of field ET measurements. This period encompassed the majority of annual ET because vegetation is senesced during the winter. The reference depth for this calculation is the high water stand in the spring at the beginning of the growing season. Water made available by declining water table (thickening vadose zone) and flux upward from the water table into the vadose zone during the growing season were considered groundwater. Determination of each component of the water balance is described in the sections below.

ET_{corr}, Actual ET. ET_{corr} was the derived by summing the daily ET_{corr} values of the Fourier model between DOY 84 and DOY 288. Please refer to Section II for a description of the EC methods and model fitting.

E_{gw}, Evaporation from Water Table. Under the arid conditions of Owens Valley, with relatively fine-textured soils in some of the sites, and in the presence of relatively shallow water table (<2 m) this component of the water balance cannot be discounted in the seasonal water balance calculation. Availability of continuous eddy covariance measurements allowed us to estimate the magnitude of direct evaporation through the soil at night when plants were not actively transpiring. E_{gw} was determined by summing nighttime ET_{corr}. Days with missing EC data were assigned the mean nighttime ET_{corr}. This method provided an acceptable and conservative (high) value for E_{gw}. estimate because it discounts soil E and leakage through plant stomata. Nighttime E values were a small component of the water balance and were consistent with theoretical estimates of maximum flux from the water table (Steinwand and Harrington, 2003) so there was no advantage to refine this value further. Note that the values of E_{gw} for all years were revised slightly since the final report was prepared to correct summation errors.

ΔS, Change in Stored Soil Water. Methods for neutron and gravimetric soil water measurements are described in Section II. Soil water stored in the soil (S) (cm/soil depth) was calculated according to,

$$S_{tube} = \sum \theta_i \Delta z_i \qquad (4)$$

where θ_i is volumetric water content depth i and Δz_i is the thickness of the soil interval represented by θ_i. The storage calculation was calculated for the entire monitoring depth which was at the top of the water table high stand in the spring, and it represents the uptake of water banked in the vadose zone. The change in soil water was taken as the maximum change observed between a measurement in the spring when S is greatest and a measurement in the late summer or fall when S was smallest. Stored soil water varied among the tubes monitored due to differing soil properties, DTW (topography), and vegetation density, but the change in S over the growing season varied little between measurement locations (Figures 22-24).

P, Precipitation. Precipitation was measured after each event by Inyo County or daily by the National Oceanic and Atmospheric Administration at the Bishop airport. Rain gauges assigned to the sites were: Inyo County RG-6: BLK100; Bishop Airport NOAA: PLC074; Inyo County RG-3: PLC185. Equation 3 assumed that all summer P is utilized by vegetation. This assumption was inaccurate as some P evaporates directly back into the atmosphere and contributes to ET_{corr}. This will have no effect on calculation of T_{gw} because the fraction of P contributing directly to ET_{corr} would be subtracted from variables on the same side of the equation (Equation 3iv). Double counting of P that infiltrated into the soil was avoided by defining S as the difference between measurements early and late in the growing season and ignoring precipitation driven increases in S during the summer.

