Water balance modeling for irrigated and natural landscapes in central Wisconsin. [DNR-201] 2009

Lowery, Birl; Bland, William Lehman
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#201

Title: **Water Balance Modeling for Irrigated and Natural Landscapes in Central Wisconsin**

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Technical Support: **Phillip E. Speth, Amber M. Weisenberger, and Mackenzy Naber**

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Project I.D.: NMI00000248

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Period of Contract: 1 June 2007 to 31 August 2009

Background/Need:
Significant decline in the water table in the Wisconsin Central Sand Plain (WCSP) has caused concern over the increase in land area devoted to irrigated agricultural crop production.

Objectives:
(1) Conduct a survey of Wisconsin Sand Plains (WSP) crop growers' current cropping and irrigation practices. (2) Develop a soil-specific determination of "field capacity" water content for a range of soil types in WSP. (3) Measure storm-based groundwater recharge rates under four vegetation types (various irrigated crops, deciduous forest, pine plantation, and natural grasslands) in WSP, by direct observation of water table changes. (4) Modify and apply a one-dimensional soil-plant-atmosphere model to estimate evapotranspiration and groundwater recharge under different vegetation types, using results from objectives 1-3.

Methods:
This study was conducted in Waushara County at the Univ. of Wisconsin-Madison Hancock Agricultural Research Station and on privately owned farmland near Hancock, WI, and in Adams County on privately owned land near Grand Marsh, WI. This area is known as the Wisconsin Central Sand Plain (WCSP) and consists of thick, uniform sand deposits that were formed in the bed of Glacial Lake Wisconsin. Soil parent material consists of glacial till overlain by glacial outwash. Groundwater is 1.2 to 9.1 m below the surface throughout the region in unconfined sand and gravel aquifers. Eight groundwater monitoring well sites were established and the wells were equipped with pressure transducers and dataloggers, rain gauges, and 30-cm long time domain reflectometry soil water content probes. The dataloggers were programmed to make measurements of water table elevation, soil water content, and precipitation every 15 minutes.

Results and Discussion:
This study was conducted to investigate the fate of groundwater in WCSP by collecting continuous water table elevation data from eight different sites. The principal objective was to quantify interactions between vegetation (irrigated agricultural crops, prairie, and forest) and depth to groundwater. Our data show that groundwater recharge patterns varied by vegetation type, season, and according to location in the groundwatershed. During the growing season, interception of precipitation by plant leaf canopy and soil surface residue for some vegetation ecosystems (namely pine plantation) reduced recharge to the water table after precipitation events as compared to sites where the vegetation and residue intercepted a minimal amount of the precipitation. In the pine plantation, precipitation events from July 2008 to February 2009 yielded little to no recharge to the water table. Precipitation events during the growing season resulted in 1.4 cm greater

water table rise under prairie than agricultural fields. After snowmelt events in winter 2008-2009, prairie vegetation yielded a 7.5 cm greater water table rise than agricultural fields. The lack of plant residue on agricultural fields lead to a continuous soil frost layer that extended to about 1 m. Cemented frost in the soil profile inhibited snowmelt water from infiltrating and recharging the groundwater. Increased residue on the surface of agricultural fields may enhance recharge to the water table in this region. Water tables responded to precipitation events differently based on their position in the groundwatershed and depth to the water table. Water tables in the discharge area of the groundwatershed (Grand Marsh area) responded quickly to precipitation events and the amount of rise increased linearly with precipitation. While agricultural crops used groundwater through irrigation, natural vegetation relied on the water table for daily transpiration needs in shallow groundwater areas. Where groundwater was further from the soil surface, in the groundwatershed recharge area (Hancock area), responses to precipitation events were buffered by the greater depth of soil above the water table. There were limited noticeable responses of the water table to rain events less than 0.4 cm, and we do not anticipate that natural vegetation will use water directly from deep groundwater. Thus, the only use of groundwater directly is by irrigation in the recharge area of the groundwatershed. We conclude that increase in irrigated agricultural lands in the WCSP alters groundwater recharge characteristics during frozen and non-frozen ground periods. Similar to measured results, data were obtained from two computer simulation models, the rather large and complex Integrated Biosphere Simulator (IBIS) and a simpler model Soil Water Balance (SWB) recently developed by Bill Bland.

Conclusions/Implications/Recommendations:
The most noticeable difference in groundwater recharge from field and natural vegetation has been the lack of recharge beneath a pine plantation. Recharge under this vegetation did not take place except for snowmelt and rain events greater than 3 cm. There was limited recharge during rain events or snow melt in midwinter under agricultural fields, but significant recharge from prairies. Differences in groundwater recharge in winter were attributed to differences in frost depth and the degree of pores filled with ice/water between the prairies and agricultural fields. The fields had a solid frost layer, suggesting that most of the soil pores were filled with ice, to a depth of 1 m or more while the prairies had a discontinuous frost layer, suggesting that soil pores were not filled with ice. Future policy should recognize the importance of various land covers on groundwater recharge in the WCPS.

Related Publications:
Bland, W.L. 2007. Research agenda for irrigation quantity issues. Proc. Wis. Annual Potato Mtg. 20:43-45.

Lowery, B., G.J. Kraft, W.L. Bland, A.M. Weisenberger, and P.E. Speth. 2008. Trends in groundwater levels in Central Wisconsin. Proc. 2008 Wis.Annual Potato Mtg. 21:33-38, Madison, WI.

Weisenberger, A., B. Lowery, and W.L. Bland. 2008. Trends in groundwater levels in central Wisconsin. In Agronomy abstracts (CD-ROM). ASA, Madison, WI.

Weisenberger, A., B. Lowery, and W. Bland. 2009. Trends in Groundwater Levels in Central Wisconsin. Proc. 2009 AWRA-Wis. Section Annual Mtg. 33:56, Stevens Point, WI.

Weisenberger, A., B. Lowery, and W. Bland. 2009. Groundwater recharge under selected vegetation in Central Wisconsin. Proc. 2009 Wis.Annual Potato Mtg. 22:121-127, Madison, WI.

Key Words: Groundwater, soil water content, drainage, groundwater recharge, water table elevation

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Final Report: A final report containing more detailed information on this project is available for loan at the Water Resources Institute Library, Univ. of Wisconsin-Madison, 1975 Willow Dr., Madison, WI 53706; 608-262-3069.

Abstract:
Water table elevations monitoring data were collected for 2 years, including winter months. The most noticeable differences in groundwater recharge from agricultural fields and natural vegetation have been the lack of recharge beneath a pine plantation, other than during snow melt and spring rains, and little or no recharge during winter snow melt under agricultural fields compared to significant recharge for prairies. Recharge under pine plantation did not take place except for snow melt and rain events greater than 3 cm. There was limited recharge during rain events or snow melt in midwinter under agricultural fields, but significant recharge from prairies. These differences in groundwater recharge in winter were attributed to differences in frost depth and the degree of pores filled with ice/water between the prairies and agricultural fields. The fields had a solid frost layer (suggesting that most of the soil pores were filled with ice) to a depth of 1 m or more, while the prairies had a discontinuous frost layer (suggesting that soil pores were not filled with ice) that was less than 0.60 m thick. Computer simulation results from two models, the rather large and complex Integrated Biosphere Simulator (IBIS) and a much simpler model Soil Water Balance (SWB), show similar results. The simple soil water balance model indicates that the difference in annual recharge between perennial and irrigated vegetative covers varies greatly from year-to-year. On average, about 30 mm more recharge should be expected from perennial vegetation than from an irrigated crop like potato.

Project Objectives:

(1) Conduct a survey of Wisconsin Sand Plains (WSP) crop growers' current cropping and irrigation practices.

(2) Develop a soil-specific determination of "field capacity" water content for a range of soil types in WSP.

(3) Measure storm-based groundwater recharge rates under four vegetation types (various irrigated crops, deciduous forest, pine plantation, and natural grasslands) in WSP, by direct observation of water table changes.

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Methods and Equipment:

This study was conducted in Waushara County at the Univ. of Wisconsin-Madison Hancock Agricultural Research Station and on privately owned farmland near Hancock, WI, and in Adams County on privately owned land near Grand Marsh, WI. This area is known as the Wisconsin Central Sand Plain (WCSP) and consists of thick, uniform sand deposits that were formed in the bed of Glacial Lake Wisconsin. Soil parent material consists of glacial till overlain by glacial outwash. Groundwater is 1.2 to 9.1 m below the surface throughout the region in unconfined sand and gravel aquifers. Eight groundwater monitoring well sites were established, and the wells were equipped with pressure transducers and dataloggers, rain gauges, and 30-cm long time domain reflectometry soil water content probes installed nearby. The dataloggers were programmed to make measurements of water table elevation, soil water content, and precipitation every 15 minutes. However, there are some missing readings because of battery problems during winter (2008/2009) associated with our inability to access some sites because of weather conditions. The soils at the sites were either Brems sandy loam (mixed, mesic Aquic Udipsamments) or Plainfield sand (mixed, mesic, Typic Udipsamments). Berms was found mainly at the Grand Marsh sites, while Plainfield was at the Hancock sites.

Grand Marsh Sites

Five of the research sites were located in Adams County, near Grand Marsh, WI. The sites were selected based on vegetation cover and similar geographic location and depth to the water table. The vegetative cover of the sites in Adams County included both irrigated annual crops (soybean: *Glycine max*, potato: *Solanum tuberosum*, and sweet corn: *Zea mays,* var. Rugosa) and natural vegetation that consisted of dry-mesic prairie plantings. Prior to 2004, the prairie area was part of a cultivated and irrigated agricultural field. In 2004, the area was planted to native prairie grasses and forbs such as switch grass (*Panicaum virgatum*), side-oats grama *(Bouteloua curtipendula)*, little bluestem *(Schzachyrium scoparium)* and several other species native to the area. Since 2004, chemical and physical controls such as spraying herbicide, mowing, and burning were implemented to manage the prairie vegetation. During the study, native prairie grasses such as switch grass, side-oats grama, and little bluestem were present along with several species of native forbs including large-flowered beardtongue (*Penstemon gradiflora*), shooting star (*Dodecatheon media*), and Ohio spiderwort (*Tradescantia ohiensis*). Approximately 10% of the prairie area was covered by weedy native herbs like ragweed (*Ambrosia artemisiaefolia*).

