Forecasting impacts of extreme precipitation events on Wisconsin's groundwater levels

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Project Summary
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Background/Need: Large precipitation events in southwest Wisconsin during 2007 and 2008 caused water table rise and flooding of about 4,400 acres several kilometers away from the flood plain of the Wisconsin River. The long-lasting flood caused $17 million in property and crop damage, and drew interest to impacts of climate change on ground water recharge and rapid water table rise.

Objectives: To evaluate potential effects of climate change on temporal and spatial patterns of groundwater recharge in a humid region. The likelihood of groundwater inundation of low-lying areas is also considered.

Methods: We applied a series of climate and hydrologic models to a study area in Spring Green, Wisconsin, for two 20-year periods in the 21st century (2046-2065 and 2081-2100). Statistically down-scaled climate forecasts (50 kilometer resolution) from eight Global Circulation Models (GCMs) were applied to a grid-based soil water balance model (SWB). Daily estimates of deep infiltration from the SWB model were applied as recharge to the water table in a three-dimensional groundwater flow model. Results include estimates of recharge, water table rise and groundwater flooding.

Results and Discussion:
Precipitation: The average of the annual precipitation rates among the eight climate models in both future periods, 886 mm, is 7% greater than simulated for the "base case" period (1981-2000). The range in average annual precipitation for future periods is wider than the base case, varying from 706 to 1,030 mm for 2081-2100. All of the climate models predict an increase in temperatures for all months relative to the base case, coinciding with the increase in CO_2 concentrations in the emissions scenarios.

Recharge: SWB model results show a trend of decreasing average annual recharge in the mid- and late-21st century. Over all eight GCMs, mean annual recharge for 2046-2065 decreased 4% (15 mm) from the base case (358 mm), but three models predict no change or an increase in recharge during this period. By the end of the century, average annual recharge decreases 25% from the base case, and none of the eight models predict an increase compared to the base case.

Although the SWB simulations are predicated on the increase in precipitation forecast by the climate models, the temperature increase common to all eight climate models results in more water partitioned to ET, which reduces recharge to groundwater. The SWB model results are sensitive to plant type, which is represented in the SWB by the soil depth parameter. An increase in this parameter effectively increases soil storage capacity, allowing evapotranspiration to occur at a high rate for a longer period of time. In this application of the SWB model, the soil depth controls partitioning between recharge and evapotranspiration.

Model results suggest that although recharge declines on average, high recharge years will occur more frequently in the future. The variability in annual recharge increases substantially in both future periods. By the late-century, recharge ranges from 41 mm to 701 mm per year, with a mean of 302 mm.

Water table conditions: Under the highest and lowest simulated recharge rates, average groundwater levels in the study area declined compared to the base case. However, both recharge scenarios produced some years of very high water table elevations, similar to those observed in 2007 and 2008. The model shows up to 3 meters in water table fluctuation during years with extreme recharge events, which is sufficiently large to cause groundwater-related flooding in the study area if antecedent conditions include above average water table conditions.

We applied the climate record for 2007 and 2008 to the SWB model to compare simulated water table response to recharge to conditions observed in 2007 and 2008. The SWB annual recharge depths for 2007 and 2008, 653 and 638 mm respectively, are among the highest values simulated for either future period. The 21st century simulations generated only one such instance of successive high-recharge years (693mm and 660 mm).

Conclusions/Implications: This series of models suggest that years of extremely high water table conditions may still occur but will remain relatively rare in the 21st century. Water resource managers should expect to see some years of high recharge amongst overall less recharge on average. This SWB model indicates warmer climate conditions will increase ET, resulting in a reduction in recharge under certain crop types or land cover.

The series of models may be applied to various settings to determine likely fluctuation in water table elevation. In the Spring Green region, the water table fluctuates 3 meters, and this estimate can be used to plan suitable development (for example, basement and foundation depths, road construction, or design of on-site wastewater treatment systems). This finding may also inform mapping of land susceptible to water table rise to the ground surface, or to evaluate the utility of crop insurance or drainage systems for agricultural lands.

The eight statistically downscaled GCMs produce a wide range and high variability in annual recharge estimates. This may limit the utility of these forecasts for water resources engineers concerned with climate change.

Recommendations: Future research should investigate partitioning of rainfall between ET and deep infiltration using more robust methods to estimate ET.

Related Publications:

Gotkowitz, M.B., Attig, J.W., McDermott, T. and Saines, M., In Review. Groundwater Flooding of a River Terrace in Southwest Wisconsin.

Key Words: climate change, recharge, evapotranspiration, groundwater flooding

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1. Introduction

In the summer of 2008, the region near Spring Green, Wisconsin, experienced flooding of 4,378 acres (1772 ha) several kilometers away from the flood plain of the Wisconsin River, outside areas currently designated as floodplain by the Federal Emergency Management Agency. Field investigation and modeling showed that surface runoff was captured in closed topographic depressions and was unable to infiltrate due to water table rise to the land surface (Gotkowitz et al., In Review). This water table rise followed record snowfall the preceding winter and unusually high summer precipitation in 2008 – including a record 432 mm in an 8-day period in early June. The floods were sustained for nearly six months, causing $17 million dollars in damage and the condemnation of 29 homes.

The extensive damage to agricultural crops and residential and commercial properties brought heightened interest to the potential impacts of climate change on ground water recharge and rapid water table rise. Concerns include the need to alter or adapt current emergency response systems, infrastructure design, building standards, and land use to these potential effects of changes in the frequency and magnitude of precipitation events. Several hydrologic analysis tools now available lend themselves to testing potential impacts of climate change in various hydrologic settings. This project was undertaken as a proof of concept wherein a series of climate and hydrologic models is applied to the Spring Green study site to predict the likelihood of significant water table rise and groundwater flooding in humid regions with a shallow water table.

Due to an increase in fossil fuel consumption over the last century and accompanying increase in concentrations of atmospheric greenhouse gases, local- and global-scale climate change is expected throughout this century (IPCC, 2007). Climate change may include changes to the intensity, magnitude, and frequency of precipitation events, daily minimum and maximum temperature, and relative humidity. Many global climate models (GCMs) have been produced to predict these changes to climate, but the models differ significantly on the degree to which precipitation and temperature will be affected in humid regions of the Midwest. While some models predict wetter conditions and others predict drier conditions, most predict more common extreme precipitation events. Additionally, increasing winter temperatures changes are expected impact the volume and timing of snowmelt. These factors are likely to impact groundwater recharge.

Groundwater recharge is of particular interest where it may cause rapid water table rise to the land surface. Groundwater flooding is defined here as ephemeral rise of the water table above land surface. Such conditions can occur in areas with poorly developed surface drainage when climatologic and hydrogeologic conditions cause rapid water rise. For this condition to occur, recharge must exceed the aquifer storage capacity and the rate of discharge to established surface water bodies. Where this condition persists or is a frequent occurrence, the surface water is more likely considered a wetland, rather than an instance of groundwater-related flooding. Groundwater flooding appears to be a rare occurrence that has received little attention in peer-reviewed literature. One exception is extensive and long-lasting flooding in 2001 of the Chalk aquifer in northern France (Negrel and Petelet-Giraud, 2005) and southeast England (Adams et al., 2010).