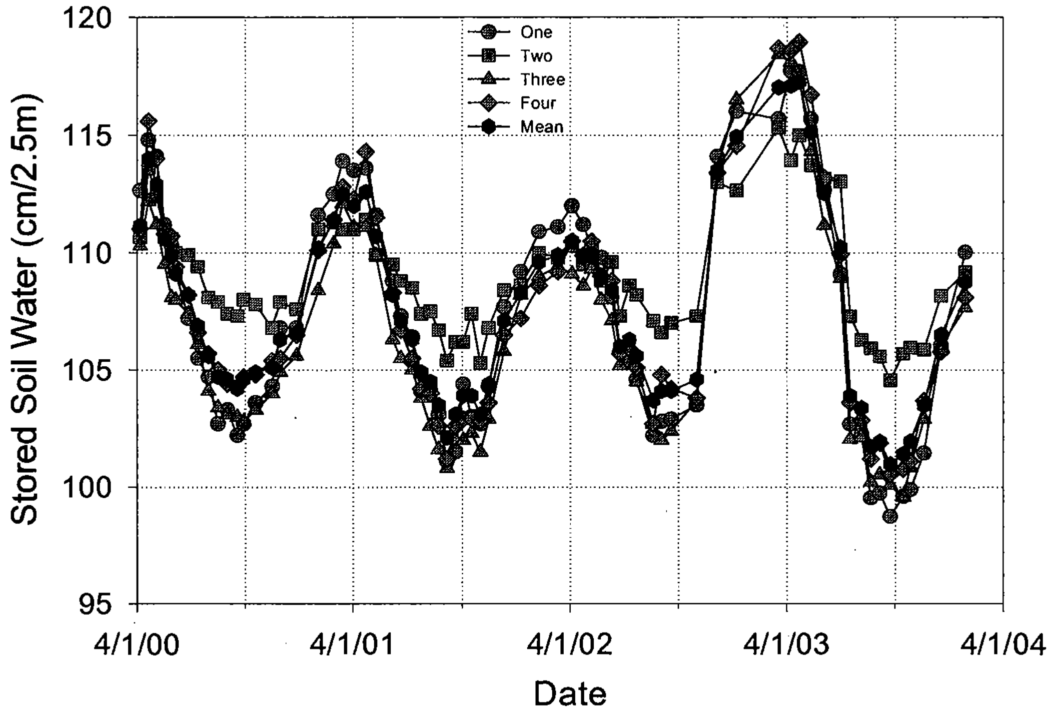

Figure 22. Time series of mean stored soil water (S) and at the four locations at BLK100.

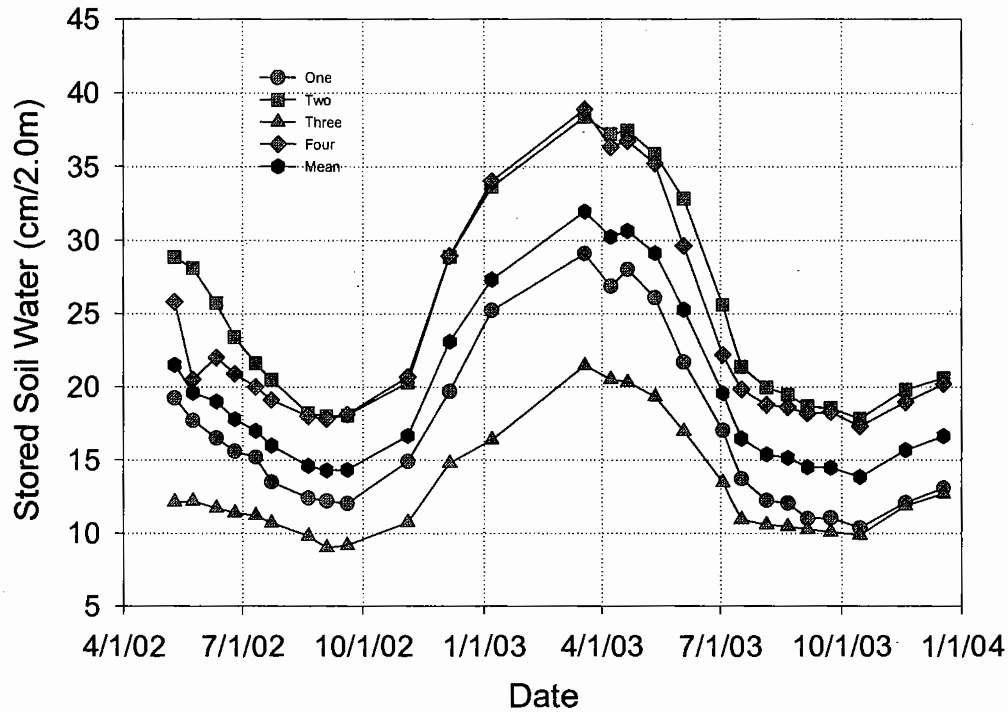

Figure 23. Time series of mean stored soil water (S) and at the four locations at PLC074.