Hancock Sites

Three sites were located in Waushara County, near Hancock, WI. Two of the sites were at the Univ. of Wisconsin Hancock Agricultural Research Station, and the third site was located on privately owned farmland just north of the research station. The sites were chosen based on vegetation cover and similar depth to the water table. The vegetation cover of all three sites in Waushara County was irrigated agricultural crops (soybean: *Glycine max*, potato: *Solanum tuberosum*, and oats: *Avena sativa*).

Results and Discussion:

Field Experiments

Groundwater Fluctuations and Vegetation Cover in Wisconsin Central Sand Plain (WCSP)

Through monitoring the water table elevations for a variety of vegetation types in WCSP, including irrigated agricultural crops and several natural vegetation covers, we have found that recharge in winter varies with vegetation type and depth to groundwater. During the winter of 2008, two significant recharge events (27 December 2008 and 10 February 2009) revealed differences between soil frozen under natural vegetation and harvested crop fields (bare soil). Sites with shallow groundwater levels (Grand Marsh) recharged during a snow melt event in December 2008, but this was not the case with the deeper water table (Hancock) setting (Fig.1). Groundwater recharge was observed at both sites (Grand Marsh: shallow water table and Hancock: deep water table) in February 2009 during a snow melt event. In both cases, there appeared to be more recharge to the water table in the natural vegetation compared to the irrigated agricultural fields. During the rain on snow event on 27 December 2008, the mixed prairie and grass prairie sites showed a rise in water table elevation of approximately 10 cm, while the water table elevation rose only approximately 3 cm under the harvested crop fields (Fig. 1). In this case, there was about two times greater rise in water table under both prairie systems [mixed prairie (with grass, shrubs, and trees) and grass prairies] as compared to the agricultural fields. A similar situation was noted for the 10 February 2009 snow melt event, as the water table level rose approximately 20 cm in the mixed and grass prairies, while the harvested soybean and harvested sweet corn sites had a rise of 5 and 10 cm, respectively. These differences in water elevation in response to melting events show a difference in frost depth and frost continuity under different vegetation types.

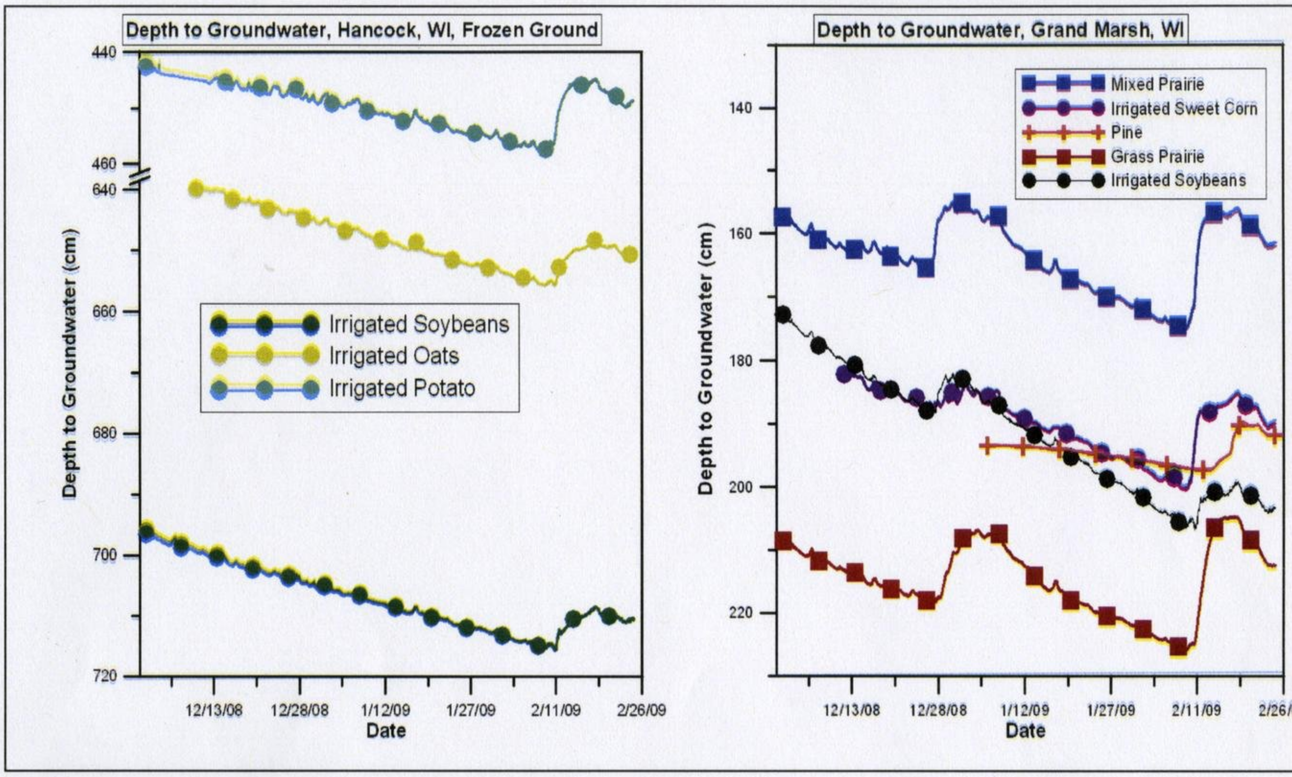

Figure 1. Depths to groundwater during snow melt events near Grand Marsh and Hancock, WI under different vegetations.

Ground penetrating radar measurements were made to show differences in frozen ground between the corn field and mixed prairie (Fig. 2). These graphs also show depth to groundwater and various other profile strata for this site. The frozen condition is deeper in the field, and it appears to be more continuous. This was verified by field tests of our ability to drive a rod into the soil. For the field, it was almost impossible to drive the rod into the soil, but under the prairie the rod was inserted with limited effort. The water table depth, as measured by ground penetrating radar (Fig. 2), was similar to our pressure transducer data for both sites.

Figure 3 shows soil water content from the soil surface to 30 cm and also depth to groundwater under the mixed prairie and irrigated sweet corn sites for the period of 6 through 11 August 2008. Daily fluctuations in soil water content, reflecting water use between day and night (diurnal cycle), are present for both the irrigated sweet corn and the mixed prairie vegetations. The two spiked water content values (very rapid increase in water content) for the corn crop is a reflection of two irrigation events on 8 and 10 August. Flow of irrigated water back to the groundwater (seen as recharge) is apparent in the groundwater elevation data on these two days as well (Fig. 3). We also see diurnal fluctuations in the depth to groundwater under the mixed prairie vegetation. This shows that the natural vegetation is using the groundwater (by roots extending to the capillary fringe, above the water table) as a water source on a daily basis to meet transpiration demands. Daily fluctuations are not seen in the depth to water table of the irrigated sweet corn, thus the corn is not tapping the water table/capillary fringe directly as a water source. Interestingly, the water table rate of decline is about the same for the two vegetation types for this period. In summary, the irrigated sweet corn crop and the mixed prairie vegetation seem to use nearly the same amount of water from the groundwater table. The difference seems to be that the sweet corn is taking advantage of the water table through irrigation, and the mixed prairie directly uses the water from the capillary fringe zone for daily transpiration losses through deep root systems.

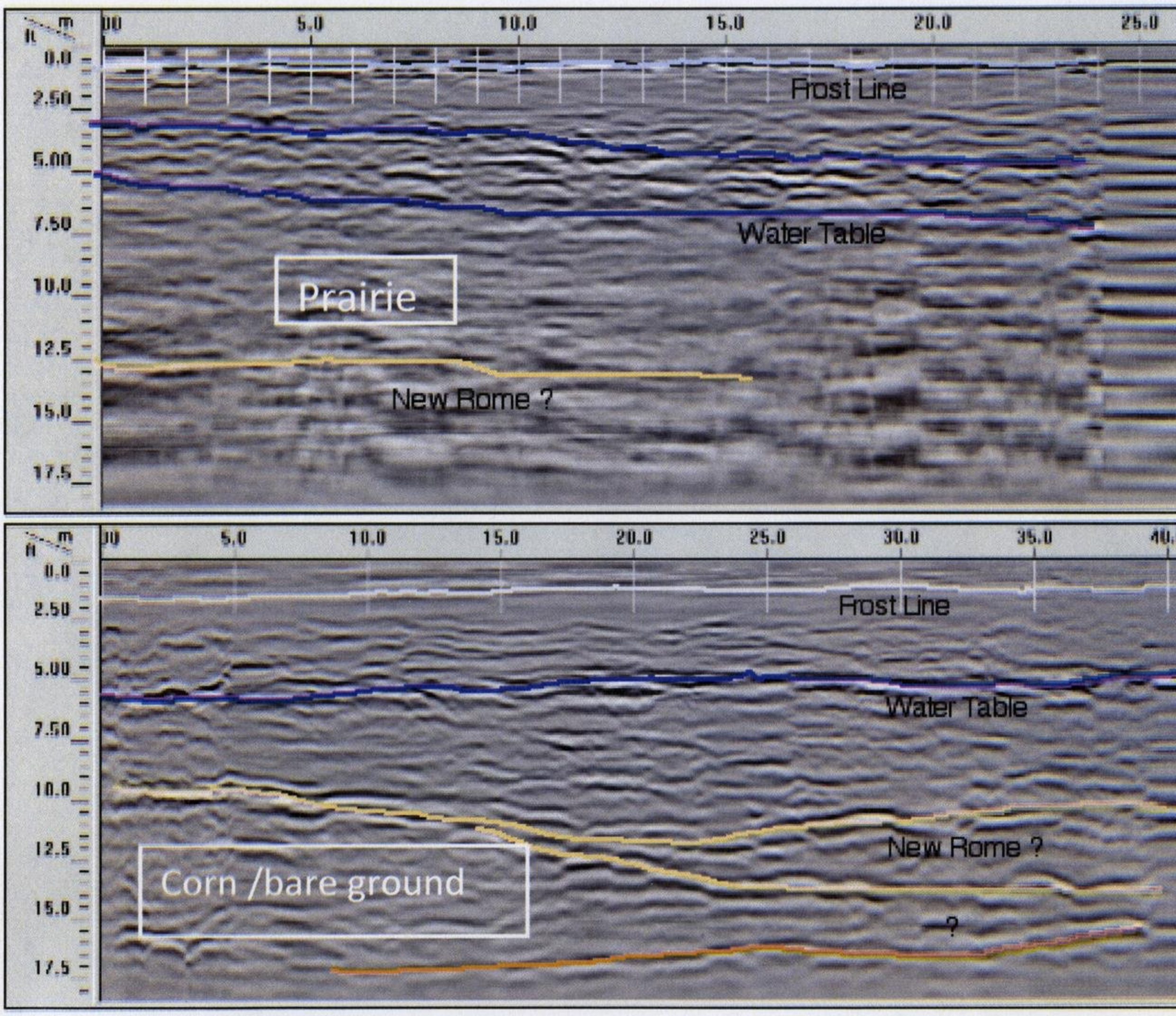

Figure 2. Ground penetrating radar of groundwater monitoring site near Grand Marsh, WI in winter of 2008/09 showing frozen soil conditions and groundwater table under a field that was used for irrigated sweet corn and mixed prairie.