1.1 Project scope and objectives

This project was undertaken as a proof of concept wherein a series of climate and hydrologic models were used to assess potential changes in groundwater recharge in a temperate climate. Output from regional scale (50 kilometer resolution) climate forecasts were applied a grid-based soil water balance model (SWB), which yielded daily estimates of deep infiltration through the soil column. The infiltration was applied as recharge to the water table in a three-dimensional MODFLOW (Harbaugh 2005) model of the region. This modeling sequence tested the utility of the downscaled climate projections in assessing future groundwater recharge patterns, and examined the vulnerability of the selected landscape to recurring episodes of groundwater inundation. The modeling approach was supplemented with a modest field investigation to determine the suitability of the existing hydrogeologic conceptual model to the study area.

Our objectives included evaluating the effects of climate change on groundwater recharge and water table elevation in a humid region with a shallow water table. We examined the likelihood of groundwater inundation of low-lying areas at the Spring Green study site under these climate forecasts, producing a series of water table hydrographs for the period studied. An additional objective of the work was to examine potential effects of alternative cropping on evapotranspiration rates and subsequent groundwater levels. This is of interest because enhanced evapotranspiration offers a potential benefit of lessening the frequency or extent of groundwater inundation.

1.2 Study Site

Most of the area flooded in the summer of 2008 is within the town of Spring Green, in southwest Sauk County (figure 1). Climate in this region is typical of the midwestern United States, with average annual precipitation of about 840 mm, most of which occurs from April through September. Average daily temperatures vary from -8.2 °C in January to 22 °C in July (National Climate Data Center, 2004).

Spring Green is in the “driftless area” of Wisconsin, a region extending into Minnesota, Iowa, and Illinois, that is free of Pleistocene glacial sediments present throughout much of the Midwest (Heyl et al., 1959). The landscape is characterized by steep hillslopes that separate river valleys from narrow, flat-topped uplands. In the study area, the Wisconsin River traverses a broad expanse of glacial outwash deposited by meltwater streams flowing from Quaternary glaciers. The 2008 flooding occurred on the upper of two terraces in the area, which lies about 7.4 m above and 4 km north of the floodplain of the river (figure 2). Extensive deposits of wind-blown sand on the terrace create about 11 m of topographic relief. A bedrock escarpment flanks the terrace to the north, rising to an elevation of 335 m. The lower parts of some stream valleys, such as Big Hollow, that cut the bluffs are lined with fine-grained sediment deposited in ancient (late-glacial) lakes.

The outwash deposits form an unconfined aquifer consisting of coarse-grained sand and gravel over 50 m in thickness (figure 2) (Gotkowitz et al. 2005). These deposits are underlain by a thick, regionally-extensive Cambrian sandstone aquifer. The uplands are capped by dolomite of the Ordovician Prairie du Chien group. Groundwater in the study site generally flows from north to south from the uplands to the Wisconsin River. Hydraulic conductivity of the sand and gravel deposits is 49 m/day on average, while the sandstone aquifer hydraulic conducitvity is about 2.4 m/day. Crystalline PreCambrian rock undelies the Cambrian units and forms the base of the deep aquifer.

The uplands are relatively well-drained with a number of ephemeral streams capable of removing surface water and high groundwater from the system. These streams generally become perennial on downstream reaches near the Wisconsin River. However, the terraces that experienced flooding in 2008 contain internally-drained closed depressions and lack any perennial streams. Rainfall runoff forms ponds; this water either infiltrates or evaporates.

2. Methods

The primary components of this project included compilation and formatting of GCM output, running a soil water balance (SWB) model, and refining and running a three-dimensional transient groundwater flow model of the study area (Figure 3). A limited field investigation added to the existing hydrogeologic characterization of the study site.

2.1 Climate Models

The Climate Working Group of the Wisconsin Initiative on Climate Change Impacts (WICCI) statistically down-scaled results from 15 of 20 GCMs submitted to the Coupled Model Intercomparison Project (CMIP3). We used eight of these GCMs (Table 1) for the years 2046-2065 and 2081-2100. All employ the A2 carbon emissions scenario, which is considered a high-end emissions scenario representing the most realistic emissions trajectory (IPCC, 2001).

Table 1. Eight down-scaled GCMs

Canadian Center for Climate Modeling and Analysis's CGCM 3.1	CCCMA
Australian Commonwealth Science and Research Organization's Mark 3.0	CSIROMK30
Geophysical Fluid Dynamics Laboratory's Climate Model 2.0	GFDL
Max Planck Institute for Meteorology's ECHAM5	MPIM_ECHAM5
Centre National de Recherches Meteorologiques Climate Model 3	CNRM
Australian Commonwealth Science and Research Organization's Mark 3.5	CSIROMK35
Model for Interdisciplinary Research on Climate 3.2 medium resolution	MIROC32
Meteorological Research Institute's CGCM2 3.2	MRI_CGCM2

The GFDL simulation for 1981-2000 provides a "base case" for comparison. All GCMs are de-biased in this early period and are constrained to produce similar results, so output from the other GCMs for this period were not analyzed. Comparison of actual and modeled monthly precipitation and monthly temperature showed that the GFDL results reasonably match observed conditions for 1981-2000.

2.2 Soil Water Balance Model

Daily precipitation, minimum temperature, and maximum temperature estimates from the downscaled GCMs drive the SWB model (Westenbroek et al., 2009) which produces spatially-varying estimates of deep infiltration. The SWB uses a daily time step and was applied to a 30m x 30m grid of the study site. The SWB requires site-specific land use, soil type, available soil water capacity, and flow direction information, which were obtained from widely available GIS datasets. For the purpose of this project, output from the SWB model was compiled as a deep infiltration (that is, recharge) depth for each grid cell for each day, for each twenty-year simulation. Ultimately, the two GCM datasets that resulted in highest and lowest average annual recharge were carried forward to the groundwater flow model.

The model estimates daily infiltration at each grid cell based on daily precipitation, antecedent soil moisture, land use, and soil type using the SCS Curve Number approach (United States Department of Agriculture, 1986). This is an empirical method that estimates the amount of runoff generated for a specified area and a precipitation event of a known magnitude. In the SWB, if effective precipitation (P) exceeds potential evapotranspiration (PE), infiltration occurs and soil moisture increases up to a maximum water-holding capacity (roughly equal to the field capacity). Any infiltration beyond this maximum value becomes deep drainage that travels below the root depth of vegetation. For the purposes of this project, this “deep infiltration” is considered recharge to the groundwater system. If PE exceeds P, the model removes water from the soil using an accumulated potential water loss value that limits evapotranspiration based on the number of consecutive days in which P < PE. Soils yield water to ET more easily when soils are relatively wet, as is typical during the days immediately following rainfall events (when P > PE).

The model routes runoff to downslope grid cells (flow direction data is obtained from a digital elevation model); runoff may then infiltrates in a downslope cell. This runoff/infiltration process continues until the water infiltrates, reaches a surficial water body, or reaches the edge of the model domain. The Spring Green area lacks surficial drainage outlets and contains many internally-drained closed depressions. To simulate these conditions, the maximum daily infiltration parameter in the SWB is set to a very high value (25.4 cm). This ensures that runoff captured in closed depressions is ultimately simulated as infiltration, rather than being routed out of the model.

In the SWB model, the “soil depth” parameter is analogous to rooting depth, and it must be specified for each grid cell. Increasing or decreasing the magnitude of soil depth alters the model’s partitioning of precipitation into evapotranspiration, infiltration, and surface runoff under a specific vegetation type. Generally, a large soil depth produces more ET as roots penetrate deeper, and more infiltration is required to produce deep drainage or recharge. The SWB model contains default soil depth parameters for each soil and land use type. These vary from 0 m open water and perennial ice and snow to between 0.6 and 1.4 m for most vegetation (including agricultural, grassland, and forested vegetation). Additional detail on the SWB is provided by Westenbroek et al. (2009).