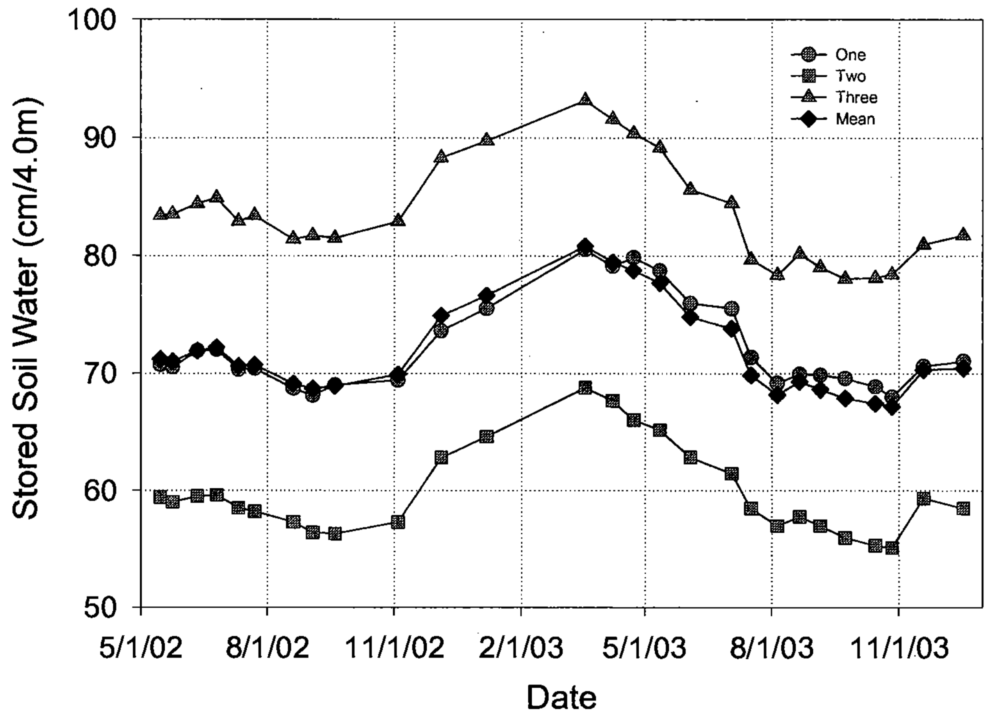

Figure 24. Time series of mean stored soil water (S) and at the three locations at PLC185.

Table 6: Soil water balance components and calculation of T_{gw} for EC sites. The values represent growing season totals (March 25 to October 15).

Year	Site	T_{gw}	ET_{corr}	P	)S_{max}	E_{gw}	T_{gw}/ET_{corr}
		(mm)	(mm)	(mm)	(mm)	(mm)	
2000	BLK 100	339	460	11	99	11	0.74
2001	BLK 100	315	446	15	104	12	0.71
	BLK 9	316	471	15	131	9	0.67
	PLC 45	93	165⊥	35	34	3	0.56
2002	BLK 100	300	377	1	68	8	0.80
	FSL 138	520	646	2	97	27	0.81
	PLC 18	11	53	3	37⊥⊥	2	0.21
	PLC 74	100	177	3	72	2	0.57
	PLC 185	36	108	3	69⊥⊥	0	0.33
2003	BLK 100	318	527	38	163	8	0.60
	PLC 74	98	282	5	177	2	0.35
	PLC 185	51	205	17	134	3	0.25

⊥: This value is exaggerated because of the poor correspondence with actual ET trends and shape of the Fourier model (see Steinwand and Harrington, 2003).

⊥⊥:Initial soil water measurement was 1 month into growing season and soil was near limiting suggesting maximum was $^{H}_{7}S_{max}$ underestimated. $^{H}_{7}S_{max}$ determined by adding winter precipitation depleted before first S measurement: PLC18, 35mm+2mm, PLC185, 35mm+34mm.

Results and Discussion

All components of the seasonal soil water balance are given in Table 6. Data for all sites and years are included in the table to allow comparison with 2003 results. The portion of T derived from the water table was estimated from the water balance as the difference between ET_{corr}, soil water depletion, precipitation, and evaporation. The component of E derived from the water table was a negligible fraction of the SWB for all sites. Summer P was slightly greater in 2003 than in previous years but was still a small component of the water balance. Direct uptake from groundwater (T_{gw}) accounted for 66 to 80% of ET_{corr} for sites with water table depths of 1 to 3 m except for PLC074 in 2003. At sites monitored more than one year, the amount of groundwater uptake was relatively constant even though total ET varied annually probably reflecting the similar water table conditions each year.