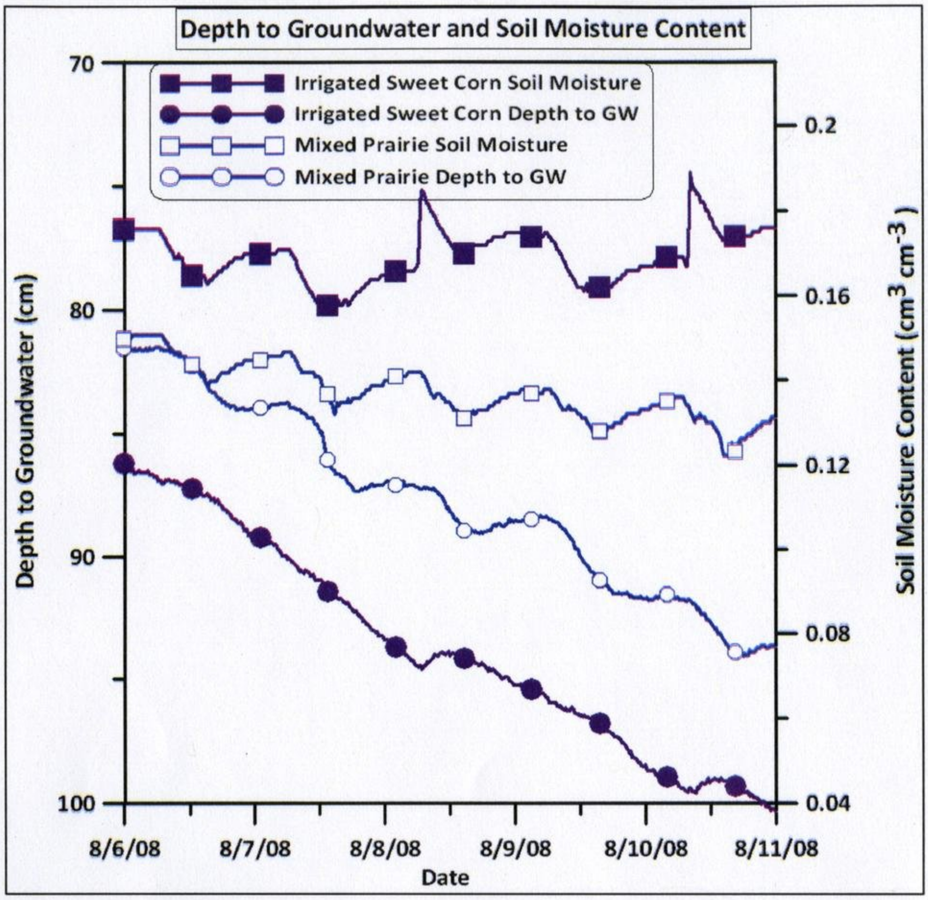

Figure 3. Graph of depth to groundwater and soil moisture under mixed prairie irrigated and sweet corn near Grand Marsh, WI.

Groundwater Assessment During the Growing Season

The amount of precipitation received, intercepted, and water table rise in response to precipitation during the growing season were analyzed for one of the two prairie vegetations near Grand Marsh. There were 30 rain events from 30 May to 1 October 2008 and 1 April to 1 June 2009 that were analyzed with total precipitation ranging in size from 0.37 to 14.5 cm (Table 1). Three events (7, 8, and 12 June) were treated as one combined event since water table rise in response to a specific precipitation event could not be determined. This event of 14.5 cm resulted in the largest water table rise recorded (78.94 cm).

The amount of precipitation and the total water table rise follow a linear trend (Fig. 4). Figure 4 includes all precipitation events presented in Table 1. A linear best fit line to these data has the following equation:

$$WTR = 5.47P - 1.71 \qquad [1]$$

where, water table rise is WTR and P is the amount of precipitation. The R^2 for Eq. [1] was 0.98. These data show that a precipitation event of 1 cm at this prairie will yield approximately 3.86 cm of water table rise. Eq. [1] also suggests that a precipitation event of 0.29 cm or less will not create a rise in the water table at this site. The slope of Eq. [1] suggests that the specific yield for the unconfined aquifer at this site is approximately 0.18.

Table 1. Event date, precipitation amount and total water table rise in response to event at a prairie near Grand Marsh.

Event date	Precipitation amount	Water table rise
	------------------cm------------------	
30 May 2008	1.09	7.76
2 June 2008	1.47	2.77
5 June 2008	1.35	6.92
7-12 June 2008	14.50	78.94
17 June 2008	0.81	0.55
27 June 2008	0.51	2.57
28 June 2008	1.44	6.90
2 July 2008	0.64	2.97
7 July 2008	0.83	3.78
8 July 2008	0.59	1.54
10 July 2008	2.70	22.53
11 July 2008	1.52	7.89
12 July 2008	1.01	4.91
16 July 2008	3.68	20.11
19 July 2008	0.67	4.09
29 July 2008	2.67	14.06
4 August 2008	3.76	15.56
13 August 2008	1.68	8.32
28 August 2008	0.61	2.53
4 September 2008	1.47	6.08
29 September 2008	1.42	3.55
20 April 2009	0.56	1.03
21 April 2009	0.93	4.66
25 April 2009	1.71	0.36
26 April 2009	3.90	31.04
6 May 2009	1.34	3.18
9 May 2009	0.80	2.13
13 May 2009	1.23	4.02
26 May 2009	0.37	1.32
27 May 2009	2.16	9.00

The depth to the water table and precipitation display rapid response to rainfall for this prairie site from May 2008 to June 2009 (Fig. 5). The water table was approximately 10 cm lower on 25 May 2009 than 25 May 2008. The large precipitation events of 7 to 12 June 2008 created the greatest water table response (78.94 cm) to rainfall since monitoring began. Melting snow and thawing of the soil in spring 2009 also resulted in a considerable rise in the water table (50 cm). After significant precipitation in early June 2008, the water table rose to 44.35 cm from the ground surface on 12 June 2008, the highest point during monitoring at this site. The lowest point of the water table at this site was recorded on 8 February 2009 at 175.31 cm from the ground surface. The total range in depth of the water table from May 2008 to June 2009 was approximately 130 cm. Total precipitation at this prairie for the non-frozen ground period of monitoring was 74.9 cm.

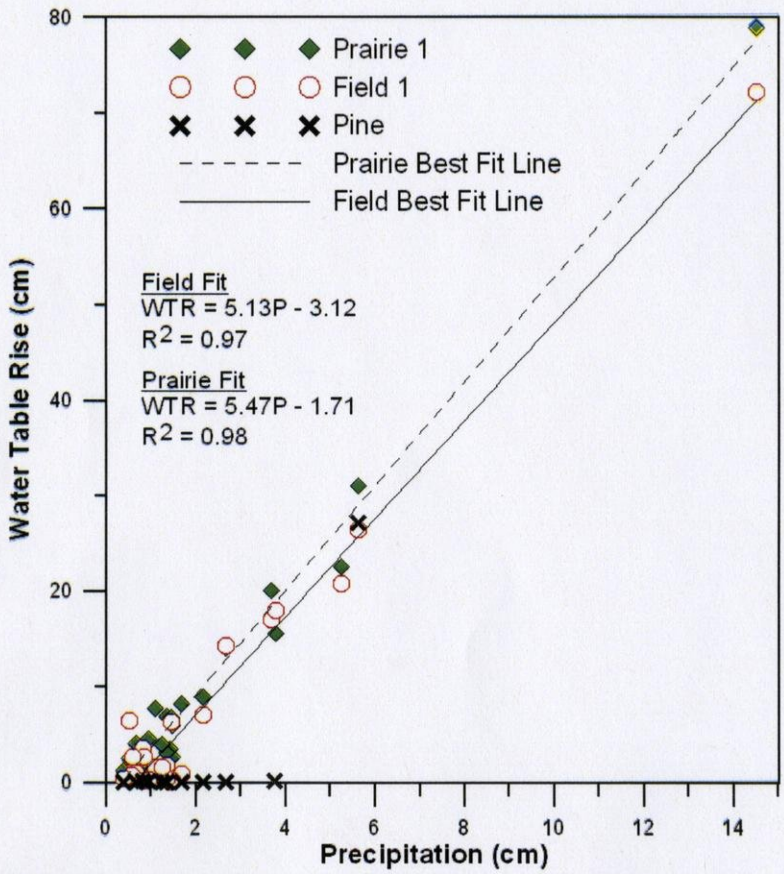

Figure 4. Water table rise (WTR) in response to precipitation (P) for irrigated corn (Field 1), a prairie (Prairie 1), and pine plantation (Pine) for precipitation events greater than 0.4 cm and during the growing season.

