Using GSFLOW to Model Groundwater Flooding Recurrence Intervals

Russell Henning (russ.henning@aecom.com), P.G. [1] | Madeline Gotkowitz, Ph.D.[2] | Jackie Marciulionis[1] | Staci Goetz, Ph.D, P.G.[1]

[1]AECOM, Green Bay, WI; [2]Wisconsin Geological and Natural History Survey, Madison, WI

INTRODUCTION

The Spring Green, Wisconsin area (Figure 1) has been susceptible to groundwater inundation flooding in the recent past in areas located outside the Special Flood Hazard Areas depicted on Federal Emergency Management Agency (FEMA) *Digital Flood Insurance Rate Map* (DFIRM) for the Wisconsin River. The flooding has not been the result of the Wisconsin River overflowing its banks, but rather has resulted from saturated soils, groundwater inundation, and overland flow runoff during periods of heavy snowpack melt and rainfall. Historic flooding during June 2008 (Figure 2) inundated nearly 7 square miles of the Spring Green area with standing water for 5 months and caused contamination to water supply wells, agricultural crop loss, and damage to homes, buildings, and infrastructure. The study objectives were to model groundwater-surface water interactions using historical climate data to predict the areas at the most risk to groundwater flooding, develop modeled groundwater inundation maps and calculate recurrence intervals based on modeled water table fluctuations. GSFLOW, a USGS coupled groundwater-surface water model was selected as the method by which to calculate the return period for the groundwater inundation flood events. This paper focuses on groundwater-surface water modeling conducted to calculate recurrence intervals for flood events and predict the areas at risk for groundwater flooding.

MATERIALS AND METHODS

GSFLOW is a coupled groundwater and surface water model based on the USGS Precipitation Modeling System (PRMS) and the Modular Groundwater Flow Model (MODFLOW) (Markstrom et al., 2008). This coupled model was used to model historical groundwater fluctuations in the Spring Green area to calculate the recurrence interval of different magnitude high groundwater events. Locations of select historical high groundwater events were mapped and compared to the field study risk areas. The GSFLOW modeled extent is shown on Figure 3.

PRMS simulates surface water hydrologic responses within the model extent. The surface water component is bounded by the top of the plant canopy and the bottom of the soil zone and simulates the effects of various combinations of precipitation, climate, and land use on watershed response. The watershed is divided into a network of hydrologic response units (HRUs) that are developed from hydrological and physical attributes such as drainage boundaries, land-surface altitude, slope and aspect; plant type and cover density; land use; distribution of precipitation, temperature, and solar radiation; soil morphology; geology; and flow direction. The PRMS model computes a daily water and energy balance for each HRU determining how much precipitation will evaporate, evapotranspirate, runoff, or recharge the subsurface (saturated and unsaturated zones).

The HRUs were developed through a series of steps in ArcGIS using 30-meter DEMs. The 30-meter DEMs were used due to the size and available data for the model extent. ArcGIS hydrology tools determined flow directions and flow accumulation, from which a watershed boundary was generated. Stream segments and HRUs or drainage areas that contribute surface water to particular stream segments were mapped. A total of 18 PRMS parameters were derived for each HRU, which were used to determine the water and energy balance for each HRU. The PRMS parameters were determined using the DEM and other GIS coverages including vegetation and soil data, as well as climate data. Climate data, including measured daily maximum and minimum air temperature and daily total precipitation were obtained from several sources for the Lone Rock Tri-County Airport weather station for the period January 1970 through December 2009 (14,610 days). Missing data for that period were supplemented by data from the Spring Green and Richland Center stations located nearby.

In GSFLOW, MODFLOW models the influx from PRMS, interflow in the unsaturated zone, and groundwater flow in the saturated zone (Figure 4). For this study, an existing MODFLOW model developed for Spring Green by Gotkowitz et al. (2002) of the WGHNS was edited and expanded. The modifications made to the WGHNS model included: 1)northern, southern, and eastern portions of the WGHNS model boundary were extended outwards to the extent of the GSFLOW model boundary; 2)grid cells were modified for the study objectives.

