

# HYDROLOGICAL EFFECTS AND GROUNDWATER FLUCTUATIONS IN INTERDUNAL ENVIRONMENTS IN THE NEBRASKA SANDHILLS

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**ABSTRACT**—Nine years of groundwater monitoring data has documented the important influence that topographic relief and location in the groundwater flow system have on the hydrologic function of interdunal valleys. The western “wet” valley at the Gudmundsen Sandhills Laboratory in central Nebraska, which is a net discharge area, is more strongly buffered from the effects of annual-scale climatic variability than the eastern “dry” valley. The east valley is generally an area of net recharge and as such is more responsive to climatic variability. This study employed a simple water balance approach to estimate evapotranspiration (ET) from water level measurements in the west valley for four specific time intervals in 1998-99 that included growing and senescence periods. The estimates of ET ranged between 5-6 mm/day in the mid-growing season and 2-3 mm/day during the period of senescence.

**Key Words:** evapotranspiration, groundwater fluctuation, interdunal valleys, Nebraska Sandhills

## INTRODUCTION

The dynamic interaction between sand, water, and vegetation over the last several thousand years has created one of the largest grass-stabilized dune regions in the world, the Nebraska Sandhills. The Sandhills region covers nearly 58,000 km<sup>2</sup>. The region has many characteristics that are similar to other sandy grassland landscapes across the globe, including the Pantanal of Brazil and the Kiskunság of Hungary. Critical components of the Sandhills landscape are the interdunal environments that exist between uplands composed of grass-stabilized sand dunes. The interdunal areas can have remarkably different hydrologic characteristics over relatively short distances depending on the regional and local geomorphology (Gosselin et al. 1994, 1999).

The water-dominated interdunal environments include an estimated 450 km<sup>2</sup> of open water (shallow lakes and ponds), 260 km<sup>2</sup> of marsh, and 4,000 km<sup>2</sup> of subirrigated wet meadows (Rundquist 1983). According to Timer (2003), these water-dominated environments represent one type of geographically isolated wetlands that are surrounded by uplands at the local scale, yet are

hydrologically connected to the groundwater system. Because of the wetland environments, the Sandhills are the second most productive waterfowl region in the United States (Labeledz 1990). The wet meadows are the primary source of hay for a cattle industry that produces a third of the beef cattle in Nebraska. These wetland environments are very important to the ecologic and economic viability of the Sandhills.

To begin to address management questions related to the viability of these areas, a monitoring well network was established in two interdunal valleys at the Gudmundsen Sandhills Research Laboratory (GSRL) in 1994 (Fig. 1; Gosselin et al. 1999). These valleys represent two of the major types of interdunal environments: dry, shortgrass valleys and subirrigated wet meadows. The subirrigated wet meadow (also known as “west valley”) is a groundwater discharge area, toward which groundwater flows from the north and south, and which has seasonally sustained, upward vertical gradients. In contrast, groundwater flow beneath the dry, shortgrass valley (also known as the “east valley”) is from west-southwest to east-northeast toward

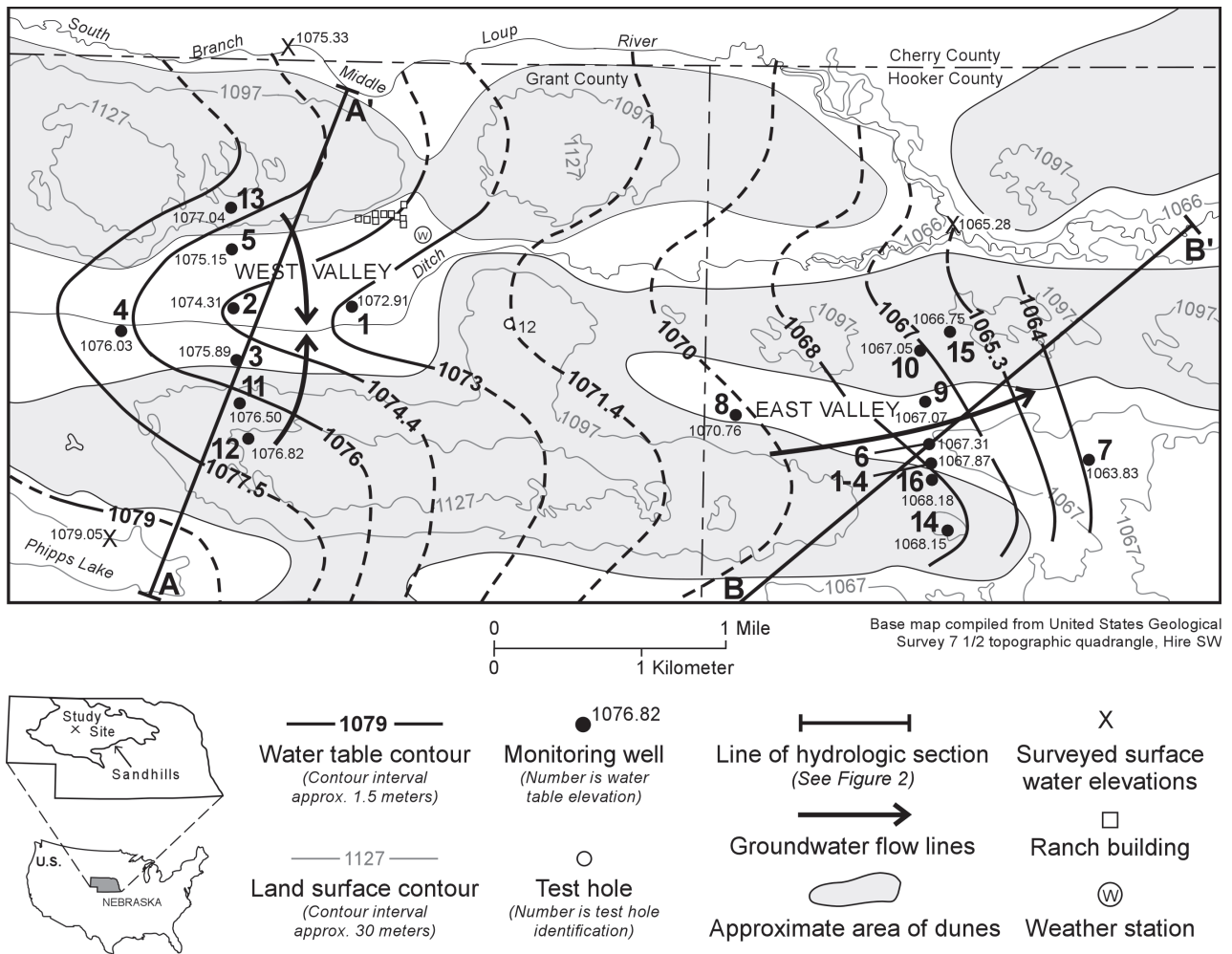


Figure 1. The study area at the Gudmundsen Sandhills Research Laboratory (GSRL), showing water table contour (dark), land surface elevation (gray), and monitoring wells and test holes. Groundwater elevations for wells and Phipps Lake were measured September 26, 1996. Elevations for the river were measured May 30, 1997.

the south branch of the Middle Loup River. When vertical gradients exist, they are downward. The dry valley is interpreted to be a “recharge” and “flow-through” valley.