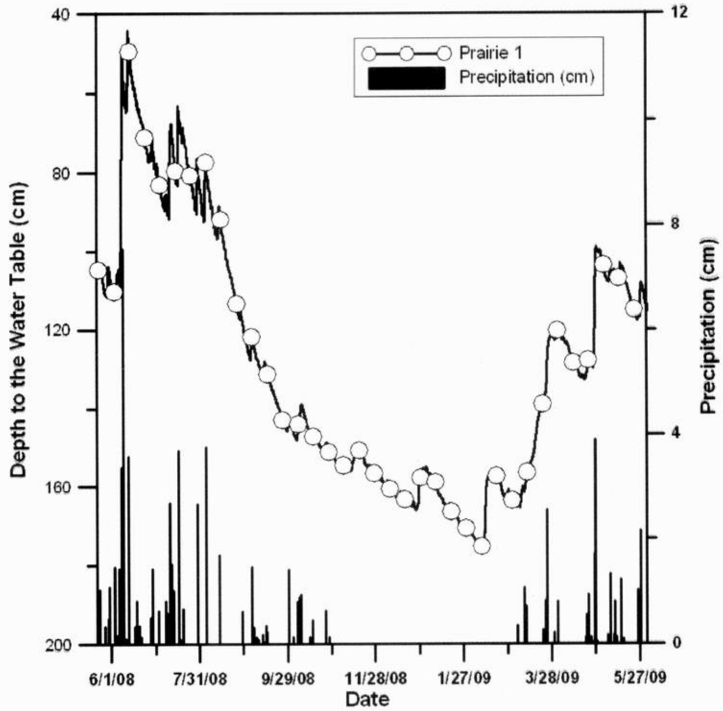

Figure 5. Depth to water table and precipitation at prairie near Grand Marsh (Prairie 1) from 23 May 2008 to 1 June 2009. Symbols plotted every 1000 data points.

Rainfall Interception by Tree Canopy in Prairie Vegetation (Prairie 1) and Pine Plantation

The vegetation in the prairie site near an irrigated corn field (Prairie 1) included mature deciduous trees that intercepted rainfall before it reached the ground surface. Interception of precipitation by trees at this site ranged from 15 to 58% of total precipitation (Table 2). Precipitation events from 30 May through 17 June 2008 were not included in this calculation because the rain gauge at this site was not operating properly during this time. The amount of precipitation recorded under the canopy increased linearly as the size of the rainfall event increased (Fig. 6). Results from the linear regression equation suggest that the canopy of Prairie 1 consistently intercepted approximately 24% of each precipitation event.

Water Table Response to Precipitation in Pine Plantation (Pine)

The amount of precipitation received, precipitation intercepted, and groundwater rise in response to precipitation during the growing season were analyzed for the mature pine stand located near Grand Marsh. Precipitation events from 17 July to 1 October 2008 and 1 April to 1 June 2009 greater than 0.4 cm at the rain gauge located outside of the pine forest were analyzed (Table 3).

The vegetation in this mature pine plantation is 50-year-old red pine (*Pinus resinosa*). The area is undisturbed with a thick layer of decomposing plant matter including pine needles and pine cones on the soil surface.

Table 2. Precipitation values at prairie in Grand Marsh (Prairie 1) and an irrigated corn field (Field 1) and the percent intercepted of each storm event at Prairie 1.

Event date	Precipitation Prairie 1	Precipitation Field 1	Rainfall intercepted
	--------cm--------		--------%--------
27 June 2008	0.43	0.51	15
28 June 2008	1.08	1.44	25
2 July 2008	0.27	0.64	58
7 July 2008	0.46	0.83	44
8 July 2008	0.41	0.59	31
10 July 2008	2.06	2.70	24
11 July 2008	1.16	1.52	24
12 July 2008	0.73	1.01	28
16 July 2008	2.95	3.68	20
19 July 2008	0.49	0.67	27
29 July 2008	2.22	2.67	17
4 August 2008	1.81	3.76	52
13 August 2008	1.06	1.68	37
28 August 2008	0.46	0.61	25
4 September 2008	1.19	1.47	19
29 September 2008	0.89	1.42	37
20 April 2009	0.33	0.56	42
21 April 2009	0.68	0.93	28
25 April 2009	1.19	1.71	30
26 April 2009	3.20	3.90	18
6 May 2009	1.00	1.34	25
9 May 2009	0.57	0.80	29
13 May 2009	0.95	1.23	23
26 May 2009	0.16	0.37	57
27 May 2009	1.57	2.16	27

Table 3. Precipitation events and water table rise in response to precipitation at Pine site.

Event date	Precipitation	Water table rise
	--------------------cm--------------------	
19 July 2008	0.03	0.14
29 July 2008	1.08	0.13
4 August 2008	1.83	0.20
13 August 2008	1.62	0.11
28 August 2008	0.57	0.23
4 September 2008	0.75	0.11
29 September 2008	0.93	0.25
20 April 2009	0.79	0.00
21 April 2009	1.35	0.20
25-26 April 2009	6.89	27.14
6 May 2009	1.35	0.14
9 May 2009	0.86	0.20
13 May 2009	1.99	1.75
26-27 May 2009	2.73	4.05

Between 22 July and 1 October 2008, the soil water content in the pine plantation ranged from 0.06 to 0.16 m^3 m^{-3}, but normally was in the range of 0.06 to 0.08 m^3 m^{-3} even following precipitation events (Fig. 7). This range is below field moisture capacity (Fig. 8, 0.14 m^3 m^{-3}), and it is likely that the thick layer of pine duff intercepts most, and in some cases all, the precipitation that is not intercepted by the tree canopy. Transpiration by the pine vegetation during the summer months contributes to lower soil water content. Water from precipitation that goes through the duff layer to the soil surface will likely replenish severely depleted soil water storage, leading to little or no recharge to the water table underneath the pine plantation during the 2008 growing season (July to October). The relationship between precipitation depth and water table rise in the pine plantation does not follow a linear pattern like Field 1 and Prairie 1 (Fig. 4).

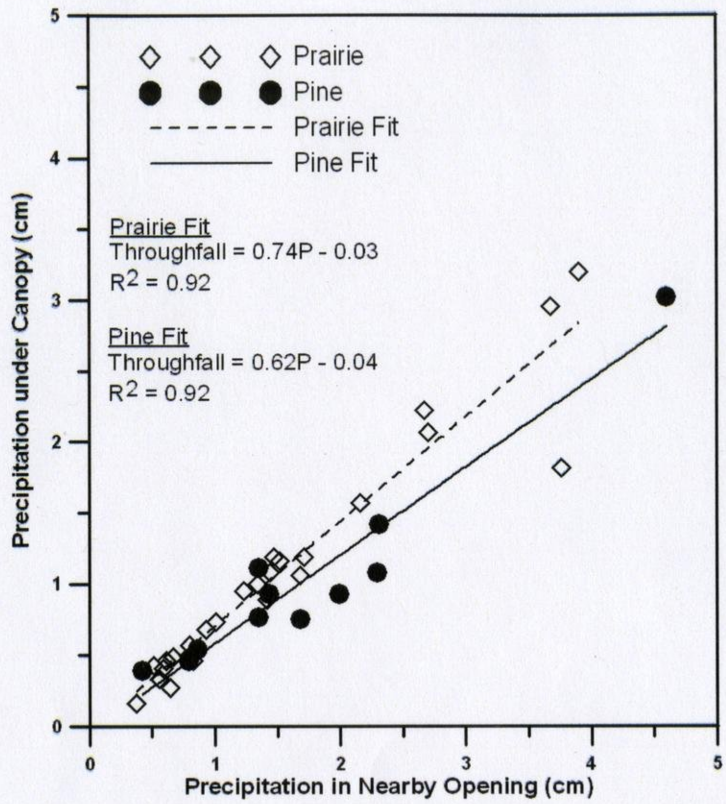

Figure 6. Amount of precipitation (P) intercepted by plant canopy related to size of rain event for prairie (Prairie 1) and pine plantation (Pine).

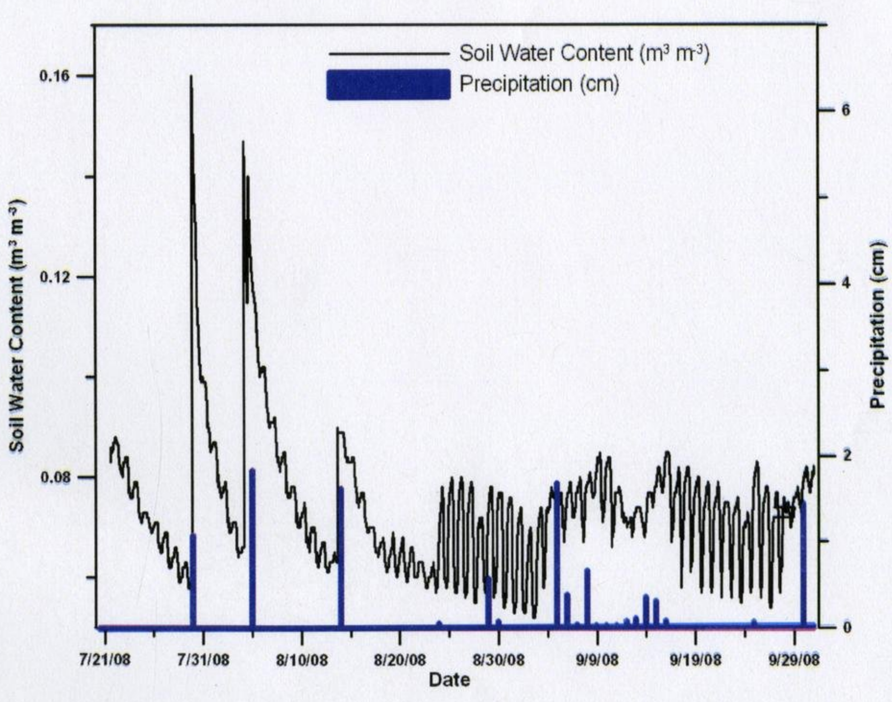

Figure 7. Soil water content and precipitation in pine plantation from 22 July to 1 October 2008.