Determination of T_{gw} as the residual in the SWB lumps error for each component into the estimate. Because of this uncertainty, it was important to compare the results with an independent estimate of T_{gw}. We examined the relationship between plant water uptake and water table fluctuations to establish independent support for the values of T_{gw} derived from water balance closure. A key step to establishing that plants indeed drive the observed fluctuations in water table depth, was to measure water table depth at high temporal resolution and differentiate between behavior during the day when plants transpire and during nighttime when T is substantially reduced. Results of high temporal water table depth measurement at BLK100 and PLC074 are depicted in Figures 25 and 26. In contrast to a relatively constant water table drawdown during the day when plants were transpiring, during the night, there was practically no drawdown.

Daily water table drawdown and concurrent related ET_{corr} results are summarized in Table 7. Assuming that the entire drawdown was driven by ET_{corr} (primarily plant transpiration) that was independently measured by the EC station, we estimated an effective yield (S_y) for the site by taking the ratio of daily ET to daily water table drawdown (r),

$$S_y = \frac{ET}{r} \tag{4}$$

The average value of specific yield for BLK100 (DOY 177-230) was 0.46, nearly identical to the value of 0.47 determined from the shorter record presented in the final report. After about DOY

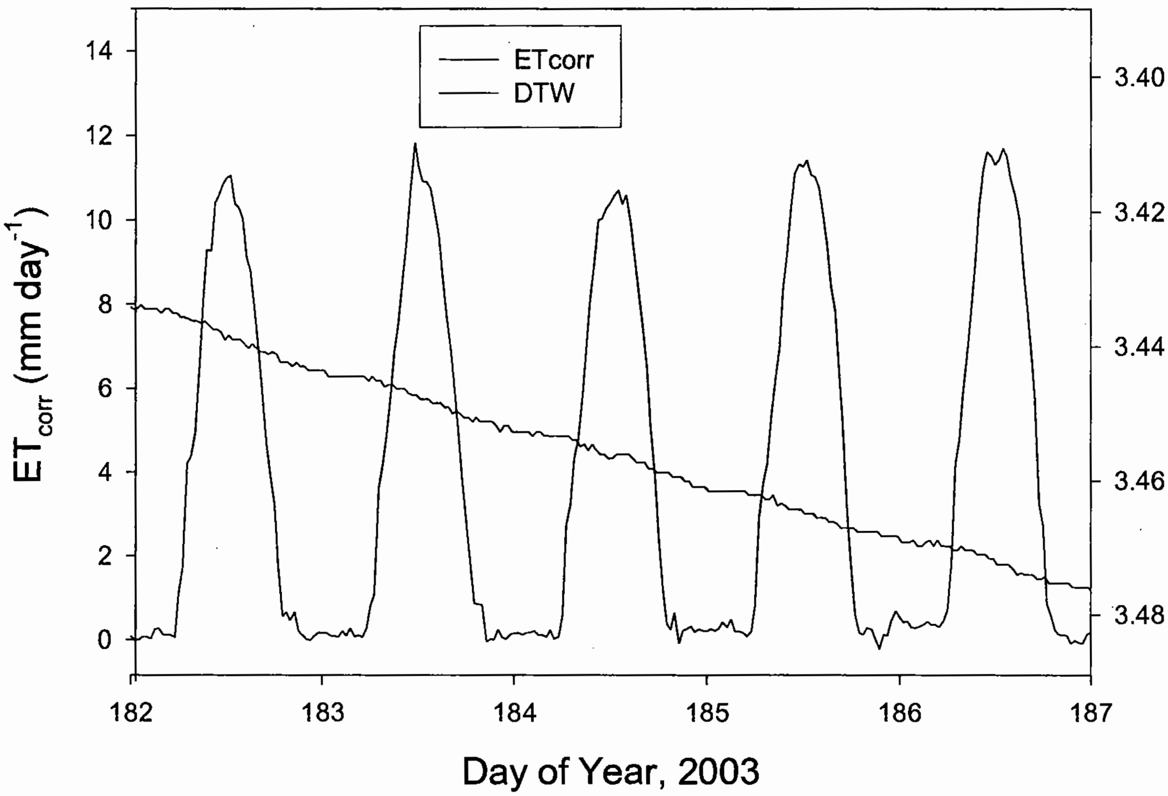

Figure 25. Diurnal fluctuations in water table depth (DTW) near BLK100. Notice a reduction in drawdown rate (smaller slope) during nighttime.