Groundwater fluctuations appear to be intimately related to spatial and temporal variations in evapotranspiration and to the duration, magnitude, and timing of precipitation, especially in the wet meadow (Gosselin et al. 1999). Our working hypothesis is that groundwater fluctuations are linked strongly to evapotranspiration in the wet valley, and these fluctuations can be used to estimate it. In this paper, we use groundwater fluctuations to estimate seasonal variations in ET in the subirrigated wet meadow. In addition, we highlight the response of groundwater in the two different valleys to short-term climate conditions.

**SETTING**

To examine this hypothesis, we used the monitoring network at GSRL, a 52 km<sup>2</sup> multidisciplinary research facility and cattle ranch in the central Sandhills of Nebraska. In this part of the Sandhills, dunes are up to 122 m high, form linear arrays trending generally east-west, and occur as intermediate- to closely spaced crescentic barchan dunes. The dunes are now inactive, stabilized by grasses. Holocene eolian sands were deposited on Quaternary and/or Pliocene alluvial sand and silts that overlay the Tertiary Ogallala and White River groups (Loope et al. 1995; Loope and Swinehart 2000). The total saturated thickness of this part of the northern High Plains aquifer in the Sandhills exceeds 300 m in some places (CSD 1986).

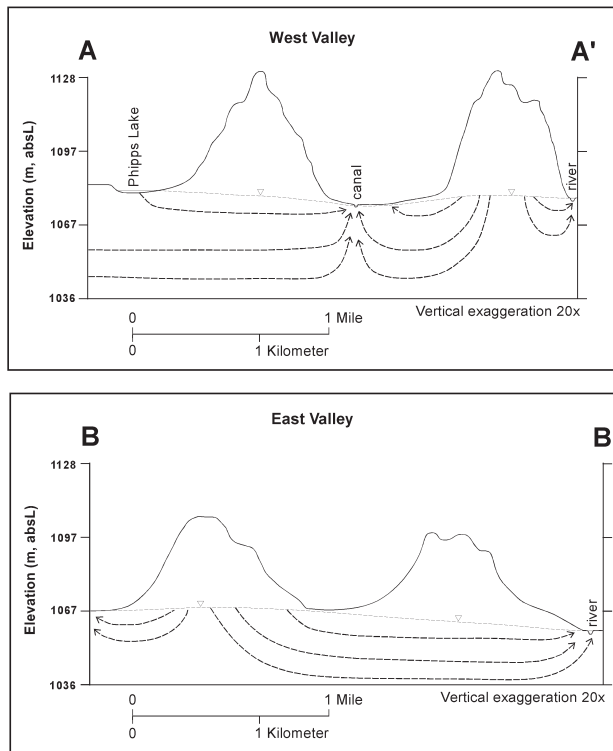


Figure 2. Schematic hydrologic sections showing dune and general groundwater configuration and flow paths of the east and west valley transects at the Gudmundsen Sandhills Research Laboratory. Inverted triangle above dashed line represents the approximate location of the water table. Locations of lines A-A' and B-B' shown on Figure 1.

### West Valley

The dunes flanking the west valley are higher (68 m above the valley floor) and have steeper slopes than those in the east valley. The floor of the west valley is a broad, flat subirrigated wet meadow, densely covered with predominantly emergent wetland grasses and alfalfa used for hay production. To minimize the impact of high water levels on the harvesting of hay from this valley, a drainage ditch trending east to west was installed in the 1930s. Both the valley and the ditch extend westward for another 5 km. Although the ditch has been constructed, its flow pattern is similar to other natural streams in the region. The discharge of the ditch is estimated to be approximately one-tenth of the amount lost to ET in the valley (Gosselin et al. 1999).

Figure 2 includes schematic hydrologic sections showing potential groundwater flow paths in the west and east valleys. The water table configuration and the vertical profiles change very little when data from other times of the year are used and there are no significant changes in flow direction or pattern (Gosselin et al. 1999). Ground-

water flows toward the center of the valley from both the north and south, and there are distinct upward vertical gradients. Available data suggest that groundwater flows laterally beneath the dune south of the west valley. Phipps Lake responds to changes in groundwater levels, and at this time, the lake does not appear to have a significant impact on the west valley. There is a groundwater mound under the large dune north of the west valley that serves as a groundwater divide between the west valley and the river to the north.

### East Valley

The dunes flanking the east valley are broad, have an irregular surface, gently slope toward the valley, and have a maximum relief of about 43 m above the valley floor. Vegetation on the dunal uplands consists of sparse bunchgrasses, small cacti, yucca, and other desert-type plants. The floor of the east valley is hummocky, with a gently rolling surface. A few small, shallow ponds are present in local depressions. Otherwise, the valley floor is dry. Very thin sandy soil is present at the surface. Vegetation density varies considerably over the valley floor but is generally moderate, with much of the total surface area bare sand and silt. Groundwater flows from the west-southwest toward the east-northeast and there are variably horizontal and vertically downward gradients.

## METHODS

### Groundwater Methods

Individual and nested wells were installed in 1993 and 1994 for long-term measurements. They form east-west and north-south transects across each of the two valleys (Fig. 1). There are three nested piezometers at locations 1 through 5 and 11 in the west valley, and at locations 6 through 9, 16, and 1-4 in the east valley. Well sites located on the dunes have single piezometers (10, 12, 13, 14, and 15). Details on well construction are provided in Table 1 and in Gosselin et al. (1999). Groundwater-level measurements have been collected using a hand-held electric tape from July 1994 to February 2004. From 1995 to 2000, water levels were obtained at approximately two-week intervals during April through October. During the winter months (November-March), wells were checked monthly. Since 2000, water levels have been obtained less frequently, typically at two- to four-month intervals. The accuracy of the measurements is estimated to be  $\pm 5$  cm.