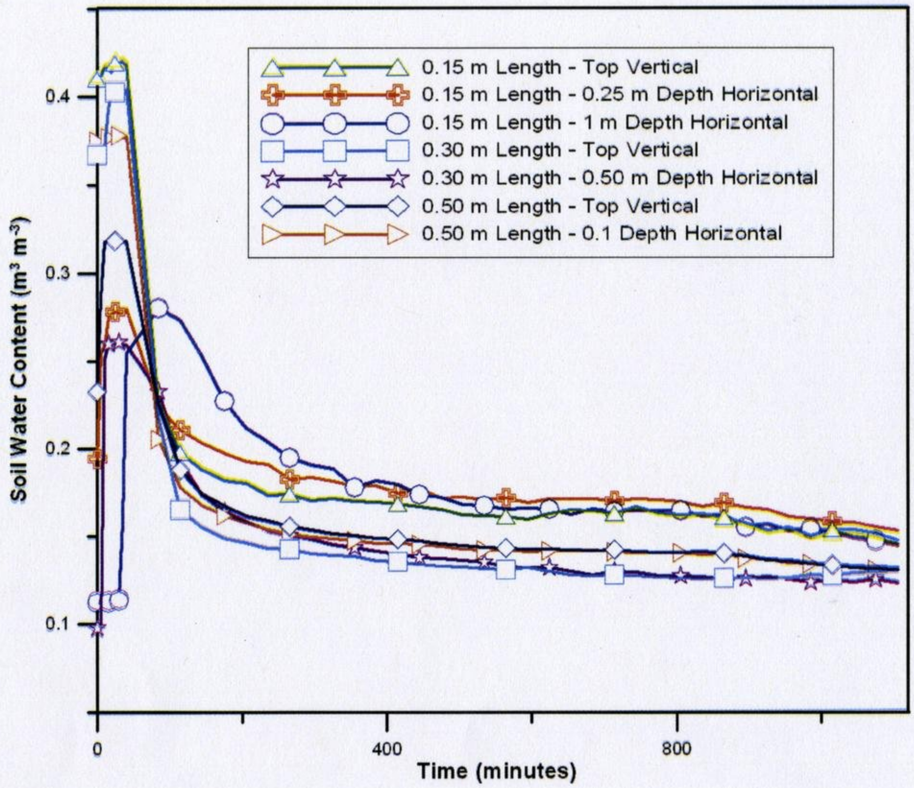

Figure 8. Field measured soil moisture capacity as determined by soil water content measurements over extended time.

Several precipitation events from spring 2009 resulted in recharge to the water table, likely because of higher soil water storage and less transpiration by the vegetation than during the last part of the 2008 growing season. Between 1 April and 1 June 2009, the soil water content (θ_v) ranged from 0.10 to 0.30 m^3 m^{-3}, but θ_v for this site other than responses to precipitation was from 0.10 to 0.15 m^3 m^{-3} in 2009 (Fig. 7 and 8). The soil profile was still storing water from snow melt and thawing soil after the winter. This above-average θ_v with respect to the 2008 growing season caused greater response to precipitation events by the water table (Fig. 10). The precipitation event of 25 to 26 April 2009 led to a 27.14-cm rise in the water table in the pine plantation (Table 3), and a 26.54-cm rise at Field 1. Thus, it is possible that the water table under the pine plantation and Field 1 would react similarly to precipitation events if the duff layer on the soil surface of the pine plantation were not present or if the soil were at or near field moisture capacity.

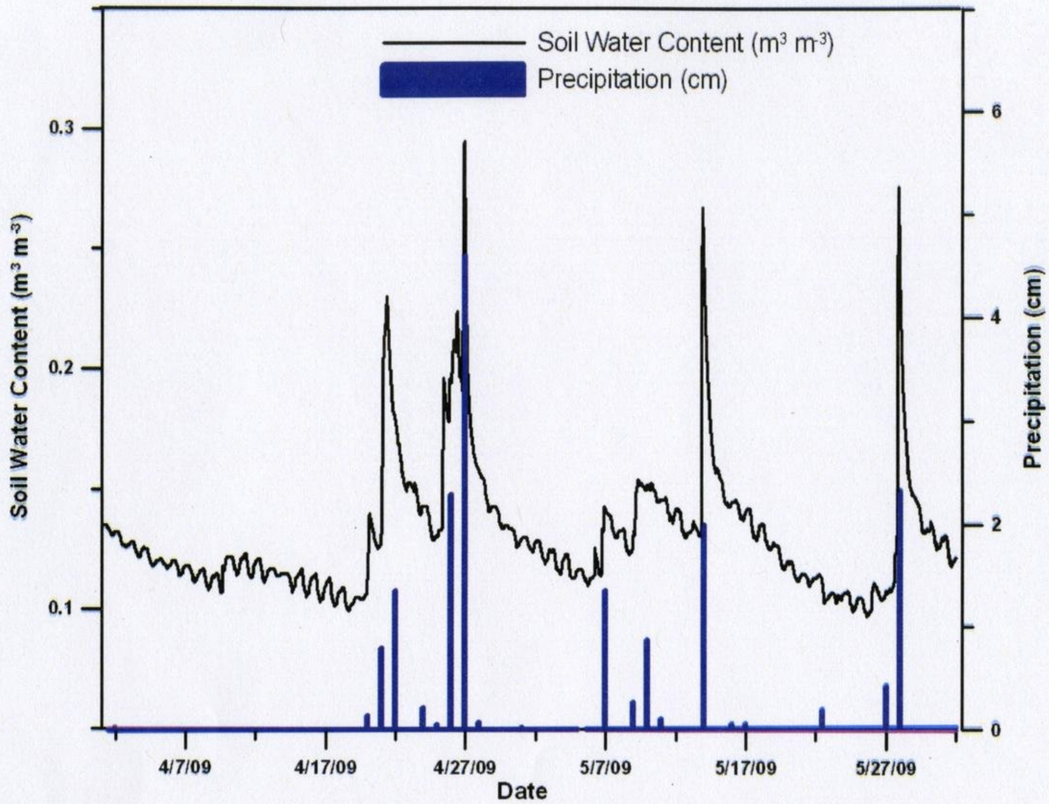

Figure 9. Soil water content and precipitation in pine plantation from 1 April to 1 June 2009.

During the period of study (July 2008 to June 2009), the water table was highest under the pine plantation when monitoring equipment was installed in July 2008. Figure 10 shows that the water table was approximately 50 cm lower on 1 June 2009 than on 22 July 2008. It is interesting to note that the 90-cm range from the highest and lowest recorded depths to the water table under the pine plantation was less than that of nearby prairie (Prairie 1) and irrigated corn field (Field 1), which were 130 and 127 cm. This may indicate more plant use of groundwater by the prairie or irrigated field than the pine plantation or less recharge to the water table in response to precipitation events at the pine plantation.

Interception by Pine Tree Canopy

The pine canopy intercepts a large percentage of each precipitation event, as shown in Table 4. The rain gauge in the nearby opening was not operational until 1 September 2008. The largest precipitation event recorded by the rain gauge underneath the canopy was 3.02 cm, while the rain gauge in an opening nearby measured that event as 4.60 cm. An average of 38% of each precipitation event was intercepted by the pine canopy. As in the prairie (Prairie 1), the amount of precipitation recorded under the forest canopy increased linearly with the size of the rainfall event (Fig. 6). The canopy of the pine plantation consistently intercepted 38% of each storm event, approximately 12% more per event than the canopy of trees at prairie.

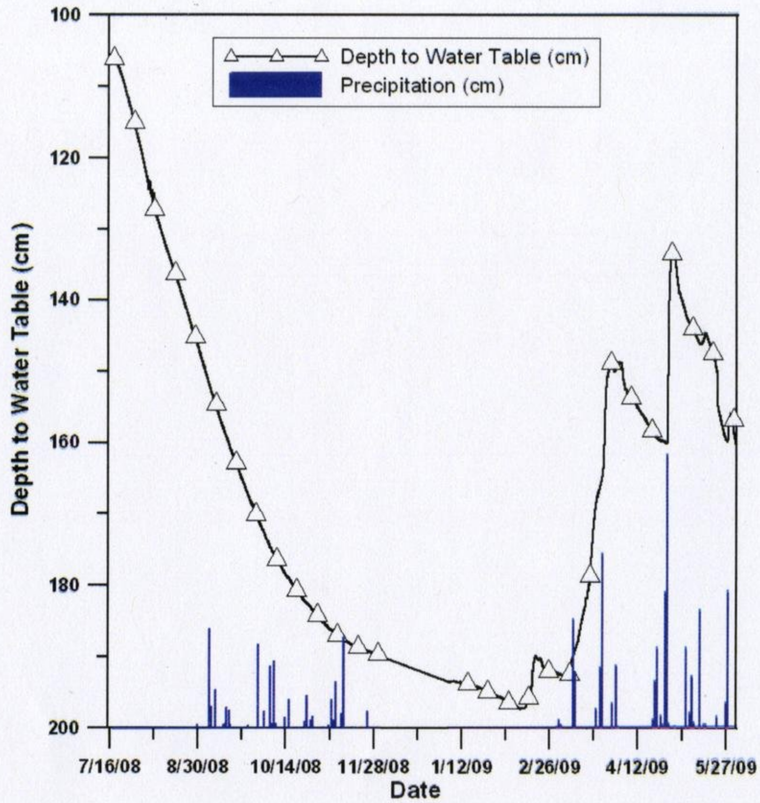

Figure 10. Depth to the water table under the pine plantation throughout the monitoring period. Symbols plotted every 1000 data points.

Conclusions:

The water table on 1 June 2009 was the same distance, at one of the eight sites, or further from the ground surface, at seven of the eight sites, than values recorded during summer. Geographic differences, five sites located in the regional groundwater discharge area (Grand Marsh area) and three sites located in the recharge area (Hancock area) of the groundwatershed, make for two distinct monitoring areas with unique groundwater recharge patterns.

In the regional groundwater discharge area of the groundwatershed, vegetative characteristics become important to recharge trends of the water table. Interception by tree canopies and decomposing vegetative layers on the soil surface can hinder infiltration of precipitation into the soil which will eventually affect the water table. Precipitation intercepted by canopies (tree and prairie vegetations) and duff layers then evaporates from those surfaces instead of infiltrating into the soil profile.

Natural vegetation in the discharge area likely uses the same or similar amounts of groundwater as an irrigated crop. In the recharge area, however, where groundwater is further from the surface, irrigated agricultural crops have the potential to use a larger amount of water than dryland agricultural crops or natural vegetation would.

Table 4. Precipitation events and amount intercepted by pine plantation canopy as recorded by rain gauge in nearby opening.

Event date	Under canopy rain gauge precipitation	Nearby opening rain gauge precipitation	Precipitation intercepted
	--------------------cm--------------------		--%--
19 July 2008	0.03	†	†
29 July 2008	1.08	†	†
4 August 2008	1.83	†	†
13 August 2008	1.62	†	†
28 August 2008	0.57	†	†
4 September 2008	0.75	1.68	55
29 September 2008	0.93	1.43	35
20 April 2009	0.46	0.79	42
21 April 2009	1.11	1.35	18
25 April 2009	1.08	2.29	53
26 April 2009	3.02	4.60	34
6 May 2009	0.77	1.35	43
9 May 2009	0.54	0.86	37
13 May 2009	0.93	1.99	53
26 May 2009	0.39	0.42	7
27 May 2009	1.42	2.31	39
Average interception %			37.8

† No data for 19 July to 1 September 2008 because rain gauge in nearby open area was not yet functional.