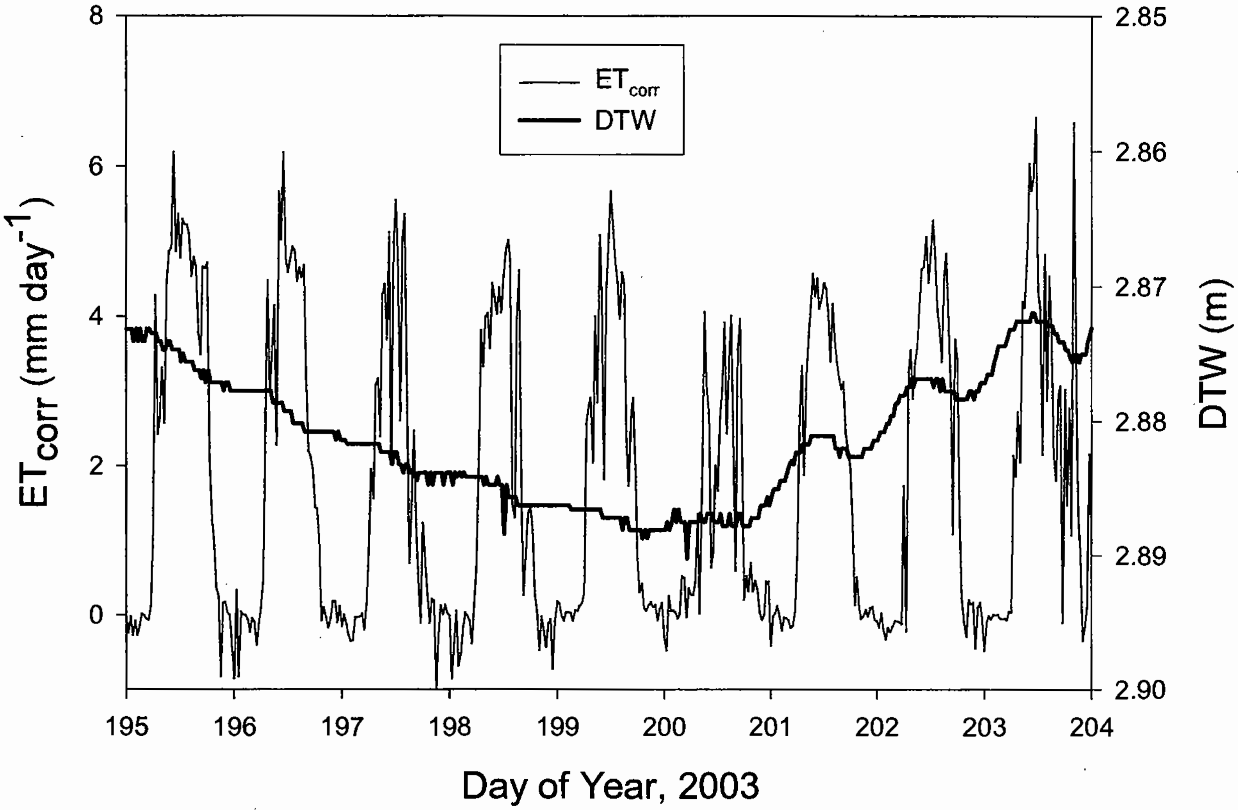

Figure 26. Diurnal fluctuations in DTW near PLC074. Notice a reduction in drawdown rate (smaller slope) during nighttime for DOY 195-199 reflecting the predominance of ET driven change in DTW. DOY 201-204 is a period of rising water table locally due to nearby irrigation, but plant uptake is still evident in the DTW signal.

Table 7. Measured diurnal changes in water table depths, daily ET (eddy covariance method), and estimated specific yield for BLK 100 during summer of 2003 (Specific yield is estimated assuming ET was a result of uptake from water table only).