TABLE 1  
 DETAILS ON MONITORING WELL CHARACTERISTICS  
 AND REPRESENTATIVE WATER LEVEL ELEVATIONS FROM MAY 21, 1996

GSRL well number	Ground elevation	Screened interval	Depth to middle of screen	Elevation middle of screen	Representative water level elevation 05/21/96	GSRL well number	Ground elevation	Screened interval	Depth to middle of screen	Elevation middle of screen	Representative water level elevation 05/21/96
1-S	1073.35	1.83	2.29	1071.73	1072.95	8-S	1073.25	3.05	13.11	1060.60	1070.87
1-M		0.46	17.15	1056.89	1073.15	8-M		1.83	24.84	1049.08	1070.86
1-D		1.83	29.57	1044.53	1073.29	8-D		1.83	36.58	1037.48	1070.64
2-S	1074.65	1.83	2.29	1072.84	1074.39	9-S	1068.80	1.83	3.35	1065.77	1067.33
2-M		0.46	17.45	1057.73	1075.11	9-M		0.91	18.14	1051.10	1067.32
2-D		1.83	29.87	1045.39	1075.20	9-D		1.83	30.78	1038.56	1067.32
3-S	1076.36	1.83	6.40	1070.47	1076.03	10	1082.59	0.61	30.48	1052.58	1067.20
3-M		0.46	21.26	1055.65	1076.03	11-S	1102.87	1.83	26.21	1077.10	1076.61
3-D		1.83	33.53	1043.45	1075.98	11-M		1.83	47.85	1055.49	1076.58
4-S	1075.81	1.83	1.52	1074.64	1076.08	11-D		3.05	60.05	1043.44	1076.58
4-M		0.46	18.06	1059.40	1077.01	12	1128.10	3.05	59.44	1069.26	1077.14
4-D		1.83	31.09	1046.89	1077.04	13	1125.75	3.05	53.34	1072.95	1077.45
5-S	1076.08	1.83	6.25	1070.05	1075.42	14	1097.25	3.05	35.05	1062.73	1068.20
5-M		0.46	21.41	1054.95	1076.00	15	NA	3.05	31.09	1061.74	1066.88
5-D		1.83	33.83	1042.60	1076.00						
6-S	1067.94	1.83	3.66	1064.76	1067.56	16-S	1081.31	4.57	12.80	1068.73	1068.32
6-M		0.46	18.06	1050.44	1067.31	16-M		0.61	29.57	1052.49	1067.11
6-D		1.83	30.18	1038.37	1067.28	16-D		3.05	43.59	1038.34	1067.27
7-S	1065.61	1.83	6.10	1059.94	1063.95	1-4S	1070.49	4.57	8.69	1061.99	1068.10
7-M		0.46	18.06	1048.03	1063.94	1-4M		0.61	12.50	1058.17	1068.06
7-D		1.83	30.48	1035.70	1063.88	1-4D*					

Note: All measurements are in meters. NA = not available. \*Damaged by cattle. Data not included.

### Potential ET Computation

Potential evapotranspiration (PET) is a measure of atmospheric demand for water from evaporation and transpiration. PET is considered the maximum limit of evapotranspiration that can occur at a given location where sufficient water and energy is available for the plants. The calculation of PET takes into account the availability of energy for evaporation and the ability of the lower atmosphere to transport evaporated moisture away from the land surface. Daily temperature and precipitation data for the study period were obtained from the Gudmundsen site, which is part of the Automated Weather Data Network (AWDN) operated by the High

Plains Regional Climate Center. The Penman combination method is used to calculate PET (Robinson and Hubbard 1990; Sridhar et al. 2006).

## RESULTS

### Climate Data

The average annual precipitation value from 1983 to 2002 at the GSRL AWDN station was 45.5 cm. The first two years of this study were conducted during a period of slightly higher than average annual rainfall (1994-1995), followed by a period of generally lower than average rainfall. Annual precipitation totals for 1994 through 1995

average 57 cm per year. From 1996 to 2002, the average annual precipitation was 41 cm. The 20-year annual average of 45.5 cm was exceeded in only two years: 1998 with 47 cm and 2001 with 57 cm.

Average monthly precipitation and PET data for 1983 through 2002 (Fig. 3A) indicate a seasonal pattern in which at least 80% of the precipitation on average occurred during the April-through-September growing season. This seasonal pattern is consistent with longer-term historic data (Wilhite and Hubbard 1990) and the 10-year May-September average for 1987-1996 at GSRL (Walz and Volesky 1997). Less than 5% of the annual precipitation falls during the winter months, December through February. Daily rainfall data from the GSRL AWDN weather station indicate that there is substantial variability in the timing, duration, and location of specific rainfall events.

During the growing season, transpiration by vegetation is the largest fraction of total ET. Average monthly PET estimates for 1983 to 2002 indicate that PET increased gradually during the growing season, reaching a maximum in July. The seasonal pattern of PET is similar to the annual rainfall distribution, but PET reaches its maximum one month later in July. Over the 20-year interval of 1983 to 2002, the average annual moisture deficit (PET minus precipitation) is about 115 cm. The moisture deficit is probably only relevant for wet meadows; for dunes and dry valleys it is an overestimate because the calculation assumes that plants have readily available access to water. This assumption is reasonable for the wet valley, but not for the other two environments (dry valley and dunes). Evapotranspiration is not uniform within and among the wet valley, dry valley, and dunes because of differences in both vegetative cover and access to soil moisture and groundwater.

Palmer Drought Severity Index data for the climatic region that includes the GSRL suggest that in 1994 and 1995, in 20 out of 24 months (83%), the moisture conditions were very to extremely wet (Fig. 3B). From 1996 through 1998 the moisture conditions were slightly to moderately wet, but became wetter in late 1998 and into 1999, in which the first eight months were very to extremely wet. In the last three months of 1999, moisture was scarcer during a transition from a mild to moderate drought in 2000. In 2002 and 2003 severe to extreme drought conditions existed over the region.