Computer-Simulation Models

Soil Water Balance Model

We have simulations from two models: (1) the rather large and complex model of one-dimensional fluxes of energy, water, carbon, nitrogen, and biomass production Integrated Biosphere Simulator (IBIS) model and (2) a much simpler model Soil Water Balance (SWB) model that was recently developed by Bill Bland (the SWB model is very simple—it contained about 140 lines of code). While the IBIS model yields sophisticated estimates of evaporation from soil and transpiration from plants, for a variety of plant types, the SWB model provides a simple analysis of the impacts of precipitation and root-zone water relations on predicted groundwater depth. In this report, we highlight two aspects of the results from the SWB model effort: the effect of replacing (a generic) perennial vegetation with irrigated potato and the ability to predict groundwater levels at a point through time.

Description of the Soil Water Balance Model

The two generic vegetation types represented in the model, perennial and irrigated, differed in root zone thickness, season duration of evaporation, and the presence of irrigation (Table 5).

Table 5. Rooting depth, available water, and evapotranspiration for two generic vegetation types.

Vegetation type	Perennial	Irrigated
Rootzone	1500 mm thick 0.12 available water fraction	300 mm thick 0.12 available water fraction
Season	April-October	May-September
Evapotranspiration	Falls below potential as function of fraction of available water	Irrigated as needed to maintain rate at potential

Potential evaporation rate (PET) was set for each month from April to October, based on an analysis of 11 years of Priestley-Taylor estimates derived from satellite and ground-based measurements in Wisconsin (Bland and Wayne, unpublished) (Table 6). The model assumes no evaporation from irrigated areas during April and October. The bare soil surface dries quickly after a rain, and there is little upward conduction of water in the sandy soils of the region to support continued evaporation. In contrast, the perennial vegetation intercepts and transpires (if green) a larger fraction of rainfall events.

Table 6. Daily potential evapotranspiration vales (PET).

Month	April	May	June	July	August	Sept.	Oct.
Daily PET (mm/day)	1.5	2.5	3.5	5.3	5	4	1

During the winter season (November to March), precipitation accumulated as snowpack. If there was more than 1 mm of snowpack on a day, 0.5 mm was sublimated and 0.01 times the snowpack content was melted, first recharging the soil to field capacity, and then entering groundwater as recharge. On 31 March, all remaining snowpack melts and becomes either soil water or recharge.

The daily precipitation dataset spanned from 1950 through 2006, and was from the recently compiled climatology of Wisconsin created by Dr. Chris Kucharik (UW-Madison, Dept. of Agronomy). Groundwater lateral flow was modeled based on observations from the U.S. Geological Survey (USGS) at Hancock; a minimum value of 1.0 mm day^{-1} increased with head above a groundwater depth of 4600 mm.

The vegetative cover of the modeling domain (an area surrounding a groundwater observation point) can vary from fully perennial to fully irrigated, and change annually as a sigmoidal increase from no irrigation to fully irrigated. Irrigation extractions are considered negative recharge, and are triggered in the model whenever the total available water in the (crop) root zone is depleted to half of its maximum. A depth of water is applied to meet the current day's evaporation and refill the soil water reservoir.

Our primary objective with the SWB model was to test the effects of vegetation on groundwater recharge. Additionally, we wanted to test these predictions by using them to predict actual groundwater levels. Moving from recharge fluxes to groundwater level involves, in addition to recharge, specific yield and a lateral outflow model. We will address first the simulated differences in recharge, followed by our attempt at predicting groundwater level.

Recharge from Perennial and Irrigated Vegetation

The comparative recharge from our vegetation types involves two competing phenomena. Irrigated crops are maintained in a well-watered state throughout their life, so actual evapotranspiration (ET) from such lands will always be at the potential rate. In contrast, ET from perennial vegetation is at the mercy of the soil water held in its (relatively thick) root zone. Thus, during the growing season ET from the irrigated areas will exceed that from the perennial areas, except in years with a considerable amount of rainfall. A potential counterbalancing effect, however, is that when the crops are not present there is little evaporation from bare soils, compared to the evaporation from perennial vegetation through transpiration and interception by standing (if dormant or dead) plant material. Thus, there may be greater recharge from the bare soils of the irrigated lands during (in our model) April and October than occurs beneath the perennial cover.

We found great inter-annual variation in the quantities of recharge from the two vegetation types and their difference (Fig. 11). Annual recharge from irrigated lands increases linearly with annual precipitation, from about -150 mm (1958) to 420 mm (1993). Perennial vegetation recharge is a more complicated function of annual precipitation, however. Although there is considerable scatter, recharge appears to be largely independent of annual precipitation up to about 850 mm. For precipitation above this value, the recharge seems to increase with annual precipitation. Their difference (perennial-irrigation) fluctuates widely, decreasing from about 200 to -100 mm as annual precipitation increases from 500 to 1000 mm. Note that in 1958, one of the largest differences in recharge between the two was found, yet this was all the result of irrigation; recharge from perennial cover was 0.

The average annual precipitation for the period of record was 799 mm. Over this time span, annual recharge from perennial vegetation exceeded that from irrigated lands by 30 mm yr^{-1}.

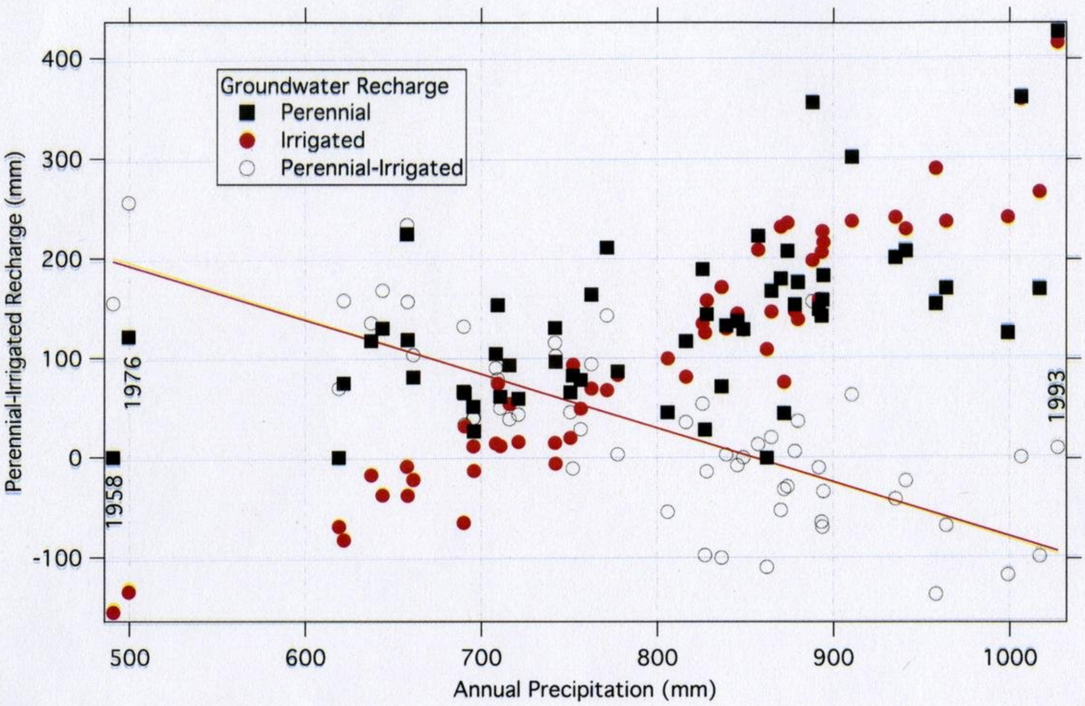

Figure 11. Relationship between annual precipitation and groundwater recharge for two vegetation types.

<u>Reproducing a Groundwater Record</u>

We have evaluated the validity of this model by comparing its predictions of water table elevations to an observed dataset of groundwater elevations. For this we use the long-term water table record compiled by the USGS for a well located at the Hancock Agricultural Research Station (site 440713089320801). We make the assumption that, of the land that supplies recharge, 10% was under irrigation at the beginning of the period and this increased to 90% between about 1985 and 1995 (Fig. 12).

We hope to do further evaluations of this model by conducting an objective optimization of the parameters in the model. This may reveal the reasons why some periods of fit between the model and actual data are better than others. We also hope to explore the hypothesis that the poor match in the early 1980s and post 2000 arise because of changes in the evaporative power of the atmosphere, something that at present is assumed constant across the years of simulations.

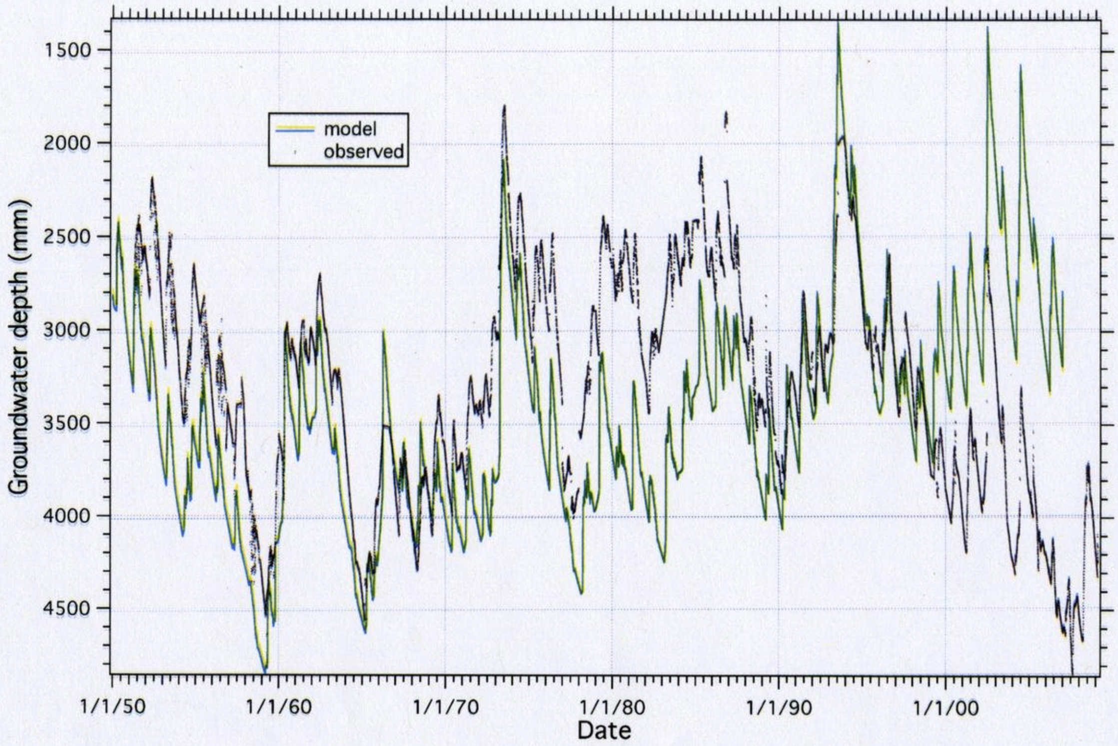

Figure 12. Comparison between model results and measured depths to groundwater.