2.3 Groundwater Flow Model

SWB-generated estimates of deep infiltration were applied to a refined version of a Spring Green MODFLOW model (Gotkowitz et al., 2002). The refined model grid consists of 372 rows and 445 columns, with a spatial resolution of 30m x 30m in the vicinity of the flooded area (figure 1). Cell size increases to a maximum of 500m x 500m at the model boundaries. The resolution provides greater accuracy near the flooded region, with decreasing resolution with distance from the site to allow for reasonable model run times. The model was then checked to ensure it maintained a good calibration.

Table 2. Hydraulic conductivity and specific yield

Area	Horizontal hydraulic conductivity (m/day)	Vertical hydraulic conductivity (m/day)	Specific Yield
Layer 1: uplands alluvium	15.2	1.52	0.15
Layer 1: valley alluvium	76.2	7.62	0.1
Layer 2: Sandstone bedrock	0.582	0.0582	0.001
Layer 2: Upland interbedded sedimentary bedrock	0.0582	0.00582	0.0001

The two-layer model contains two hydraulic conductivity zones per layer (Table 2, Figure 2). Boundary conditions consist of specified heads on the west, north, and east edges of the domain, derived from simulated conditions obtained in previous modeling of the area (Gotkowitz et al., 2002). The Wisconsin River is assumed to be fully penetrating and is the southern model boundary. Streams high in elevation are treated as MODFLOW drains. This approach is useful because many upland reaches of these streams are ephemeral, and the drain feature simulates groundwater discharge only if the simulated water table exceeds the modeled stream elevation.

2.4 Field Investigation

Using direct-push methods, we collected sediment cores and installed monitoring wells at the locations and depths shown in Figures 1 and 4. Fine-grained sediments were encoutnered in Big Hollow, north of the flooded area. No fine-grained sediment was observed within the outwash deposits on the terrace. These points provided measurements of vertical hydraulic gradients in the study area.

3. Results
3.1 Climate Predictions

Seasonal and daily precipitation data generated by the GCMs were averaged for the base case period, 1981 – 2000, and mid- and late- 21st century time periods. The mean annual precipitation forecast for the area is 886 mm for 2046-2065 and 2081-2100, an increase of about 7% from the average for the base case period (828 mm per year). As illustrated in Figure 5, the range in average precipitation increases in both future period increases from the base case. Six of the eight models predict that conditions in 2081-2100 will be similar or wetter than 1981-2000. Comparison of the GFDL base case with the 21st century results suggests that on average, seasonal differences may include drier summers with wetter spring and autumn (Figure 6). Winter precipitation increases slightly by the end of the century.

All eight GCMs predict an increase in temperatures for all months relative to the base case period, coinciding with increasing CO_2 concentrations in the IPCC emissions scenarios (2007). On average, the simulated monthly temperatures rise from the base case average of 7.9°C by 2.9 °C by 2065 and by an additional 2.8 °C at the end of the century (Figure 7). Predicted mean annual temperatures range from 10.4 °C (CSIROMK30) to 12.4 °C (MIROC32) in 2046-2065, with a larger range predicted for 2081-2100, from 10.6 °C (CSIROMK35) to 16.7 °C (MIROC32).

3.2 Recharge Estimates

The SWB model provides spatial estimates of recharge over the model domain. The pattern of recharge in the study area includes higher values in the Wisconsin River valley, where coarse-grained sandy soils and the lack of streams and drainage enhance infiltration (figure 8). Recharge in the uplands to the north is generally lower with the exception of the forested slopes. Recharge averaged across the model domain for the base case period is 358 mm. This is consistent with SWB results in neighboring Dane County, WI, which indicate about 350 mm of recharge in the western, unglaciated areas in the county (Hart et al., 2009). The mean annual recharge distribution for the base case period was slightly negatively skewed, indicating years of low recharge were more likely than years of high recharge. Annual recharge during this period ranged from 190 to 510 mm per year.

Mean annual recharge simulated from the eight GCMs for 2046-2065 was 343 mm (table 3), a 4% decrease (15 mm) from the base case. These simulations have a positively-skewed frequency distribution, indicating that the likelihood of high recharge years increases compared to the base case (figure 9). The range varies from about 100 mm to up to 752 mm per year. Mean annual recharge varies from 101 mm under the MIROC32 scenario – a decrease of 25% from the base case, compared to 389 mm under GFDL, which is an increase of 8.5% from the base case. Some models, such as MIROC32, have a positively skewed distribution, while the CNRM model yields a distribution close to normal.

Mean annual recharge simulated for the late century, 2081-2100, was 302 mm. The frequency distribution was also positively skewed (figure 9); overall, these simulations predict a decrease in average annual recharge but an increase in the number of years that fall above average. Figure 10 shows a greater range in recharge in the late-century period than the mid-century. Model ECHAM5 results in the greatest annual recharge of 701 mm, while MIROC32 produces the lowest year, of 41 mm. Several of the models yield an average annual recharge near that of the base case (358 mm). The MIROC32 model produces an average recharge almost 50% lower (170 mm).

Table 3. Annual recharge by GCM for future climate periods. All values are in centimeters.

	2046-2065					2081-2100				
	Min	Max	Mean	Change from Base	Skew	Min	Max	Mean	Change from Base	Skew
CCCMA	19.3	72.0	37.5	+1.6	0.97	21.1	64.6	35.8	-0.05	1.31
CNRM	18.3	46.3	31.5	-4.3	0.09	8.30	35.6	20.5	-15.3	0.03
CSIROMK30	13.9	75.3	35.7	-0.15	0.74	11.3	61.8	34.0	-1.8	0.28
CSIROMK35	12.7	61.8	35.0	-0.8	0.33	12.7	61.6	35.0	-0.84	0.33
GFDL	17.5	61.5	38.8	+3.0	0.15	16.7	48.3	30.9	-4.9	0.38
MIROC32	9.88	65.0	26.9	-8.9	1.17	4.11	50.9	16.8	-19.0	2.17
MPIMECHAM5	14.8	59.4	34.3	-1.6	0.20	10.7	69.2	35.5	-0.30	0.56
MRICGCM2	22.8	54.6	34.3	-1.5	0.48	13.1	50.9	33.9	-1.9	-0.30
ALL GCMs	***16.1***	***62.0***	***34.2***	***-1.6***	***0.97***	***12.2***	***55.4***	***30.3***	***-5.5***	***0.53***

Figure 11 compares the proportion of average annual recharge, evapotranspiration, and precipitation for each model during both future climate periods. The CNRM model illustrates the case where increased precipitation produces an increase in ET and a decrease in recharge. The SWB model simulates an average of 452 mm of ET annually in the base case period; this value rises to 510 mm in 2046-2065 (average of 8 GCMs) and 549 mm for the late 21st century. These models indicate that a higher proportion of rainfall is partitioned into ET, decreasing recharge.

3.2.1 Evapotransipiration and the soil depth parameter

The SWB model applies a user-specified soil depth parameter (roughly analogous to rooting depth) to calculate ET at each model cell. Model sensitivity to this parameter was evaluated by doubling soil depths from base case values and generating five years of SWB output with CCCMA (2046-2050) climate data. Total annual ET increased between 45 mm and 51 mm, decreasing recharge by about 10% (between 45 to 59 mm). This decrease in simulated recharge indicates that the SWB model is sensitive to plant type. Soil depth is an important determinant in the model's partitioning between recharge and evapotranspiration because it increases soil storage capacity and allows ET to occur at a maximum potential rate for a longer period of time.