#### Long-Term Groundwater-Level Measurements

**West Valley Floor Wells.** Hydrographs for valley floor wells 1, 2, 3, 4, and 5 indicate a distinct seasonal pattern for all west valley wells (Fig. 4). The peaks in the

seasonal groundwater levels occur in January through March, and the depth to water is generally less than a half a meter. A comparison of the highest peak water levels, which occurred in either 1996 or 1997, to the lowest peak water level in February 2004, indicates an overall drop in the groundwater levels within the water table wells of between 0.44 and 0.63 m. The lowest water levels occur between late July and late September. The seasonal range between high and low values in the shallow wells at 1, 2, and 5 is 0.74 to 1.28 m. Seasonal variation in wells 3 and 4 is less than 0.6 m. Upward gradients (0.01 to 0.04) exist at wells 1, 2, 4, and 5. Data from well nest 3 indicate that flow is predominantly horizontal. The upward gradients persist throughout the year, being greatest between the medium and shallow piezometers. Horizontal gradients are at least an order of magnitude lower than the vertical gradients and range between about 0.001 to 0.0035.

**West Valley Dune Wells.** Hydrographs for dune wells 11, 12, and 13 are similar to those of valley wells and have a distinct seasonal pattern (Fig. 5). However, the highest and lowest levels in the dune wells occur later in the year. The highest levels occur between March and July. The lowest levels for wells 12 and 13, in which the depth to the water table exceeds 50 m, occur in October or November. At well 11, where the depth to the water table is less than 30 m, the lowest levels occur in September from 1995 to 1997 but as late as November in 1998 and 1999. The groundwater levels progressively increased 0.43 to 0.55 m at the three locations from September 1994 to March or April 1997. Since this time, water levels progressively decreased. A comparison of the highest peak water levels, in 1997, to the last peak, in June 2003, indicates an overall drop in the water table under the dunes that ranges from 0.70 to 1.15 m. The seasonal range between high and low values in the dune wells is 0.10 to 0.28 m. At well 11, the only location for which there are multiple wells, the gradient is horizontal.

**East Valley Floor Wells.** Hydrographs for the east valley floor wells 6, 7, 8, 9, and 1-4 indicate water levels increased from September 1994 to their highest value in June 1996, with the exception of well 6, which peaked in March 1996 (Fig. 6). Water levels are generally 1 m or more below the surface when levels are at their peak. Since March 1996, the water levels have progressively decreased 0.9 to 1.2 m. This is approximately twice the amount that is observed in the west valley floor wells. Wells 6 and 1-4 have seasonal patterns that are most similar to wells in the west valley. The maximum difference in water levels between the highest and lowest seasonal values is 0.26 and 0.44 m

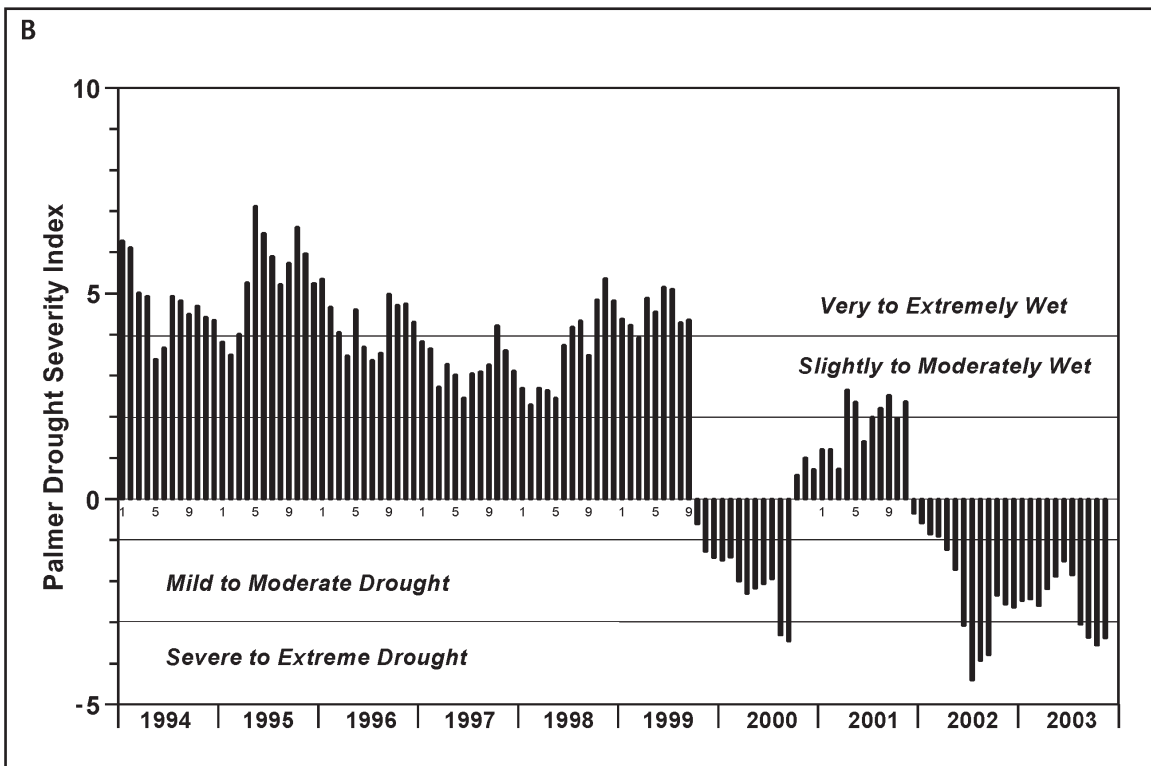
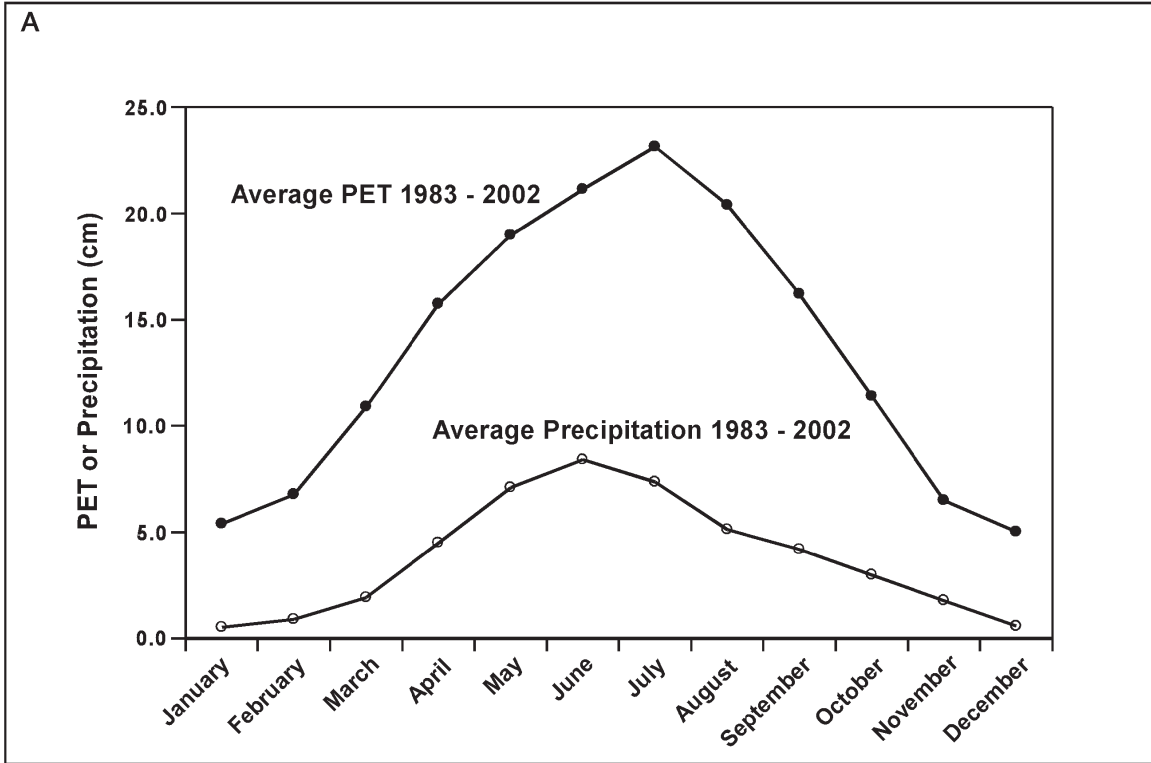
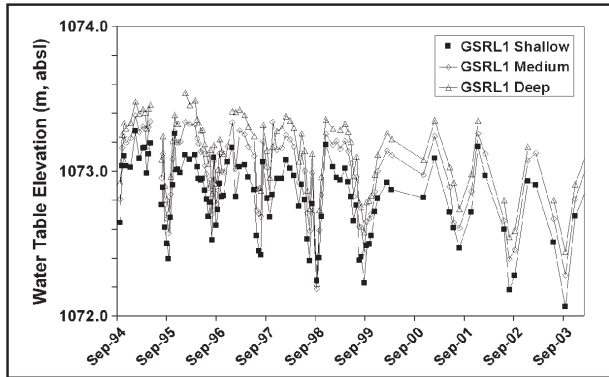
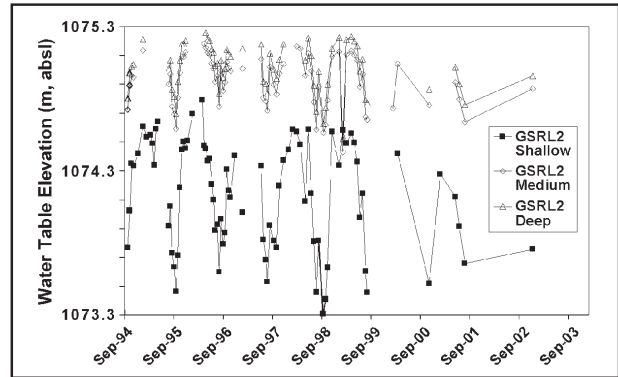