Conclusion Soil Water Balance Model:

The simple soil water balance model indicates that the difference in annual recharge between perennial and irrigated vegetative covers varies greatly from year to year. On average about 30 mm more recharge should be expected from perennial vegetation than from an irrigated crop, like potato. We believe that the effects of perennial vegetation type (e.g., pine plantation, prairie) and of irrigated crop type are relatively small, but more sophisticated models will offer insight into this assumption.

Our simple model offers a reasonable simulation of actual groundwater levels through many decades, but not during others. Possible reasons for this include, improper estimation of irrigated land fraction in the well vicinity, that our outflow function is either wrong, or that evaporative demand changes at this timescale. Further objective optimization of the model and research on atmospheric demand will clarify these possibilities.

Integrated Biosphere Simulator (IBIS)

Parameters for IBIS have been adjusted to reflect conditions in the WCSP, and these have been spot checked for agreement with our field data or literature values. It should be noted that volumetric soil water content (θ_v) and field capacity significantly effect groundwater recharge. Field measured values of daily average θ_v, and θ_v response to rain events (field data collected by Amber Weisenberger, see first part of this report), were compared and have been found to agree with model output. Leaf area index, rain water interception values, and water budgets are comparable with published values.

The following five graphs summarized IBIS results, by decade, for the five decades covering 1956 to 2006 (Fig. 13-17). The climate data were provided by Chris Kucharik and are specified for the Hancock area. The model has two sand possibilities, a full profile of coarse sand (single layer) and the loamy sand layer over coarse sand (double layer). We used the double layer profiles because the single coarse sand layer did not reflect field measured daily average θ_v values and measured soil water response to precipitation. The soil was considered to be 80 cm of loamy sand over 170 cm of coarse sand. Since IBIS does not consider organic matter and the space occupied by roots, it is better to use the double layer to better reflect actual upper soil profile conditions found in the WCSP. Water use by four perennial plant functional types (pfts) was compared with irrigated corn. The pfts were prairie grass, coniferous and deciduous shrubs, mixed deciduous cold forest, and mixed temperate coniferous forest. The contribution of plants to pft leaf area index (LAI) is presented in Table 7.

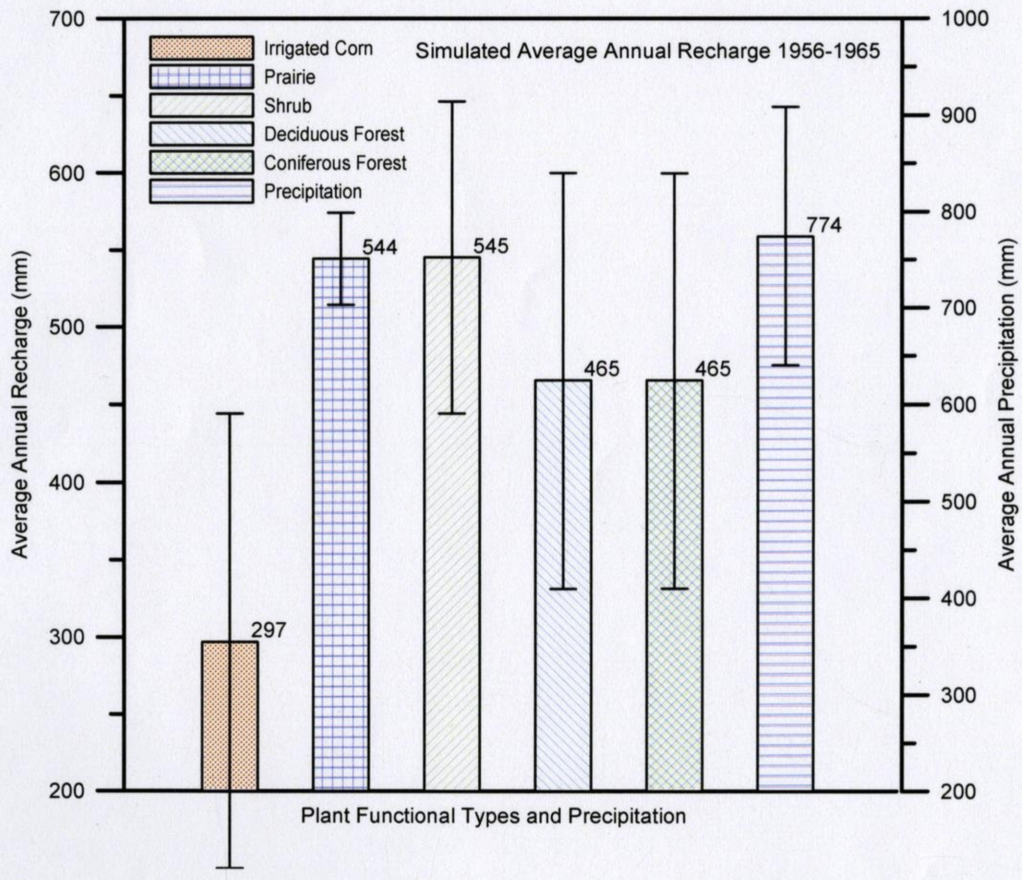

Figure 13. Model simulated recharge results in mm (y-axis) for 1956-65 for several vegetation types.

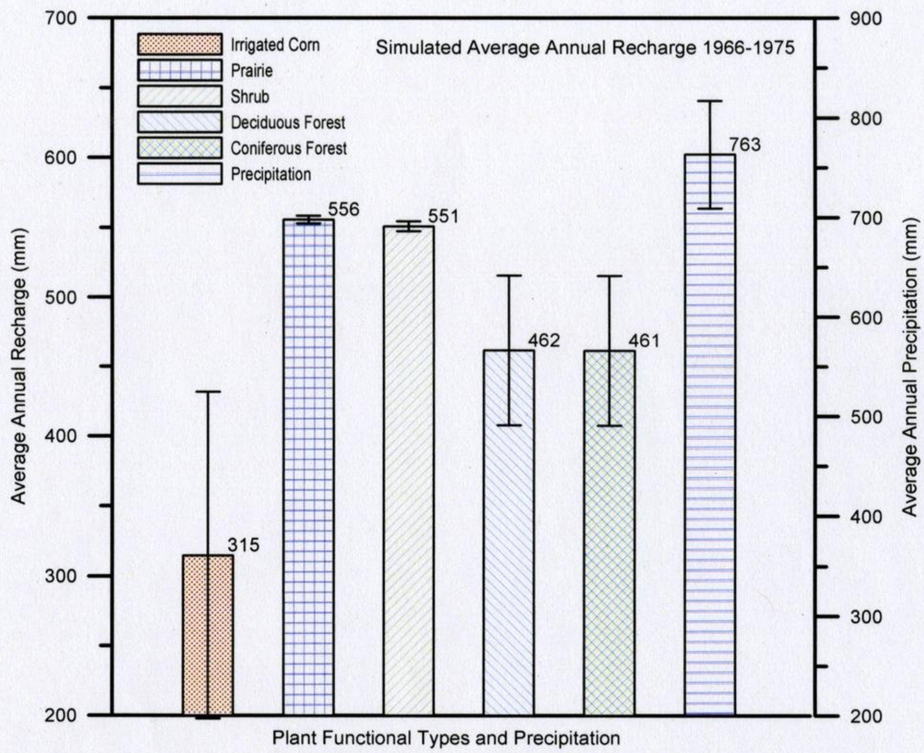

Figure 14. Model simulated recharge results in mm (y-axis) for 1966-75 for several vegetation types.

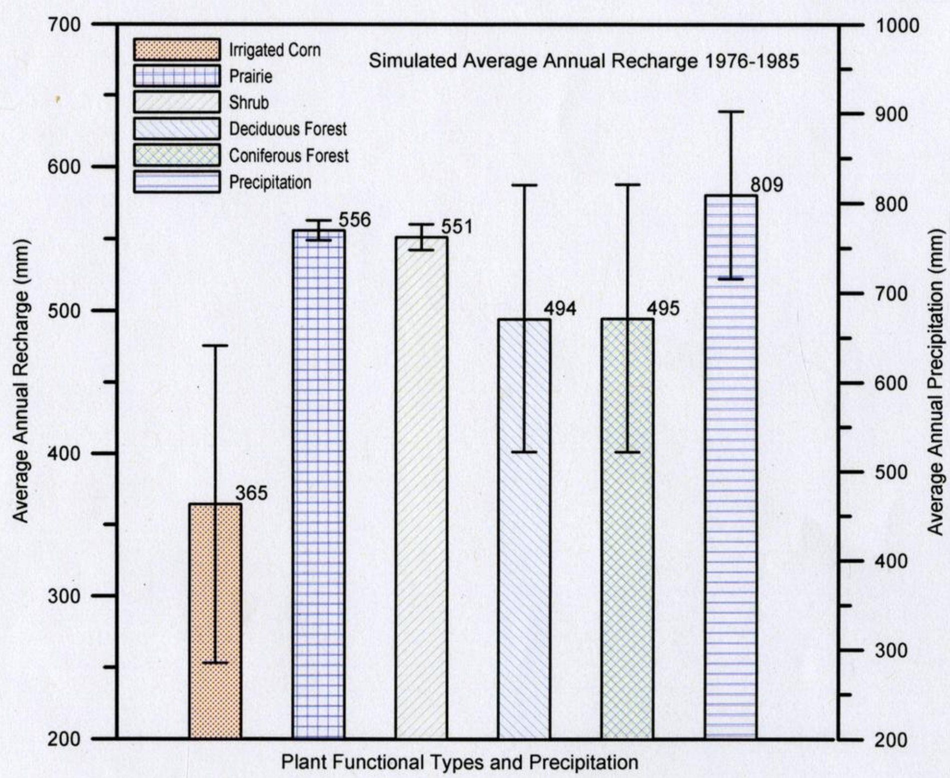

Figure 15. Model simulated recharge results in mm (y-axis) for 1976-85 for several vegetation types.