One of the most poorly-understood aspects of climate change is potential changes in ET, which is highly dependent upon vegetation type and soil water availability. Doubling the SWB soil depth parameter, as described above, simulates a change in dominant vegetation from relatively shallow- to deep-rooted plants (for example, switching from corn to poplar trees). This suggests that a change in cropping patterns could exacerbate changes to the hydrologic system resulting from an increase in temperatures, increasing the proportion of precipitation that is evapotranspired.

3.2.2 MODFLOW Model under Observed Climate in 2007 and 2008

We evaluated the ability of the SWB recharge estimates to simulate observed water table response to recharge using 2007 and 2008 climate data from Spring Green (Automated Weather Observation Stations, 2010). Annual precipitation totaled 1240 and 1070 mm in 2007 and 2008, respectively, with a record 430 mm during an 8-day period in June, 2008. With this precipitation record as input, the SWB model simulates 653 mm of recharge in 2007 and 638 mm in 2008. These values are similar to the maximum recharge depths predicted under the eight GCMs during the mid- and late-century periods (Figure 10).

The simulated daily recharge for 2007 and 2008 was applied to the MODFLOW model. Figure 12 illustrates the match obtained between the simulated water table and observations from Peck's well, located in Spring Green. A second comparison (Figure 13) between daily measurements from a monitoring well in Mazomanie, Wisconsin (located about 20 km east of Spring Green) and model results shows that the model reproduces large peaks as well as gradual increases and decreases in water table elevation during 2007 and 2008. The simulated magnitude of water table fluctuation is greater at Spring Green than in the record observed at Mazomanie, which is attributed to differences between actual recharge in Mazomanie and the simulated recharge applied to the model in Spring Green.

3.3 Water Table Response to Recharge

The effect of changing recharge in the 21st century was investigated by applying the highest and lowest recharge records from the GCMs (CCCMA and MIROC32 respectively) to the MODFLOW model. The head distribution generated from a dynamic-equilibrium run-up period provided the initial conditions for this transient simulation. Hydrographs (Figure 14) were compiled for two locations in the model domain; Peck's well, which was flooded in 2008, and SG2, which did not experience flooding.

These model results indicate that groundwater rising to the land surface may re-occur, but will remain a rare event. In simulations of the mid-21st century, high recharge conditions result in a relatively steady water table, at about 216.6 meters, with annual fluctuations of up to three meters in extreme cases. Low recharge conditions result in an average water table elevation of 215.2 meters by 2055, with annual fluctuations of about 1.5 meters. Both the wet and dry models predict one instance of groundwater flooding (defined as the water table reaching the land surface elevation of 219 meters). The model shows numerous instances of the water table rising to within one meter of the land surface.

By the late 21st century, both high- and low-recharge models suggest about a 0.5 meter decrease in the average water table elevation from the mid-century, about 216.0 and 214.8 m respectively. The water table rises to within one meter of the land surface once under high-recharge conditions and not at all under the low-recharge model.

Results at well SG2A are similar with respect to the absolute change in the water table. The high-recharge model causes a water table decline of about 0.6 m by the end of the century, and low-recharge conditions yield a similar decline, from about 215.4 meters in 2055 to 214.8 meters at the end of the century. Because this location has a higher elevation and a greater initial depth to water, it is not susceptible to water rise to the ground surface in any of the simulations.

4. Discussion

The eight GCMs and the SWB model applied to the study area indicate that on an annual basis, recharge will be more variable under future climate conditions. Figures 9 and 10 are perhaps most illustrative in portraying the potential ranges in annual recharge; some of the GCMS suggest that average conditions may not change, but low- and high-recharge years may occur more frequently. These graphs show a general downward trend in average recharge by the late-21st century, and three of the GCMs indicate that average recharge may fall below the 25th quartile of that seen in the 20th century. During the mid-21st century, recharge is expected to drop about 4% from the base case. However three models predict no change or an increase in recharge during this period. By the end of the century, the drop in recharge increases to 25% from the base case, and none of the models predict an increase from the base case.

The changes in recharge predicted by the SWB model are driven by the magnitude of precipitation and changes in temperature in the down-scaled GCM results. MIROC32, for instance, predicts the lowest annual precipitation and the highest temperatures (figures 5 and 7), resulting in both the lowest average and the lowest range of annual recharge (figure 10). CCCMA predicts the highest precipitation, resulting in high average recharge. The large difference in simulated recharge generated from these eight GCMs indicates the importance of using more than one GCM to examine potential hydrologic conditions under changes in climate in this region. Additionally, the importance of increasing temperature in the recharge estimates is driven by the partitioning of soil water between ET and recharge in the SWB model. Minimum, maximum, and average daily temperatures are employed in a Thornthwaite-Mather approach to estimate ET. The importance of ET to these recharge estimates suggests additional, robust methods to estimate ET could be useful to further investigate the impact of temperature and vegetation type on the fate of water in the vadose zone.

Applying the highest and lowest estimates of recharge from the SWB to the groundwater model causes water table decline *under both conditions* during the late 21st century (Figure 14). The high recharge case, the CCMA model, undergoes a large increase in ET from mid- to late- 21st century (Figure 11). This change in the soil water balance drives the decrease in recharge to the water table. By 2100, both high- and low-recharge conditions result in water table elevations at Peck's well area that are well below the land surface, suggesting that rising temperatures and their affect on ET will alter the hydrologic cycle.

High groundwater conditions may be a recurring issue during the mid-21st century. Both high-and low-recharge scenarios produce years of water table elevations as high as those experienced in 2007 and 2008, generating one instance of groundwater flooding at Peck's well. The high-recharge simulation causes several instances of water table rise to within a meter of land surface. By the late-21st century, these two models do not generate years of such high water table conditions. However, as described below, such a result would likely have occurred had the late-century recharge estimates from MPIM_ECHAM5 been carried forward to the groundwater model.

To compare future recharge and water table response to actual conditions in 2007 and 2008, we applied daily climate observations from Spring Green to the SWB model. This produced annual recharge of 65.3 and 63.8 cm, respectively, among the highest values generated by the eight GCMs for future periods (Figure 10). The combination of two high recharge years in succession likely played a role in the occurrence of flooding. Successive years of high recharge are rare in the GCM results. The MPIM_ECHAM5 model generated 69.3 and 66.0 cm of recharge in 2094 and 2095, respectively. This analysis also provides a sense of the annual depth of recharge that may be required to raise water table elevations above the land surface.

5. Conclusions and recommendations

This series of models suggests that while years of extremely high water table conditions may occur, they are likely to remain relatively rare events in the 21st century. The highest estimated recharge rates for the study area cause a 3-meter fluctuation in water table elevation, and this information may be of interest for planning residential and commercial development in similar climatic and hydrogeologic settings. Construction of buildings and infrastructure (basement and foundation depths, road construction, and design of on-site wastewater treatment systems) should consider the upper range of potential water table elevations to avoid problems such as the extensive damage from water table rise in Spring Green.

These findings may also inform efforts to map flood-prone or fully-saturated regions, or to evaluate the costs and benefits of long-term mitigation strategies, such as surface water detention basins, drainage systems, and crop insurance.

The analysis of the Spring Green area was intended as a proof-of-concept for this modeling approach. The eight statistically downscaled GCMs produce a wide range in estimates of annual recharge, which may ultimately limit the utility of these forecasts for water resources engineers concerned with climate change. However, general findings may prove more useful. For example, the range of simulated recharge constrains potential impacts of climate change, given the aquifer storage capacity in this setting. Based on this work, a reasonable range of recharge to apply to flow models incorporating different hydrogeology is vary the calibrated recharge value by a decrease of 25% and an increase of about 8%. As demonstrated for the study area, a time series of recharge based on the ranges from each GCM could be developed for transient simulations.