The final step in building the GSFLOW model was to spatially link the HRUs in PRMS and the grid cells in MODFLOW through gravity reservoirs, which transfer water between the HRUs and MODFLOW grid-cells (Markstrom et al., 2008). Several MODFLOW grid-cells are assigned to each PRM HRU for the transfer of water. Once PRMS and MODFLOW are coupled, water is exchanged between the surface and soil zone, lakes and streams, and the subsurface based on flux and storage of water through the simulated hydrologic system. The model components and coupled model outputs were calibrated to the following data sources:

PRMS

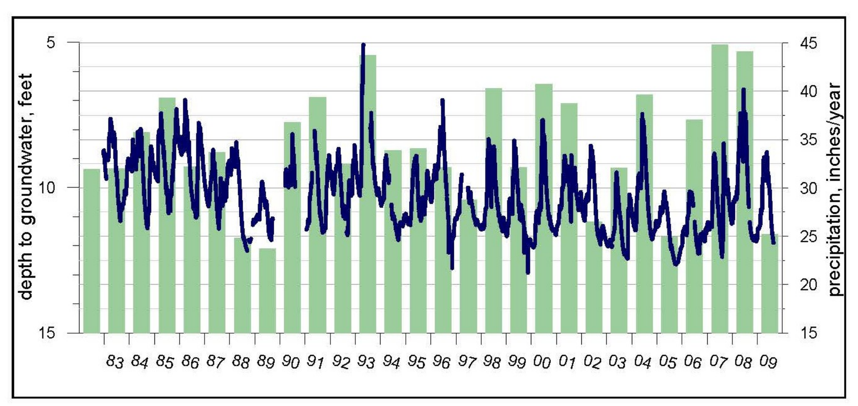
- USGS Muscoda stream gaging station (05407000)
- Precipitation records (NOAA National Weather Service, 2010)

MODFLOW

- Sauk County regional water table and target elevation heads (Gotkowitz et al., 2005)
- USGS Muscoda stream gaging station (05407000)
- 2008 Flood extent (Iausly, 2008)
- Qualitative risk areas map

GSFLOW

- 2008 Flood extent (Iausly, 2008)
- Qualitative risk areas map (Marciulionis et al., 2011)
- USGS Mazomanie groundwater station (431312089475301)



Depth to groundwater in Mazomanie (blue line) and annual precipitation (green bar) in Madison, WI adapted from Gotkowitz (2009)

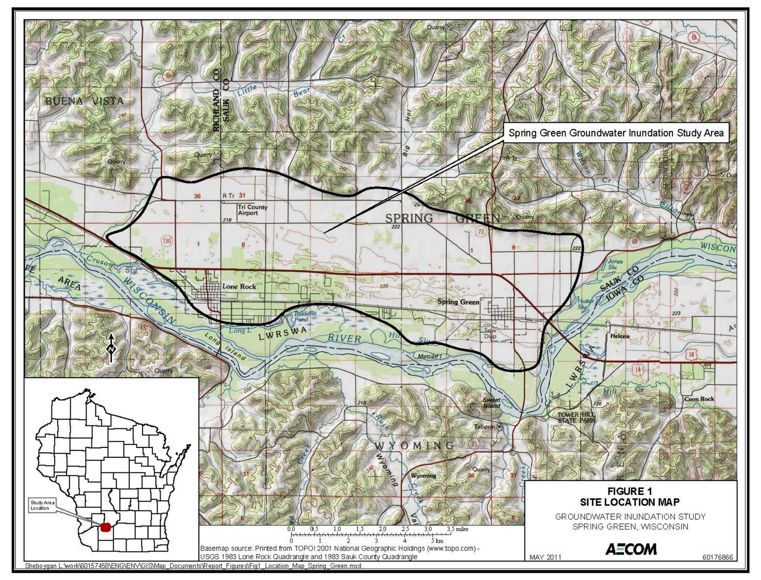


Figure 1- Study Area Location.