Figure 3. (A) Comparison of average monthly totals of potential evapotranspiration (PET) and precipitation for 1983 to 2002. Data are from the Automatic Weather Data Network station at Gudmundsen Ranch. (B) Palmer Drought Severity Index for September 1, 1994, to December 31, 2002, Nebraska Climate Region 2 as defined by the National Climate Data Center, National Oceanic and Atmospheric Administration.

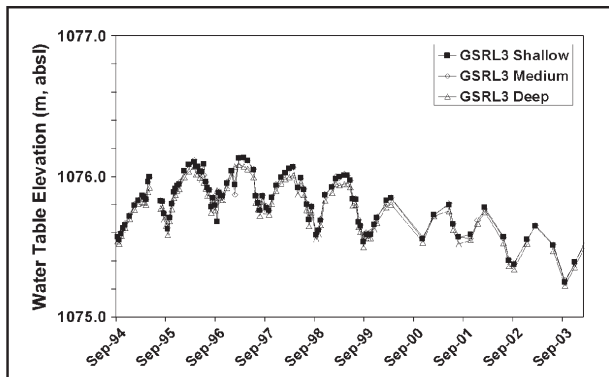
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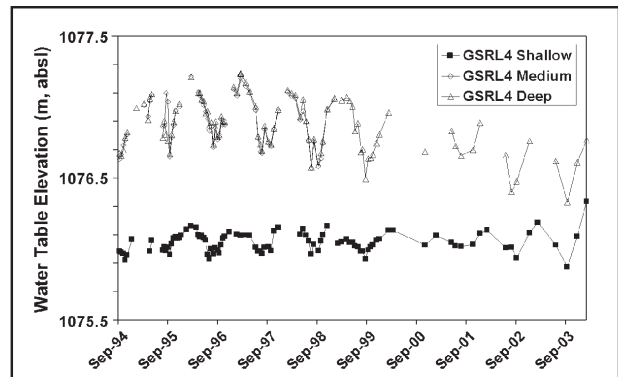
**GSRL 2**



**GSRL 3**



**GSRL 4**



**GSRL 5**

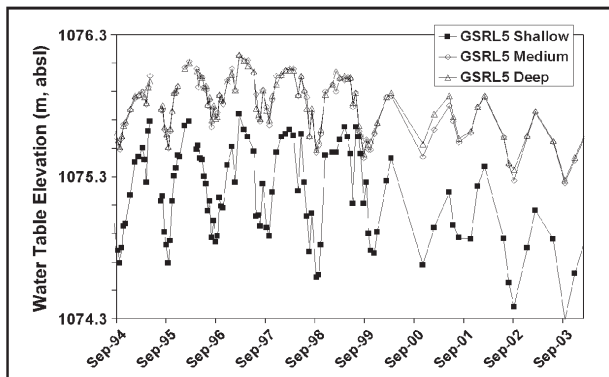


Figure 4. Hydrographs for valley wells in the west valley (well numbers are GSRL 1, 2, 3, 4, and 5).

for well 1-4 and 0.69 to 0.81 m for well 6. The seasonal water level patterns for the other east valley floor wells are more irregular than the west valley in terms of the timing of highest and lowest levels. Relatively rapid short-term rises in the water table occurred in all well clusters in June 1996, November 1998, and May 1999. These are related to one or more heavy rainfall events. A steep rise in water levels during April 1995 occurred before the last frost of the season but after several significant spring precipitation events.