Future research in this area should investigate partitioning of rainfall between ET and deep infiltration. More robust methods to estimate ET should be compared to those generated from this application of the SWB.

6. References

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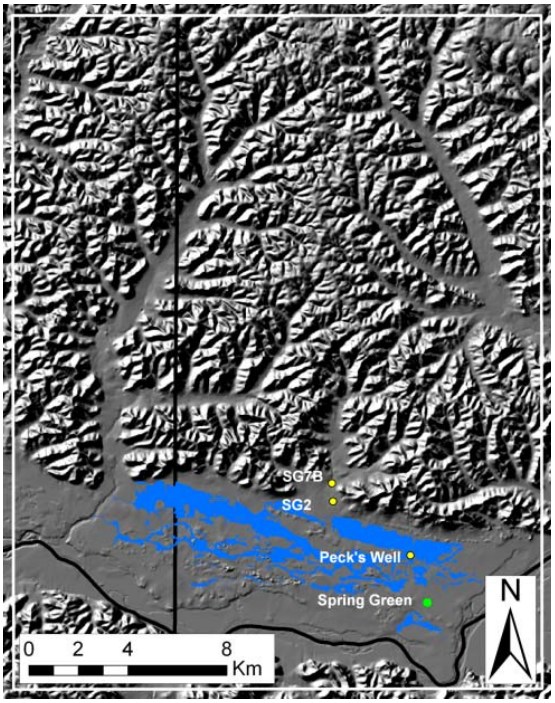


Figure 1. Study area in Sauk and Richland Counties (above) and topography (left). Blue shaded area indicates extent of flooding in 2008. White border is the extent of the MODFLOW model domain.

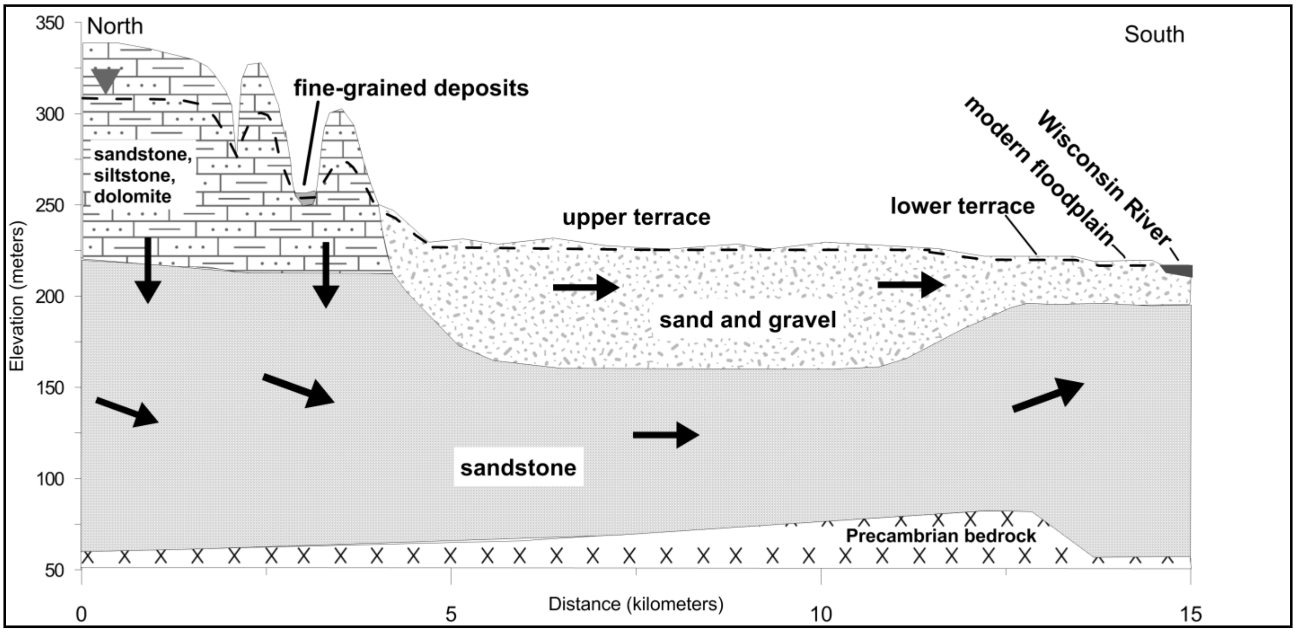


Figure 2. Spring Green hydrostratigraphy

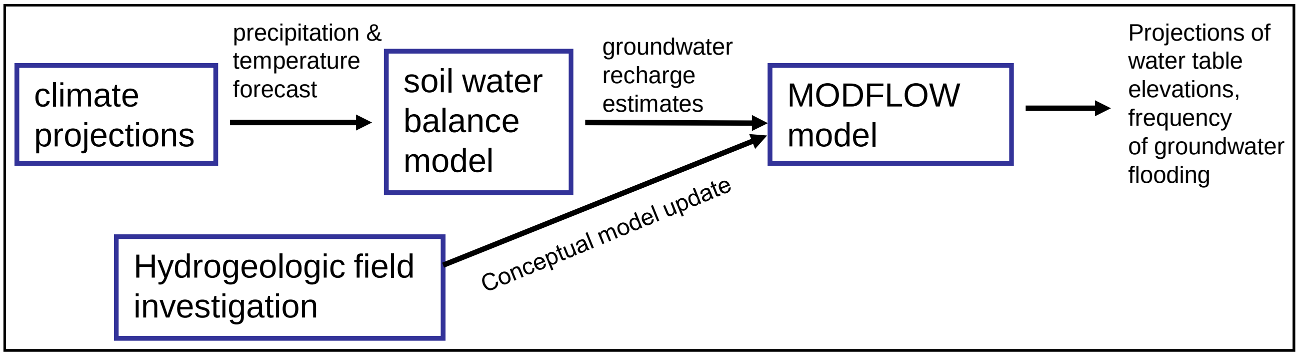


Figure 3. Project sequence.

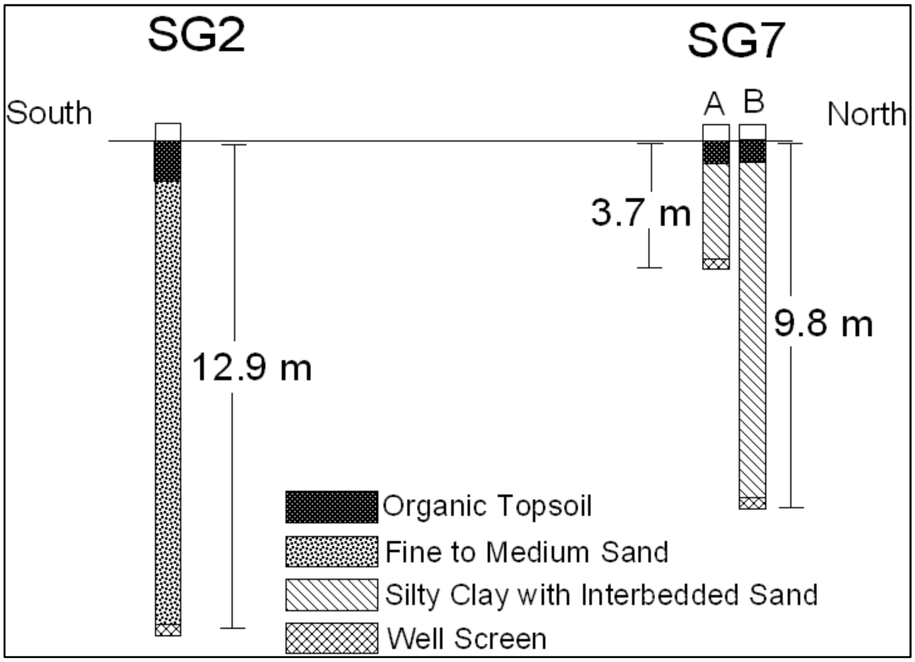


Figure 4. Boring depths and material (not to scale).