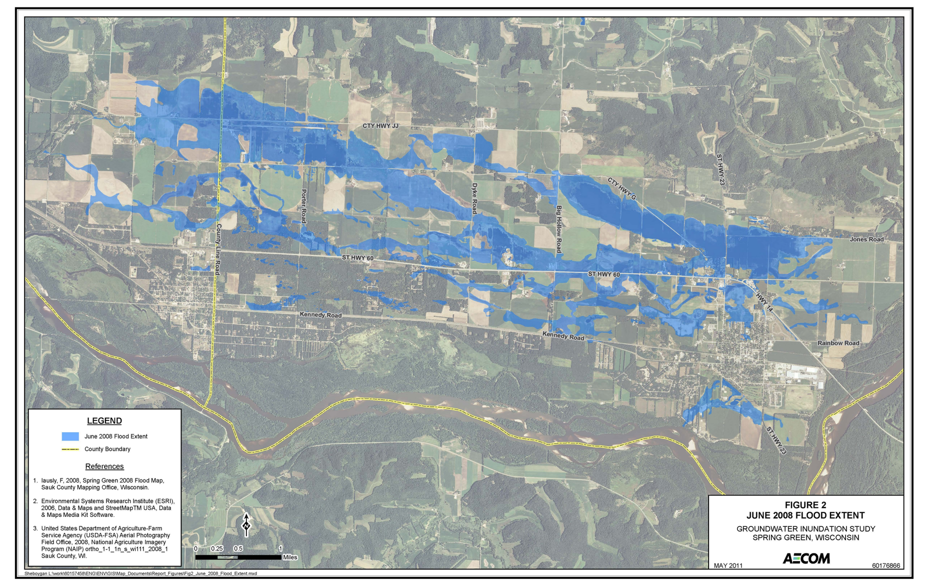


Figure 2 - June 2008 Flood Extent.

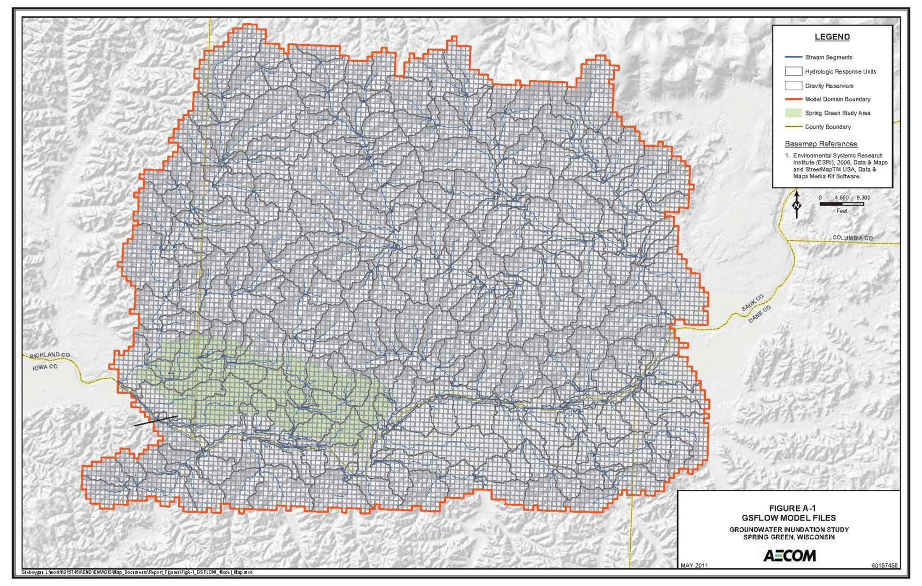


Figure 3 - GSFLOW Model Boundary and HRUs.