Site	Day of Year	Diurnal decline in DTW (mm)	Daily ET_{corr} (mm)	Specific yield (-)
BLK100	177	6.10	3.82	0.63
	178	8.23	4.07	0.49
	179	8.23	4.13	0.50
	180	9.20	4.00	0.44
	181	9.45	3.96	0.42
	182	9.15	3.96	0.43
	183	9.15	3.89	0.43
	184	8.84	3.89	0.44
	185	7.62	4.04	0.53
	186	7.62	4.28	0.56
	187	8.23	4.11	0.50
	188	8.23	4.10	0.50
	189	10.1	3.93	0.39
	190	6.40	4.04	0.63
	191	6.71	4.24	0.63
	192	8.23	4.39	0.53
	193	10.37	4.36	0.42
	194	8.84	4.41	0.50
	195	9.15	4.20	0.46
	196	8.84	4.05	0.46
	197	9.45	2.67	0.28
	198	7.32	2.86	0.39
	199	8.54	2.75	0.32
	200	7.32	1.83	0.25
	201	7.62	3.42	0.45
	202	8.23	3.74	0.45
	203	10.37	4.03	0.39
	204	7.01	2.57	0.37
	205	8.23	2.70	0.33
	206	6.71	1.73	0.33
	207	8.23	2.85	0.35

Site	Day of Year	Diurnal decline in DTW (mm)	Daily ET_{corr} (mm)	Specific yield (-)
BLK100	208	8.23	3.47	0.42
	209	5.49	3.42	0.62
	210	4.88	2.62	0.54
	211	8.23	2.81	0.34
	212	0.61	NA	missing EC data
	213	0.00	1.51	rain
	214	4.88	2.36	0.48
	215	7.62	3.11	0.41
	216	6.71	3.23	0.48
	217	6.10	3.15	0.52
	218	8.54	3.13	0.37
	219	6.10	3.24	0.53
	220	5.18	3.50	0.68
	221	7.01	2.77	0.40
	222	6.10	3.28	0.54
	223	4.88	3.49	0.71
	224	10.37	3.35	0.32
	225	7.62	3.29	0.43
	226	4.57	2.39	0.52
	227	6.40	2.69	0.42
	228	6.10	2.52	0.41
	229	5.49	3.10	0.56
	230	8.23	3.33	0.40
			mean	**0.46**
PLC074	193	3.66	2.29	0.62
	194	3.05	2.35	0.77
	195	4.57	2.31	0.50
	196	3.66	1.90	0.52
	197	2.44	1.46	0.60
	198	2.44	1.56	0.64
	208†	3.35	1.49	0.45
	209	3.96	1.64	0.41
	210	5.18	1.34	0.26

Site	Day of Year	Diurnal decline in DTW (mm)	Daily ET_{corr} (mm)	Specific yield (-)
PLC074	211	7.31	1.58	0.22
	212	2.43	1.34	0.55
	216	1.83	1.45	0.79
	217	3.05	1.44	0.47
	227	2.43	1.11	0.46
	228	4.27	1.20	0.28
	229	3.65	1.35	0.37
	230	3.05	1.41	0.46
	234	1.52	1.70	0.77
	235	3.05	1.10	0.36
	236	1.80	1.11	0.61
	237	2.13	0.99	0.46
	240	2.44	1.06	0.44
	241	3.05	1.16	0.38
	242	2.44	1.10	0.45
	243	2.13	0.90	0.42
	245	2.13	1.13	0.53
	246	1.22	0.96	0.79
			mean	**0.50**

†: Gaps in sequence represent periods of rising water table due to irrigation of neighboring pastures

230 the water table could have been affected by groundwater pumping violating the assumptions in Equation 4, and calculated S_y were not used in the average. DTW at PLC074 was affected by regional water table fluctuations as well as ET and increased slightly during five periods over the summer. Note that the impact of transpiration on the water table is still evident during periods when the water table was rising (Figure 26). In that situation, the application of Equation 4 is still valid but drawdown would have to include subtraction of the rising background trend instead of relying on the simple difference in daily DTW. For simplicity, this additional procedure

Table 8. Groundwater uptake estimated from SWB and from seasonal change in depth to water table and average specific yield. Note that the values of SWB T_{gw} determined from the water balance were adjusted to match the time period for corresponding minimum and maximum DTW.