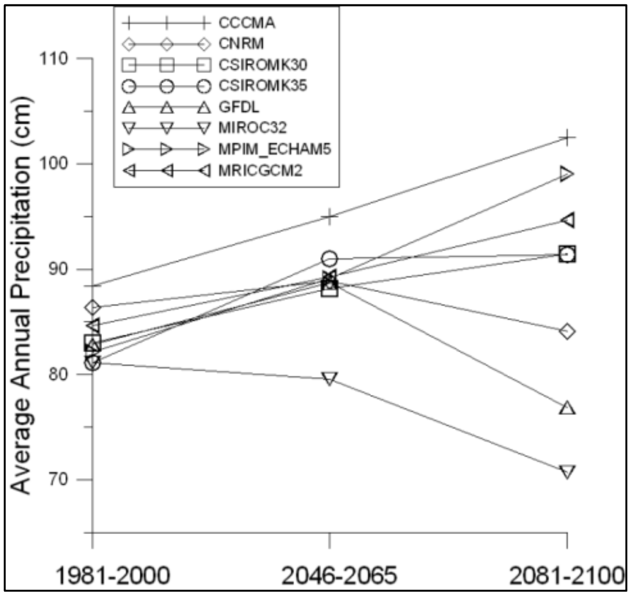


Figure 5. Average annual precipitation by GCM for three time periods.

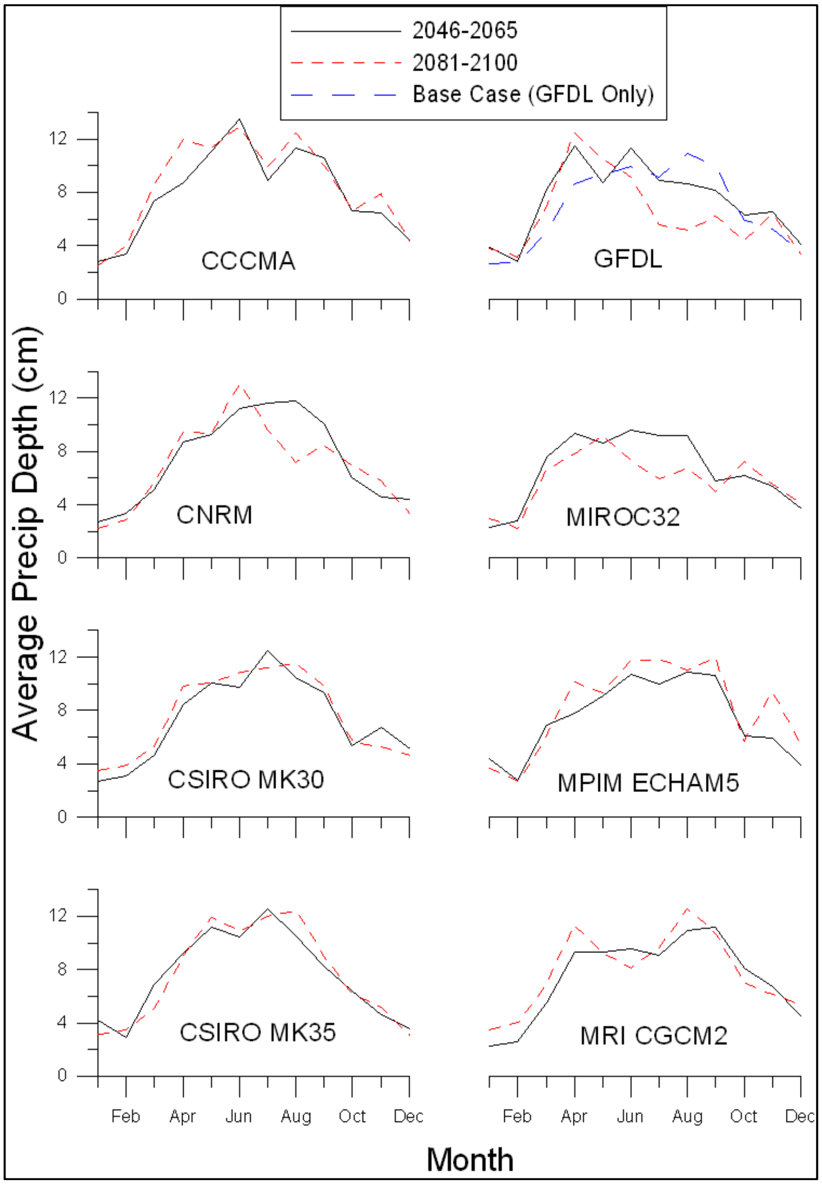


Figure 6. Average monthly precipitation, 2046-2065 and 2081-2100. The base case period is shown for GFDL only. Precipitation is the water equivalent depth for snowfall.

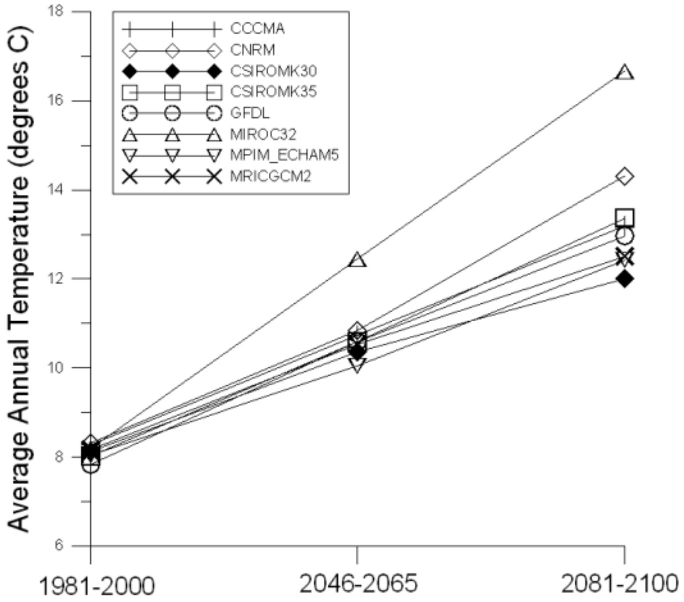


Figure 7. Average annual temperatures simulated by GCMs.