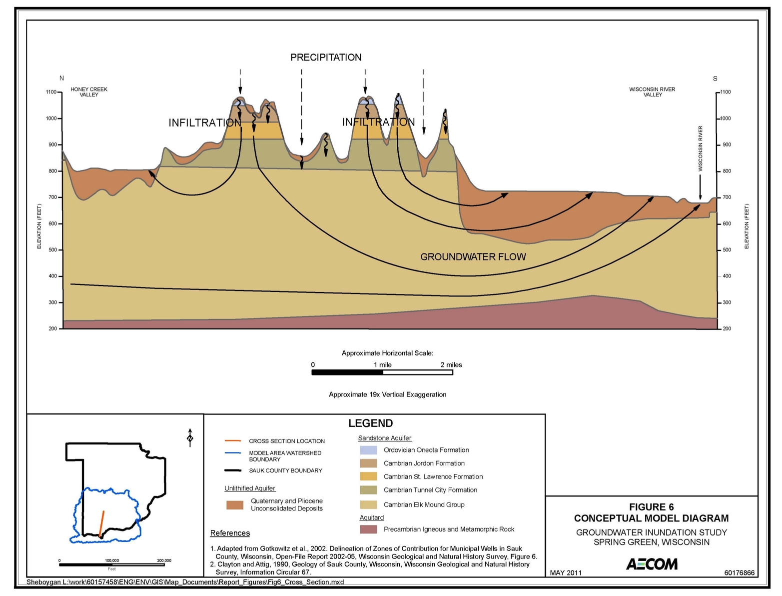


Figure 4 - GSFLOW Conceptual Model.

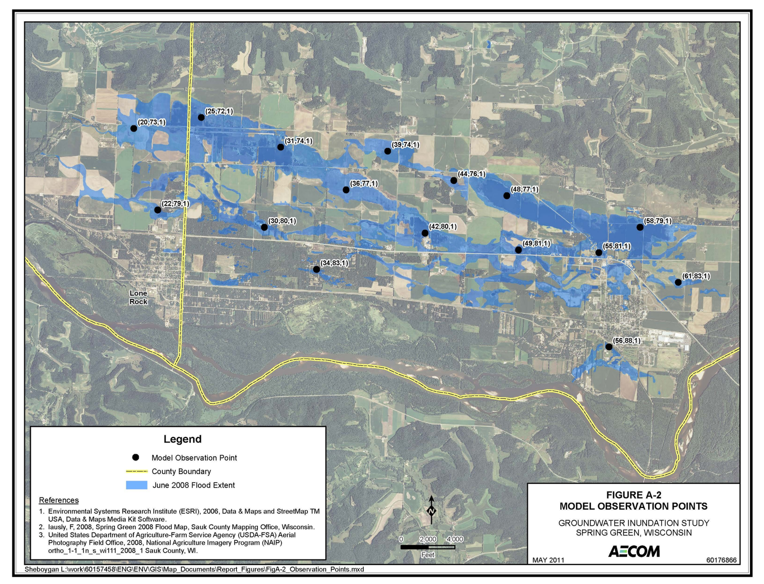


Figure 5 - GSFLOW Model Observation Points.