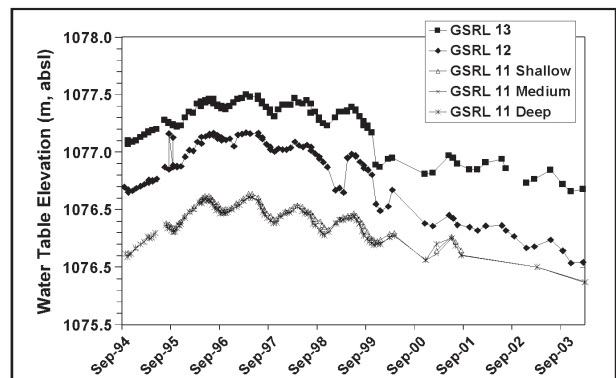
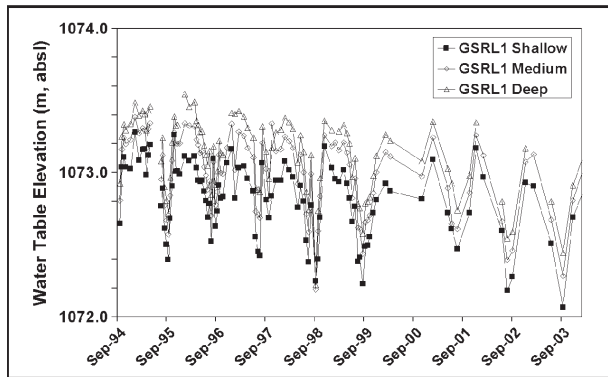


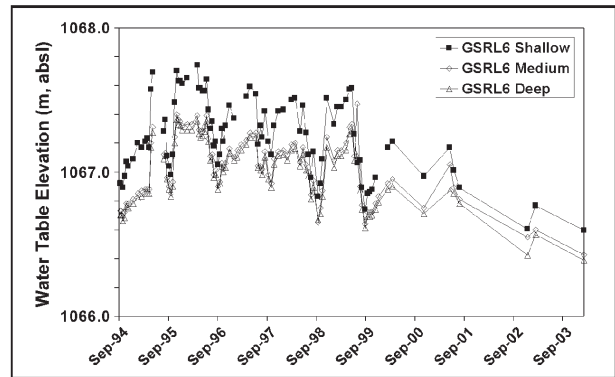
Figure 5. Hydrographs from dune wells in the west valley (GSRL 11, 12, and 13).

Downward vertical gradients predominate at well nests 6, 7, 8, and 1-4 but are generally less than 0.02. Downward gradients appear to be greater (>0.005) on the south and west sides (well nests 6, 8, and 1-4) than those

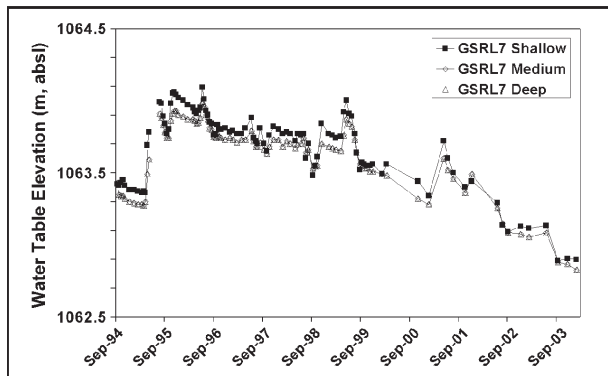
**GSRL 1 - 4**



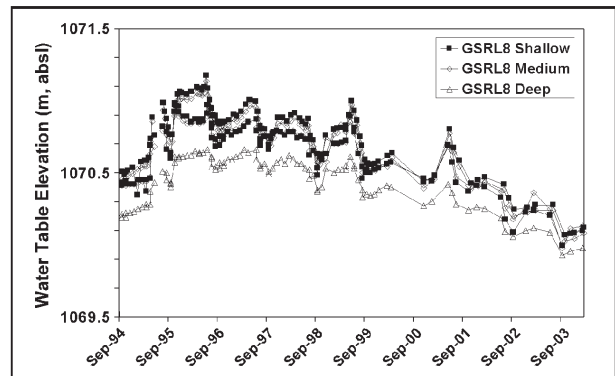
**GSRL 6**



**GSRL 7**



**GSRL 8**



**GSRL 9**

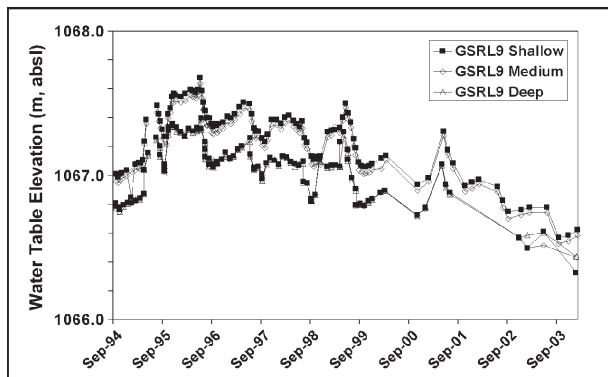


Figure 6. Hydrographs for valley wells in the east valley (well numbers are GSRL 1-4, 6, 7, 8, and 9).

on the east end of the valley at nest 7 (<0.005). On the north side of the valley, the hydrographs for well nest 9 indicate groundwater flow is predominantly horizontal.

**East Valley Dune Wells.** Site 16 has three piezometers, and the other sites have a single piezometer, screened just below the water table beneath the dunes. Groundwater levels increased from 0.51 to 0.67 m from late September 1994 to mid-June 1996 (Fig. 7). Although the magnitude of this increase is similar to the dune wells flanking the west valley, the water levels under the east valley dunes started their decline 9 to 11 months earlier than those in the west valley.

A comparison of the near-peak water levels from February 1996 to February 2004 indicates an overall drop in the water table under the east valley dunes that ranges from 0.75 to 0.95 m. The water level declines in the wells on the south side of the valley (sites 14 and 16) were 0.14 to 0.20 m greater than those on the north side of the valley (sites 10 and 15). Although the decline started earlier in the east valley, the magnitude of the decline in the water table was very similar to that observed under the dunes in the west valley. A downward vertical gradient exists between the shallow piezometer and the two deeper ones at well site 16.