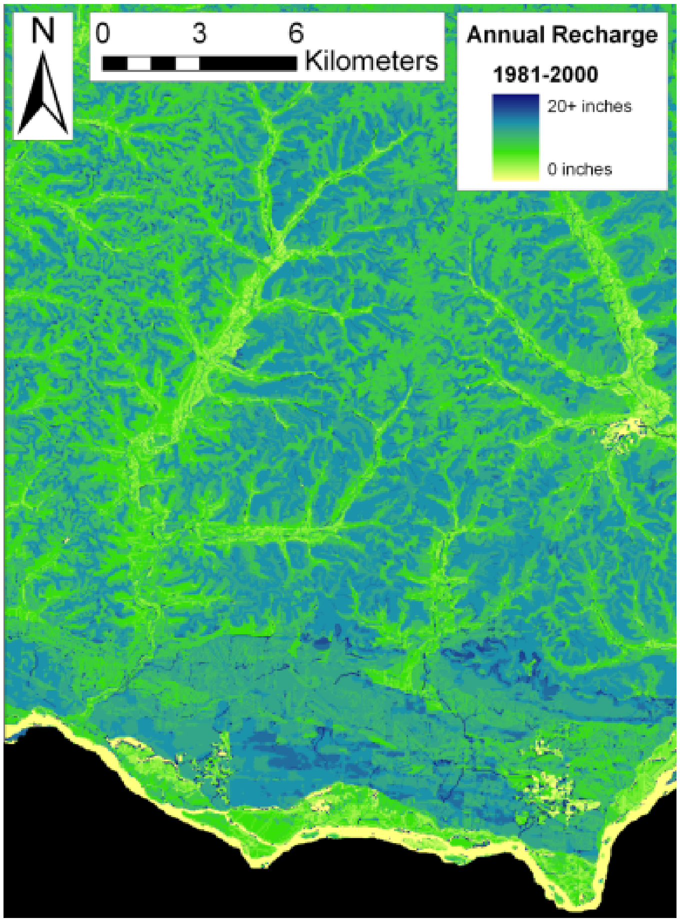


Figure 8. Base case simulated average annual recharge (from GFDL), 1981-2000.

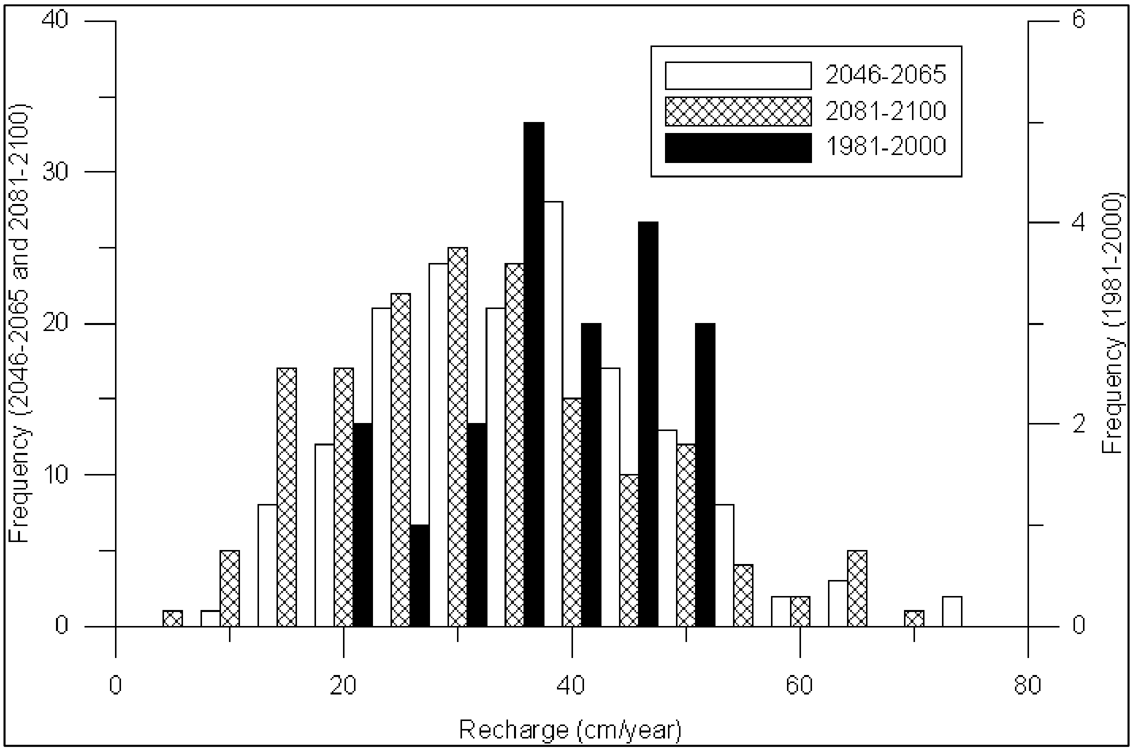


Figure 9. Annual recharge frequency distribution under two future climate periods (left axis) and the base case (GFDL only; right axis).

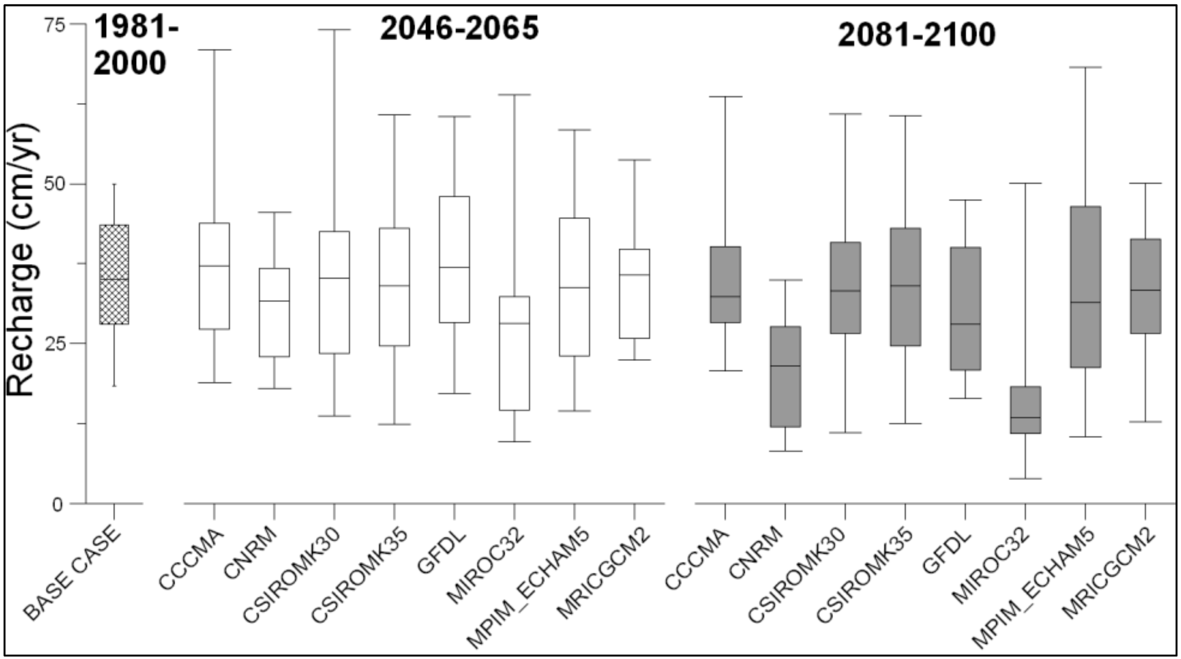
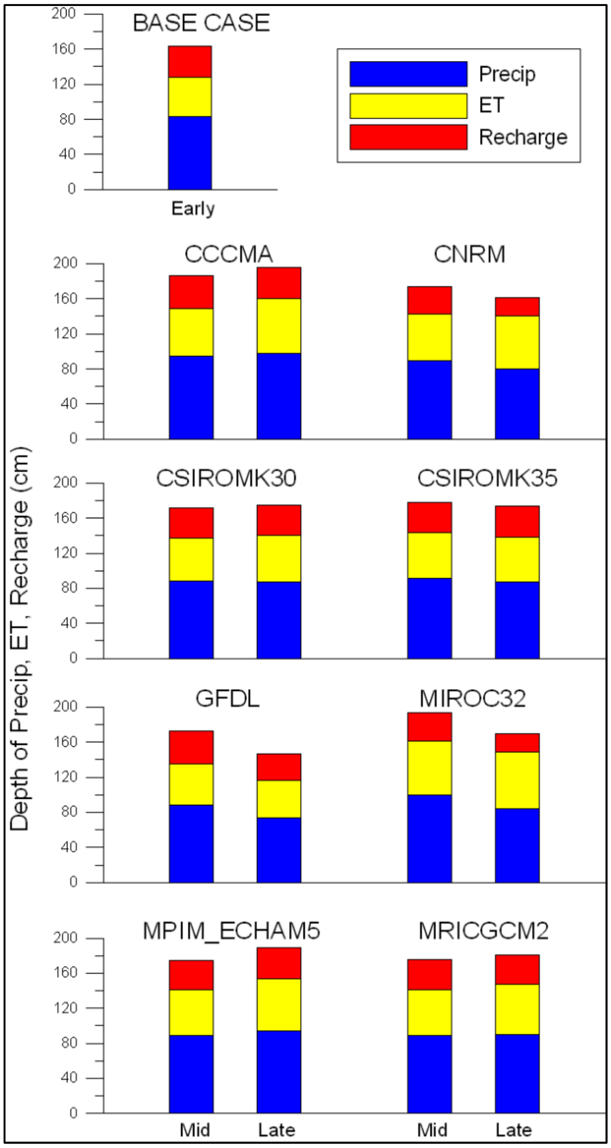