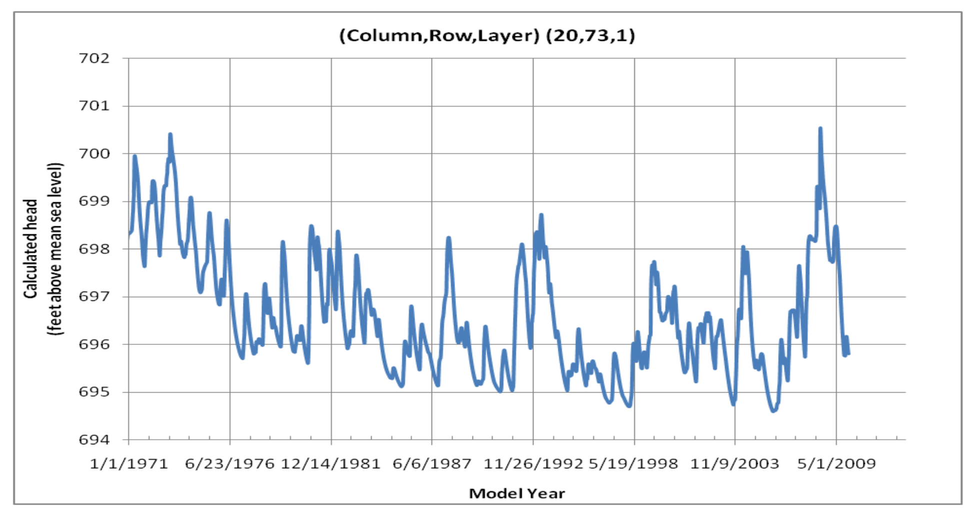


Figure 6 - Predicted Groundwater Head for Observation Point (20,73,1).

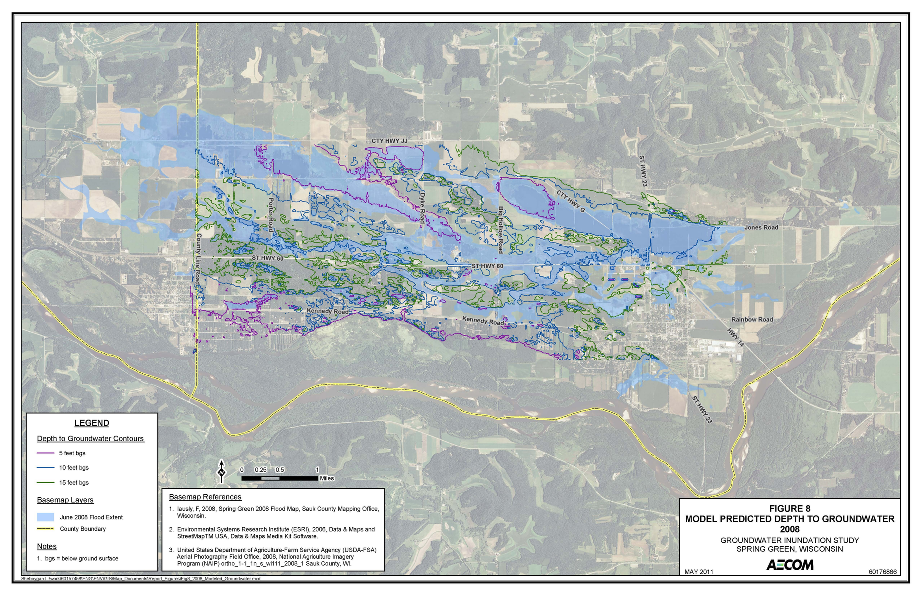


Figure 7 - GSFLOW Model Predicted Depth to Groundwater 2008. Note: Predicted depth to groundwater was estimated from Sauk Co. LiDAR data. Predicted depth to groundwater was not estimated for Richland Co. since LiDAR data is not currently available.