**DISCUSSION**

**Decadal Oscillations in Groundwater Level**

Precipitation is the primary source of groundwater recharge in both valleys, and visible signs of overland flow are minimal (Gosselin et al. 1999). Similar observations were made by Keen (1992) in the Crescent Lake National Wildlife Refuge in the southwestern Sandhills.

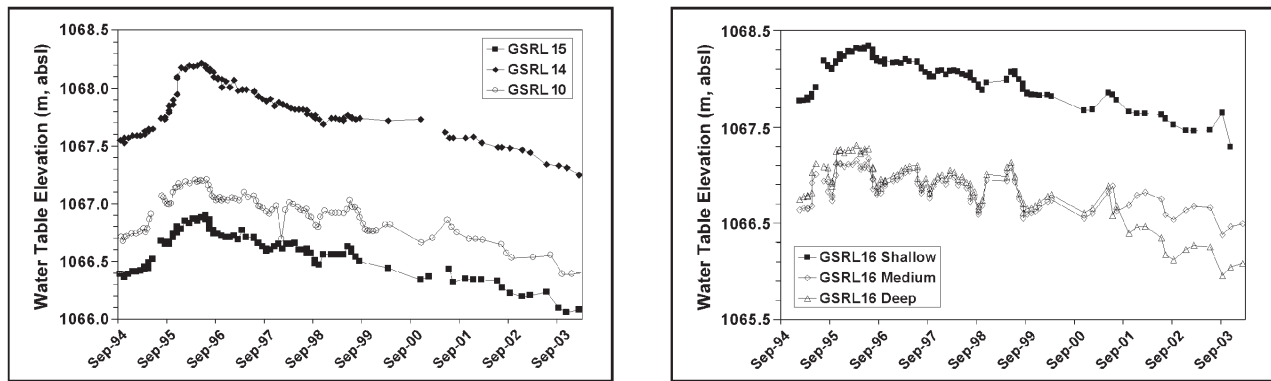


Figure 7. Hydrographs from dune wells in the east valley (well numbers are GSRL 10, 14, 15, and 16).

The groundwater system in both valleys will be most strongly influenced by climatic variability as it produces variations in precipitation and evapotranspiration. The overall wet conditions during 1994 and 1995 resulted in a progressive increase in water levels in all wells. This was especially the case in the east valley (Figs. 6 and 7), where the peak values in both the dune and valley wells occurred between March and June 1996 as the integrative result of the very wet to extremely wet conditions throughout 1995 into the first four months of 1996. Although slightly to moderately wet conditions prevailed from 1996 to 1998, water levels for the most part continuously declined in both the dune and valley wells. With the onset of mild to moderate drought in late 1999 through most of 2000, which was briefly interrupted in 2001, the rate of decline persisted and continued into early 2004. The overall decline in water levels from the peak values in 1996 for both the dune and valley wells in the east valley ranged from 0.80 to 1.2 m.

In the west valley from 1994 through 1996, the groundwater levels in the dune wells increased about the same amount as those in the east valley. The 0.8 to 1.15 m decline from the maximum to minimum peak values in the west valley is similar to that observed in the east valley dune wells. Although the magnitude of the rise and fall in groundwater levels is similar, the dynamics of the response to the variations in climatic conditions is fundamentally different as reflected in the hydrographs (Figs. 5 and 7). While the rate of decline in water levels was continuous in the east valley, the west valley dune wells maintained their relatively high water levels with only a slight decline in peak water levels through late May 1999 when drought conditions became prevalent.

The increase in water levels during 1994 through early 1996 for the dune wells is likely the result of the very wet to extremely wet conditions that existed during this period. A secondary cause of the water level rise is also likely

related to a rise in the regional water table. The wells (6, 8, and 16) associated with the southern and western parts of the east valley have predominantly downward vertical gradients, indicating that these are areas of net recharge and in the up-gradient part of the flow system. The seasonal response of the groundwater system in the west valley is analogous to the decrease in water levels caused by seasonal pumping to meet the demands of crops, followed by groundwater level rises once transpiration had ceased.

#### Hydrological Effects of Seasonal ET Variations in the Wet Meadow

Groundwater level fluctuations in the wet meadow are strongly linked to the seasonal growth patterns of vegetation. In environments such as this, we can apply the water-table fluctuation approach to provide information about evapotranspiration fluxes (White 1932). Groundwater-level-based methods for ET, as well as recharge, are best applied to shallow water tables where there are distinct water-level rises and declines. Because the water level measured in an observation well is representative of an area of at least several square meters, the water-table fluctuation approach can be viewed as an integrative method and less a point measurement than those based on unsaturated zone measurements (Healy and Cook 2002).

The hydrographs in the west valley have distinct water-level rises and declines and therefore the water-table fluctuation (WTF) approach can be used to provide semiquantitative information about evaporative flux in this type of valley. In this system, we can use the change in groundwater storage ( $\Delta S$ ) during a specified period to estimate ET using the following equation:

$$\Delta S = P - (GW + ET) \quad (1)$$

TABLE 2  
COMPARISON OF THE AVERAGE CALCULATED TOTAL EVAPOTRANSPIRATION (ET) FROM GSRL  
WELLS 1, 2, 4, AND 5 TO THE POTENTIAL EVAPOTRANSPIRATION (PET)

Time interval	Number of days	$K_v = 1 \cdot 10^{-4}$ cm/s				Automated Weather Data Network PET
		0.15		0.20		
		Total ET (cm)	ET (cm/d)	Total ET (cm)	ET (cm/d)	Total (cm)
4/1/98-9/10/98	164	98	0.60	101	0.62	100
9/10/98-11/14/98	66	28	0.42	22	0.33	18
4/6/99-8/25/99	143	77	0.53	80	0.56	92
8/25/99-11/11/99	79	21	0.26	20	0.26	39

Note: See text for discussion of  $K_v$  ( $1 \cdot 10^{-4}$  cm/sec) and  $S_y$  assumptions (0.15 and 0.20).

where ET, GW, and P are the fluxes of evapotranspiration, groundwater inflow, and precipitation, respectively, during a specified period;  $\Delta S = \Delta H_s \cdot S_y$ , where  $\Delta H_s$  is the rise or fall in the water level in the shallow well in centimeters (cm) between time 1 and 2; and  $S_y$  is the specific yield of the aquifer. The  $S_y$  values used are 0.15 and 0.20 (Gosselin and Khisty 2001; Chen and Chen 2004) and are consistent with values reported for silty sand to fine-grained sand (Fetter 2001).