Year	Site	DOY	DTW range	est. ET_{gw}†	est. T_{gw}†	SWB T_{gw}⊥⊥
			m	mm	mm	mm
2001	BLK 100	93 to 263	2.17-3.02	400	284	290
2002	BLK 100	95 to 268	2.25-3.12	409	327	276
	PLC 74	112 to 246	2.09-3.31	573	60	70
2003	BLK 100	98 to270	2.15-2.36	105	343	294
	PLC 74	98 to 300	2.07-2.44	185	65	91

⊥: estimated based on S_y and measured water table fluctuations.

⊥⊥: T_{gw} calculated from soil water balance (Equation 3) for the specified time period.

wasn't completed and average S_y was based only on days with declining water levels during the day and relatively constant water level at night. The average S_y for PLC074 was 0.50.

These values of S_y are considerably higher than expected for a profile under hydrostatic conditions. Freeze and Cherry (1979) suggested that the specific yield for unsaturated soil profiles with fluctuating shallow water table should be less than the drainable porosity for the soil, and could be estimated from a soil water characteristic curve. The primary flaw with this argument is that in the presence of plant uptake the soil profile is far from the quasi-equilibrium state expected for gravity drainage of a hydrostatic profile. Instead, the processes can be viewed as direct uptake that creates a propagating drying front induced by plant roots.

Extrapolating for the period between high and low DTW measurements, seasonal plant water uptake was estimated using Equation 4 and the mean S_y for BLK100 and PLC074. This method was not tested for PLC185 because of the absence of DTW monitoring. At BLK100, the calculated seasonal ET from DTW fluctuations and average S_y ranged between 400mm and

573mm (Table 8). For PLC074, ET_{gw} estimated from water table change was 105mm and 185mm in 2002 and 2003 respectively. Ideally, T_{gw} should be used in place of ET in Equation 4, cannot be determined on a daily basis using the frequency of field measurements in this study. As a result, the quantity of ET calculated from seasonal water table fluctuations include E and T_{soil} and should overestimate T_{gw} by ~0.65 to 0.80 at BLK100 and ~0.33 and 0.57 at PLC074 (Table 6) if the T_{gw} estimates from the SWB are accurate. Given the similarity of the values of T_{gw} in Table 8 and the imprecision of the unrelated methods, we concluded that SWB estimates of T_{gw} were reliable for these shallow water table sites.

Analysis of the water balance closure quantified the contribution to ET_{corr} from the water table when the root zone and the water table were "coupled". Groundwater pumping may lower the water table and decouple the water table from the root zone. Under such conditions, it would be expected that the contribution from the water table would decrease and reliance on stored soil water would increase (and/or T would decrease). Thus, modeling the soil water balance also requires an expression to reduce T_{gw} as the water table declines.

The vadose model and groundwater models currently contain a function to account for water table uptake as a function of DTW, but it is related to assumed rooting depth and not well quantified. This study did not artificially lower the water table during the growing season preventing direct observation of this process. The study sites, however, spanned a range of water table and vegetation conditions including coupled and decoupled sites. Simple inspection suggested that T_{gw} was related to LAI and/or DTW (the latter are weakly correlated for this set of locations). The relationship between T_{gw}, LAI, and DTW is presented in Figure 27. Normalizing T_{gw} by peak LAI accounted for inherent site differences in plant community due to other edaphic