Table 1

Recurrence Intervals
Groundwater Inundation Study
Spring Green, Wisconsin Area

Year	Composite Score	Rank	Recurrence Interval (years)
2008	15.59	1	40.0
2009	13.48	2	20.0
1973	12.32	3	13.3
1980	11.33	4	10.0
2007	11.06	5	8.0
1994	9.98	6	6.7
2004	9.87	7	5.7
1999	9.70	8	5.0
1971	9.05	9	4.4
1976	8.75	10	4.0
1993	8.39	11	3.6
1982	8.05	12	3.3
1974	7.84	13	3.1
2006	7.77	14	2.9
1979	7.56	15	2.7
2003	7.14	16	2.5
2005	6.99	17	2.4
1992	6.80	18	2.2
1984	6.65	19	2.1
1988	6.44	20	2.0
1981	6.35	21	1.9
1987	5.97	22	1.8
1972	5.70	23	1.7
2000	5.64	24	1.7
1998	5.61	25	1.6
1975	5.42	26	1.5
1983	5.21	27	1.5
1991	5.15	28	1.4
1986	4.80	29	1.4
2001	4.37	30	1.3
1989	4.28	31	1.3
1978	3.96	32	1.3
1985	3.95	33	1.2
1977	3.81	34	1.2
1990	3.76	35	1.1
2002	3.37	36	1.1
1996	3.21	37	1.1
1997	3.03	38	1.1
1995	3.02	39	1.0

RESULTS

The GSFLOW model was run for the 40-year (14,610 days) period for which climate data was obtained. Model outputs were used to calculate recurrence intervals of different magnitude flood events. Fifteen observation points were selected throughout the Spring Green area for the model to generate water levels, shown on Figure 5. The model calculated daily water levels for each point for the 40-year period. Recurrence intervals were calculated for modeled groundwater heads as:

$$T = \frac{(n+1)}{m}$$

Where T is the recurrence interval in years, n is the number of year of record, and m is the rank of the magnitude of the annual high groundwater level (Dunne and Leopold, 1978).

Recurrence intervals derived from modeled groundwater heads at the observation points are presented in Table 1. The model terrain resolution, uncertainty of model groundwater storage parameters in the transient model and the long duration of high groundwater heads means a traditional approach to calculating recurrence intervals does not yield meaningful results. For this reason, groundwater heads at each observation point were normalized to the maximum head in each respective model cell. The normalized maximum value for each cell was then weighted or scored for how well it reproduced the 2008 flood event as having the maximum magnitude. The normalized values were summed by year to get an overall score. The scores were then ranked from highest to lowest, which serves as the magnitude, *m*, in the recurrence interval equation.

Figure 6 shows a plot of calculated heads at model cell location row 20, column 73, layer 1, beginning in year 2 of the model (1971). The model results confirm that flood events are typically preceded by a longer-term build up of groundwater heads and, as previously reported by Gotkowitz (2009), do not result from high precipitation events alone. Therefore, recharge by groundwater throughflow in the sandstone aquifer and interflow in the unsaturated and soil zones may also contribute to the conditions that lead up to groundwater flood events.

Modeled depths to groundwater for the June 2008 event at the observation points are presented on Figure 7. Shallow groundwater areas are consistent in location and magnitude with those derived from the regional water table contours. The 5 and 10 feet below ground surface (ft bgs) contours generally conform to the mapped extent of the June 2008 event, with the 10 ft bgs contour being somewhat more expansive than the 2008 flood extent. The consistency between the modeled shallow groundwater extents and risk areas indicates good agreement between the model and field indicators. Also, changes in head at model observation points range from 2 to 4 feet during the 2008 event, which is consistent with the 4-foot change in head observed at the Mazomanie and Richland Center groundwater wells. Although there are consistencies between the model results, field indicators, and regional groundwater records; the calculated groundwater heads do not breach the ground surface to cause surface water flooding which may be due to resolution limitations associated with 30-meter DEMs. The elevations of the 30-meter DEMs are, on average, 4 to 8 feet higher than the elevations of the LiDAR-generated terrain model and have the effect of subduing topography. Thus, the 30-meter DEMs are too high, on average. Further refinement of the model with the higher resolution terrain model could result in the calculated groundwater heads breaching the groundwater surface.