The ET values were computed using the WTF approach for four distinct time periods: (1) April 1 to September 10, 1998, and (2) April 6 to August 25, 1999 (two representative intervals of water-table decline); and (3) September 10 to November 14, 1998, and (4) August 25 to November 11, 1999 (two representative intervals of water-table increases). Precipitation data were obtained from the GSRL AWDN station. Quantifying the GW term is a challenge because the groundwater flux term at any given well has both lateral and vertical components. We took a two-step approach to evaluating the GW term. First, we assumed that, at a given monitoring location where there was a significant upward vertical gradient ( $>0.015$ ; GSRL wells 2, 4, and 5), the change in water level,  $\Delta H$ , was predominantly controlled by changes in the vertical groundwater flow component. This is reasonable considering the vertical gradient is at least an order of magnitude greater than the horizontal gradient. We used the following equation to calculate the average daily aggregated groundwater flux:

$$GW = [K_v \cdot (\Delta H/\Delta L)] \cdot \text{Days} \quad (2)$$

where GW is the groundwater flux in centimeter per unit area,  $K_v$  is the vertical hydraulic conductivity (cm/s),  $\Delta H/\Delta L = \text{average of } [(H_s - H_m)/\Delta L]_{\text{Time 1}}$ , and  $[(H_s - H_m)/\Delta L]_{\text{Time 2}}$ , where  $H_s$  and  $H_m$  are the water levels in the shallow- and medium-level monitoring wells and  $\Delta L$  is the difference in elevation between the center points of the screened intervals of the shallow and medium wells, and

days are the number of days within a measurement period. Second, we compared the calculated ET from equation 1 to the PET value from the GSRL AWDN station for the given measurement period (Table 2). Because the AWDN PET value in essence represents the maximum amount of water that can be extracted from the system by plant activity, the calculated ET can only be less than or equal to PET. Differences between the calculated ET, which is equal to the average daily aggregated groundwater flux, and the AWDN PET are attributed to the contributions from the horizontal component of groundwater flow or from soil moisture. This methodology is applicable only to areas that have similar characteristics to the west valley.

To calculate the GW term, the hydraulic conductivity term needs to be estimated. Using soil textural data for the Gammet fine sandy loam (USDA-SCS 1977), which is the dominant soil type in the west valley, as input into the Rosetta Model (Schaap 1999), saturated horizontal hydraulic conductivity ( $K_h$ ) values ranging from  $2.0 \cdot 10^{-3}$  cm/s to  $1.0 \cdot 10^{-4}$  cm/s were determined. Unpublished slug test data from the authors at GSRL well 2 suggest  $K_h$  values around  $5 \cdot 10^{-3}$  cm/s. Zhan and Zlotnik (2002) indicated a range of  $K_h$  values for dune-related deposits, from  $3.2 \cdot 10^{-3}$  cm/s to  $7.2 \cdot 10^{-2}$  cm/s. To determine the  $K_v$  value for use in equation 2, the ratio of horizontal K ( $K_h$ ) to vertical hydraulic conductivity ( $K_h:K_v$ ) is needed, but these are typically not well known. Anderson and Woessner (1992) indicate that a trial and error process can be used to constrain this value. Using this approach, we selected a  $K_v$  value of  $1 \cdot 10^{-4}$  cm/s that is consistent with applying a  $K_h:K_v$  ratio between 10 and 100 to the range of  $K_h$  values for GSRL.

Table 2 compares the average calculated ET from groundwater data at GSRL wells 1, 2, 4, and 5. The time intervals chosen for the calculations represent the primary growing season (end of April to mid- to late August) and senescence (mid- to late August to mid- to late November).

The calculated ET for the growing seasons April 1–September 10, 1998, and April 6–August 25, 1999, are within 15% of the AWDN PET and suggest water fluxes on the order of 5 to 6 mm/day. Burba et al. (1999a, 1999b) indicated that measured ET was 75% to 100% of PET during the early to peak growth stages (June to August) for reed grass (*Phragmites australis*) in a Sandhills wetland. Our calculated ET fluxes are also similar to the ET values reported by Burba et al. (1999a, 1999b) of 0.25 to 0.66 cm/day for reed grass and 0.2 to 0.8 cm/day for open water, which were measured from mid-June to mid-September for a wetland in north-central Nebraska.

For the period of senescence in September–November of 1998, our calculated ET from the groundwater data was higher than the AWDN PET value (28 cm vs. 18 cm), whereas for the senescence period in 1999 the calculated ET (21 cm) was about 50% less than the AWDN PET value (39 cm). Burba et al. (1999b) recorded a similar range of values for the senescence of *Phragmites* in the northern Sandhills. During senescence, the plants are preparing themselves for changes in their environmental conditions and winter dormancy. However, the transition period is not a time of total inactivity for these plants, but reduced activity. As long as temperatures are above freezing water, the perennial wetland/grassland plants, which dominate the west valley, will maintain some level of productivity and continue to flux water. Although our calculated ET values during the senescence period may not compare as well to the AWDN PET data as they do during the growing period, the important point is that they do record the general reduction in plant activity and water use.

## SUMMARY AND CONCLUSIONS

The east and west valleys are distinctly different in terms of their morphology and topographic relief and this has resulted in different hydrologic responses from each valley to environmental conditions. The east valley is generally an area of net recharge, and the water levels reached their peak in response to moderately wet to extremely wet conditions during 1995 and early 1996. The overall decline in water levels from the peak values in 1996 for both the dune and valley wells in the east valley ranged from 0.80 to 1.2 m. The west valley is located at the end of a groundwater flow path, and it takes additional time for the effects of drought to propagate from areas of net recharge to areas of net discharge. The west valley dune wells maintained their relatively high water levels with only a slight decline in peak water levels through late May 1999, when drought conditions became prevalent.

A simple water-balance equation was used to calculate ET from water-level measurements in the west valley and to compare with the PET estimates from the Gudmundsen site. This approach could not be used in the east valley because the groundwater table is not within the rooting zone and the groundwater flow direction is downward or horizontal. The estimates of ET ranged between 5–6 mm/day in the mid-growing season and 2–3 mm/day during the period of senescence. These values are reasonably close to ET estimates of well-watered grass areas in the Sandhills. Although the assumptions of our approach are simplistic, the results record changes in the ET environment and provide ET values that are consistent with independently derived AWDN PET data. This suggests that the methodology was reasonable. However, the application of this approach is extendable only to regions that have similar hydrogeologic conditions to those at the GRSL site.

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