Figure 10. Recharge distribution for each GCM during future climate periods. Maximum, 75th quartile, mean, 25th quartile, and minimum are shown.



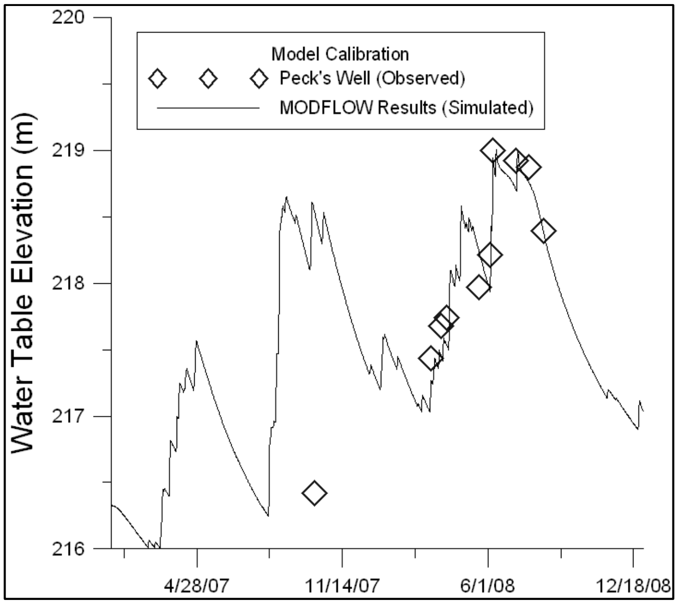


Figure 11. Annual average precipitation, evapotranspiration, and recharge (cm). Eight GCMs are compared to the base case.

Figure 12. Observed and simulated water table elevation, 2007 – 2008. See Figure 1 for location of Peck's Well.

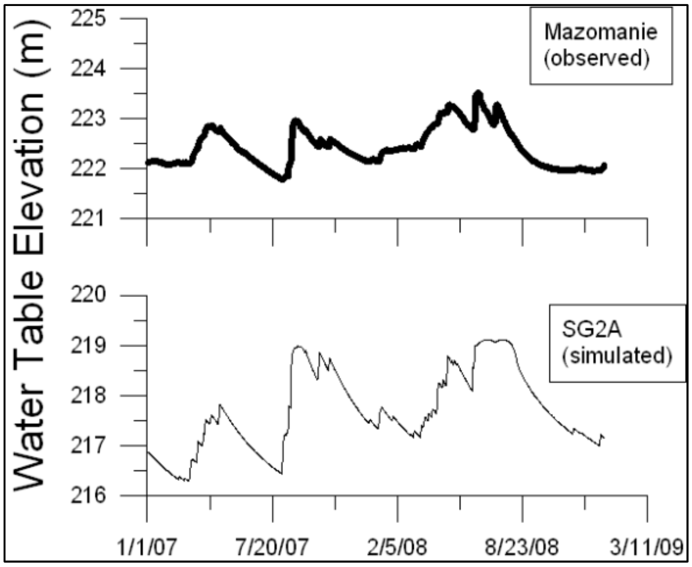


Figure 13. Observed and simulated water table, at Mazomanie well and Spring Green, respectively.

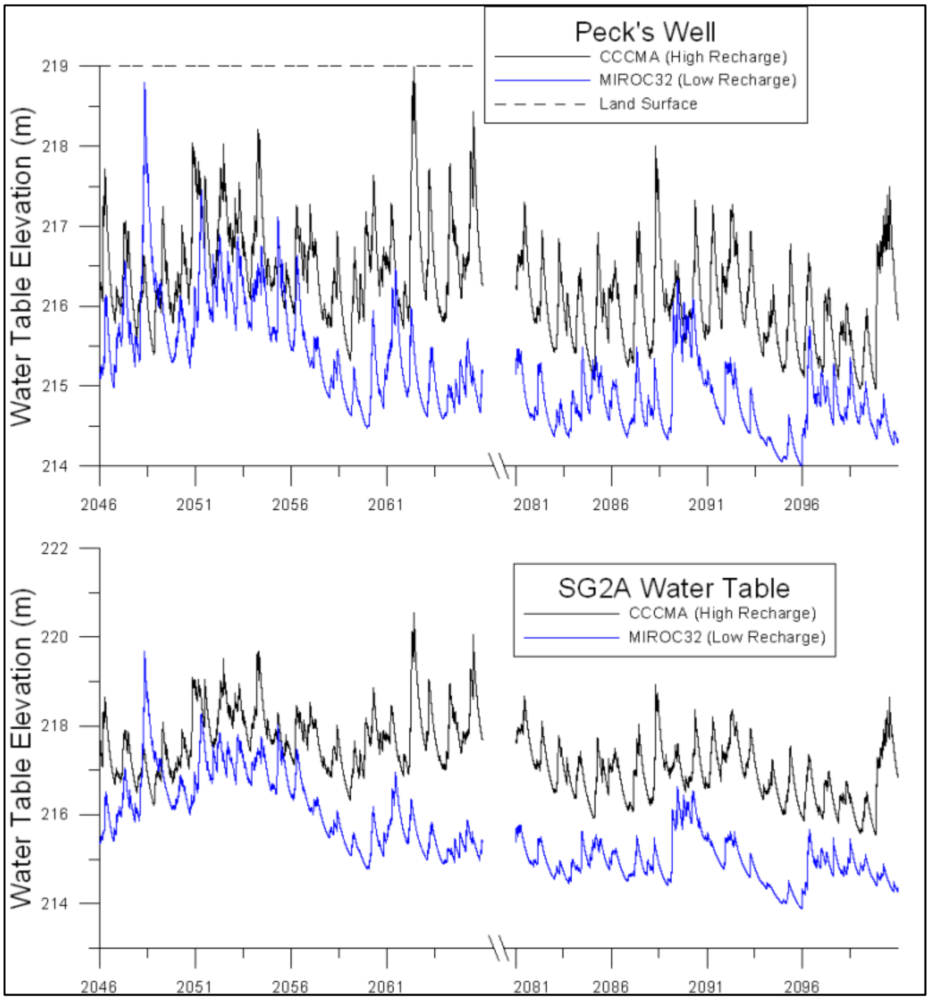


Figure 14. Water table hydrographs under high- and low-recharge conditions.