CONCLUSIONS

- Local measured climate data spanning a 40-year time period was used for the model
- The steady-state PRMS results of the GSLOW model was consistent with measured stream-flows and storm events over the 40-year model time
- A modified calibrated steady-state groundwater flow model was used as basis for GSFLOW groundwater flow portion of model
- The modified steady-state groundwater flow model was calibrated to groundwater heads
- The steady-state PRMS model was coupled to the modified MODFLOW model in GSFLOW providing transient predictions of groundwater head over time
- High groundwater recurrence intervals were estimated using GSFLOW model predicted heads for study area
- The qualitative risk area map for Spring Green in conjunction with the model predicted depth to groundwater provide planners with tools to predict, prepare for and manage groundwater flood events.

FURTHER RESEARCH

Based on the model outcomes, several recommendations for modifications to the model are suggested:

- Update GSFLOW with a higher resolution terrain model after Richland Co. LiDAR data is obtained;
- Refine the recharge rate in the MODFLOW portion of the steady-state model and storage parameters in transient model ;
- Adjust model HRUs to incorporate field-determined risk areas;
- Generate fewer stream segments in PRMS to reduce model complexity and run time; and
- Calibrate GSFLOW by collecting additional tributary stream data so flow contribution of Spring Green area to Wisconsin River discharge can be estimated.

REFERENCES

Bradbury, K. 2009. Potential Impacts of Climate Change on Groundwater in Wisconsin. PowerPoint presentation dated September 29.
Clayton, L and Attig, J.W. 1990. Geology of Sauk County, Wisconsin, Wisconsin Geological and Natural History Survey, Information Circular 67.
Dott, R. H. Jr. and J.W. Attig. 2004. Roadside Geology of Wisconsin. Mountain Press Publishing Company, Missoula, Montana, 184 p.
Dunne and Leopold. 1978. Water in Environmental Planning. W.H. Freeman and Company, New York.
FEMA. 2008. Hydrogeological and NFIP Interpretation of Terrace Flooding Northwest of Spring Green, Wisconsin, and Possible Mitigation, August 2008.
Gotkowitz, M., K.K. Zeiler, C.P. Dunning, and J. Thomas. 2002. Delineation of Zones of Contribution for Municipal Wells in Sauk County, Wisconsin. Wisconsin Geological and Natural History Survey, Open-File Report 2002-05.
Gotkowitz, M.B., Zeiler, K.K., Dunning, C.P., Thomas, J., and Lin, Y., 2005. Hydrogeology and simulation of groundwater flow in Sauk County, Wisconsin, Wisconsin Geological and Natural History Survey Bulletin 102, 43 p.
Gotkowitz, M. 2009. Update on groundwater levels and long-term rainfall record. Letter to the Supervisors of the Town of Spring Green, WI dated October 1.
Gotkowitz, M. 2008. Water and the Valley – Issues Underlying the Flood of 2008. PowerPoint presentation.
Gotkowitz, M. and Attig, J.W. 2008. Water and the Valley – Issues Underlying the Flood of 2008. Power Point presentation (http://basineducation.uwex.edu/lowerwis/pdf/WaterintheVallley.pdf).
Gotkowitz, M and J. Exo. 2008. The Role of Geology and Groundwater in 2008 Flooding in the Spring Green Area, University of Wisconsin Extension.
Iausly, F, 2008, Spring Green 2008 Flood Map, Sauk County Mapping Office, Wisconsin.
Marciulionis, J., Amelse, A., and Goetz, S. 2011. Identification of Shallow Groundwater Flood Risk Areas, Spring Green Area, Wisconsin. Geological Society of America Abstracts with Programs, v. 43, n. 5, p. 460.
Markstrom, S.L., Niswonger, R.G., Regan, R.S., Prudic, D.E., and Barlow, P.M. 2008. GSFLOW—Coupled Ground-water and Surface-water FLOW model based on the integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW-2005): U.S. Geological Survey Techniques and Methods 6-D1.
State of Wisconsin International Charter and Eagle Vision, 2008. Report of the June 2008 Midwest Floods, October 2008.
Winter, T.C., Harvey, J.W., Frank, O.L., and W.L. Alley, 1998, Groundwater and Surface Water, A Single Resource, USGS Circular 1139.