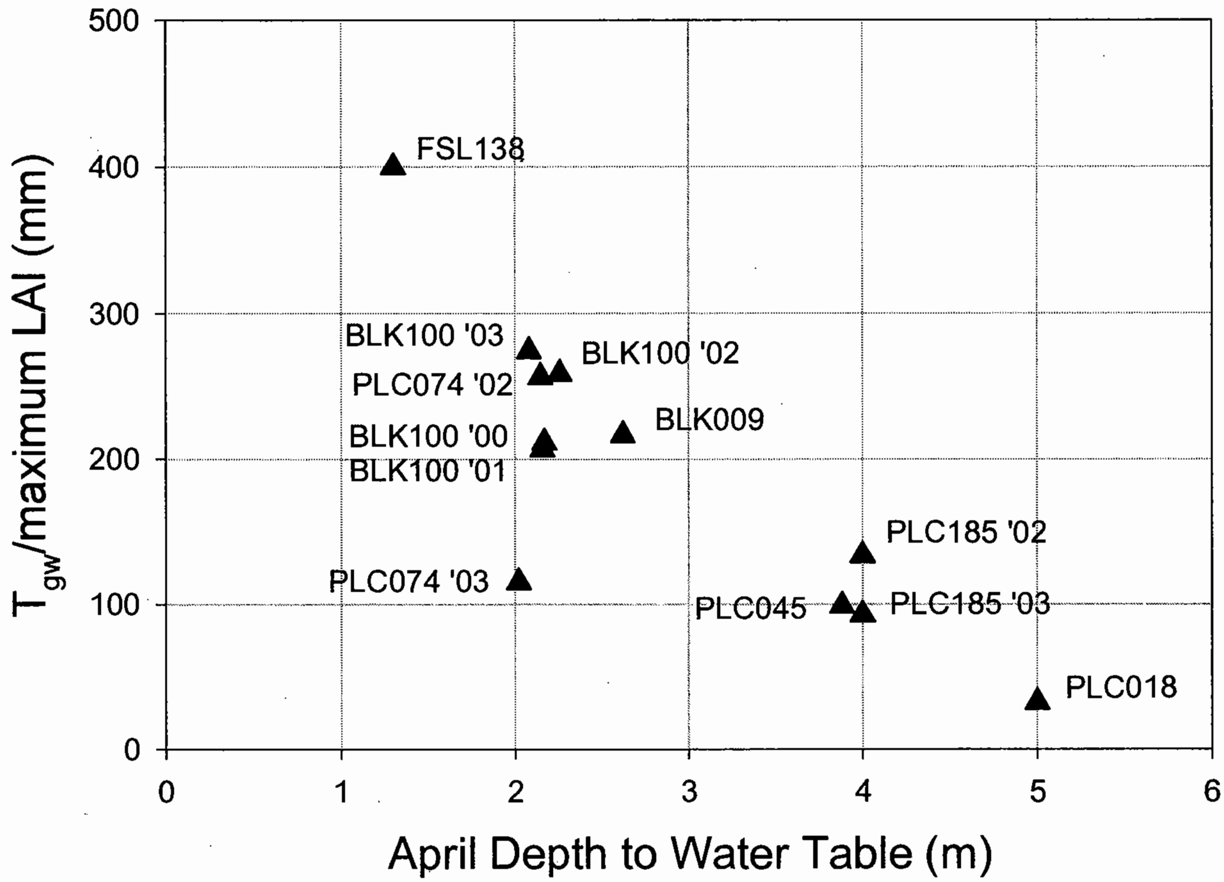

Figure 27. T_{gw} scaled by maximum LAI as a function of DTW. DTW values for PLC018 is an estimate and could be deeper (i.e. >5.0m). DTW for PLC185 was determined at the time of access tube installation. Note that PLC074 in 2003 did not fall on the same trend as all other sites/years.

factors or stress induced reduction in leaf area. The amount of groundwater as a function of LAI and DTW followed a well defined trend except for PLC074 in 2003. It is difficult to generalize from a single result but the function may not apply at some sites where the vegetation leaf area shows substantial response to precipitation. Depending on the method to derive ET estimates (if based on LAI for example) this function may be able to accommodate the groundwater uptake for coupled sites and for sites affected by pumping. Further experimentation with the vadose zone model is necessary to determine if this function is applicable to reformulate the pertinent model parameters.

Conclusions

Total ET following the much wetter winter in 2003 was greater than previous years , but the absolute quantity of groundwater used for transpiration was nearly the same in both years. At most sites with shallow water tables, 60-80 % of the ET_{corr} was derived from the water table directly and is not reflected in changes is soil water content. Detailed observations of diurnal ET and DTW were utilized to derive estimates of groundwater uptake to compare with those derived from the SWB. The two independent approaches gave similar values suggesting detailed observation of water levels could potentially give "real time" qualitative assessment of whether plant roots were tapping groundwater and quantitatively could be used to estimate ET once the specific yield is estimated. Quantifying T_{gw} also has direct bearing on the parameterization of the vadose zone water balance model and groundwater model, and a function relating T_{gw}, LAI and DTW was prepared to guide future conceptualization of the models.

V. References

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