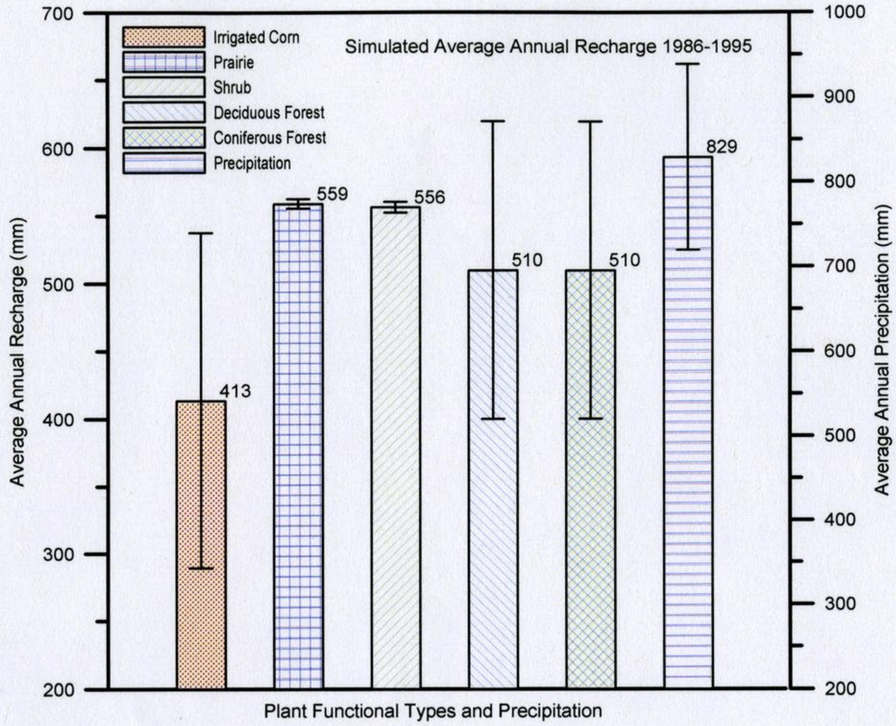

Figure 16. Model simulated recharge results in mm (y-axis) for 1986-95 for several vegetation types.

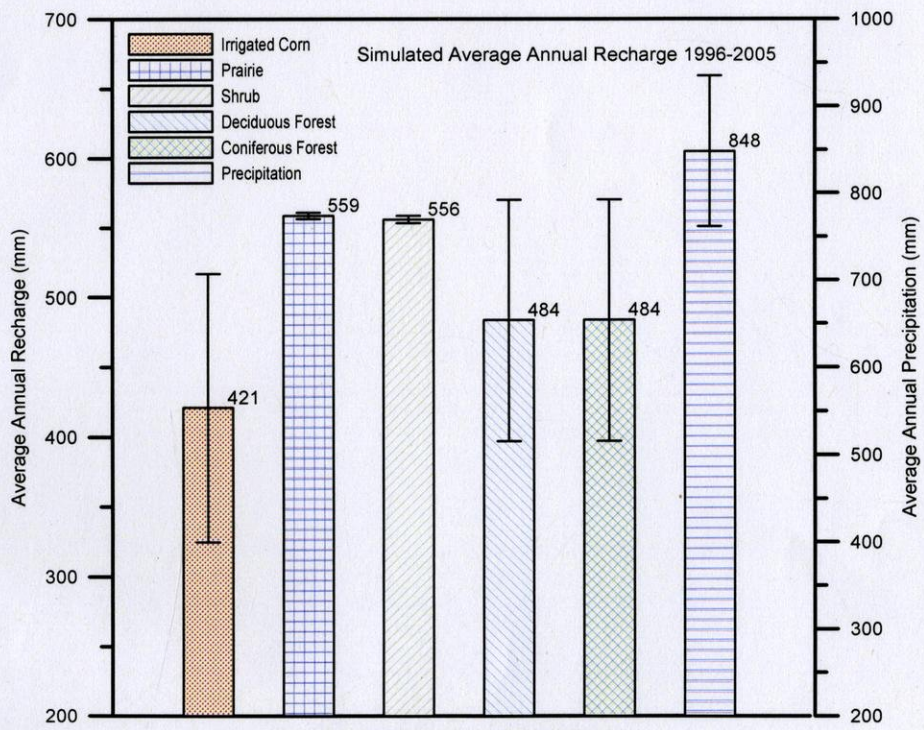

Figure 17. Model simulated recharge results in mm (y-axis) for 1996-05 for several vegetation types.

Table 7. Perennial plants leaf area index (m^2 m^{-2}) constant values for growing season.

Plant functional type †	4.00	5.00	9.00	10.00	11.00	12.00	Total
Grass	0.00	0.00	0.00	0.00	1.25	1.25	2.50
Shrub	0.00	0.00	0.50	0.50	0.25	0.25	1.50
Deciduous	2.00	2.00	0.00	0.00	0.00	0.00	4.00
Conif	3.00	1.00	0.00	0.00	0.00	0.00	4.00

† Plant functional type: 4 = temperate conifer evergreen tree, 5 = temperate broadleaf cold deciduous tree, 9 = evergreen shrub, 10 = cold deciduous shrubs, 11 = warm C4 grasses, and 12 = Cool C3 grasses

The significant components of yearly water budgets are precipitation, ET, and rain water interception by plant material (interception). Surface runoff and changes in soil water storage make up a small portion of the annual budget for this area; thus, these were excluded. The annual water budget was checked and it balanced (data not shown). It should be noted that the IBIS model does not kill plants when they become water stressed. Rather plants are allowed to go dormant until water is again available. This is a true assumption for natural vegetation, but this is not the case for agricultural crops; thus, this is not an accurate assumption in IBIS. However, it makes for an easy comparison of increased ET with irrigation. In the model, water draining below 2 m is considered recharge to groundwater. In IBIS, irrigation is applied below the plant canopy on top of the soil surface similar to rain. Thus, irrigation water is not taken from the groundwater as is the case in actual field operations; the model does allow water to evaporate from the soil surface and water not used by the plants (transpired by plants) or evaporated from soil surface is returned to groundwater. We set the model to apply irrigation water in sufficient amount to keep θ_v near 0.16 m^3 m^{-3} during the growing season. This value was chosen based on data collected as part of our field measurements (and presented in the first part of this report; see Fig. 3) of soil water content during the growing season under irrigated corn. Because the model does not remove groundwater for irrigation, the recharge for irrigated corn has been corrected for irrigation. That is, recharge is the difference between total drainage below two meters and total amount of water used for irrigation. Annual amounts of irrigation and precipitation does not fit a linear regression (Fig. 18). The fit has an R^2 vale of 0.32. We had anticipated that as total precipitation increased the amount of water needed for irrigation would decrease.

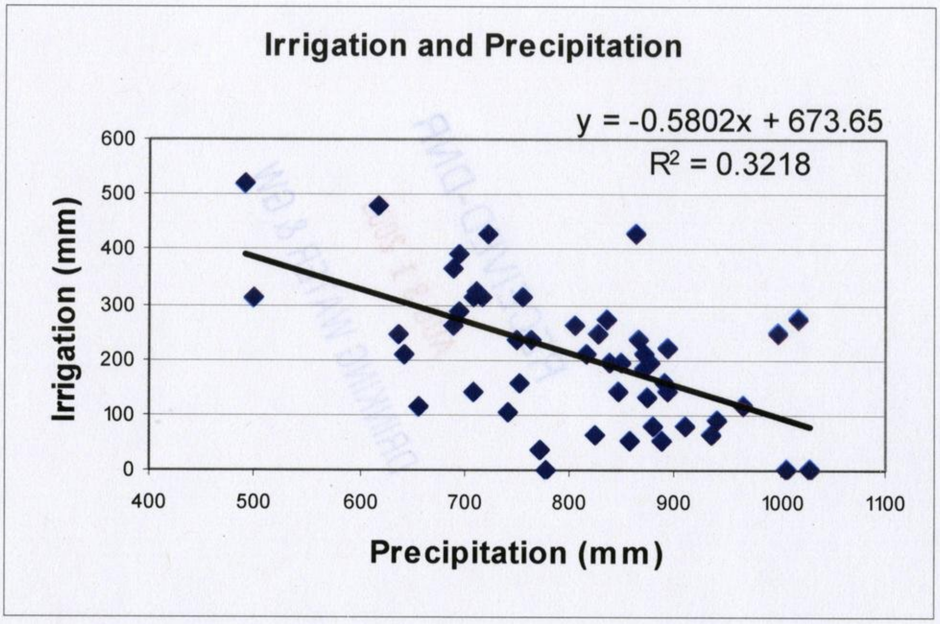

Figure 18. Model computer relationship between irrigation and precipitation.

Conclusion Integrated Biosphere Simulator:
Estimating evapotranspiration (ET) and ground recharge by computer simulation modeling of the water budget is prone to error resulting from imperfect assumptions. Thus, modeling results should be considered given the conditions set in the model and applied with caution. The simulated amount of groundwater recharge varied between decades, but it was always greater for non-irrigated vegetation types.

Summary and Further Research Needs:
Continuous groundwater monitoring in the WCSP is important to understand seasonal and annual variations in water table depth on a more discrete measurement scale. Results from this study have shown that vegetation can play a significant role in recharge patterns of groundwater. Vegetation cover can cause differences in soil frost depth, allowing recharge to the groundwater table during the winter months. Results from this study also confirm that natural vegetation can use the water table as a significant water source in parts of the WCSP. It is important that additional data on groundwater use be collected for the WCSP to further our understanding of the effect that irrigated and natural vegetation have on the water table over a longer time span. There is a need for obtaining a better understanding of potential changes in climate on groundwater recharge, especially changes in relative humidity and solar radiation.