Groundwater quantity fundamentals in Wisconsin's central sands region

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Purpose

This brief summary was requested by the Wisconsin Food, Land, and Water Project Groundwater Quantity Work Group during a meeting on November 10, 2016. The intent of this document is to summarize key concepts related to groundwater, high-capacity wells, and groundwater-surface water relationships in the central sands region of Wisconsin. The authors of this document are technical experts in hydrogeology with experience working in the central sands region of Wisconsin. This document is not meant to outline policy or specific solutions, but rather to summarize the state of the science on groundwater issues in the Central Sands.

Approach

This document presents fundamental concepts related to central Wisconsin's water resources. For each concept a brief explanation is provided along with a description of its relevance to water resources decision making. The intent is to break down the issues into individual parts to facilitate clear understanding. In the end, these components are all parts of a whole and are tied together. The organization is as follows: We start with a review of the hydrogeology of the Central Sands (1, 2); then review the behavior of groundwater wells, regardless of their purpose (3,4,5); connect the use of wells to irrigation (6); review the importance of changes over time (transience: 7); summarize observations of stream and lake responses in areas with higher numbers of irrigation wells (8,9); discuss the use of groundwater flow modeling to tie all these parts together (10); summarize details of evapotranspiration (11); and finally discuss possible explanations for streamflow and lake level declines other than pumping (12).

Fundamental concepts and their implications

1. **Concept: A single groundwater flow system occurs throughout the central sands**

   Details: The central sands groundwater flow system occurs mainly in a single, interconnected sand-and-gravel aquifer that underlies virtually all of the region. It is highly permeable and ranges from very thin to nearly 200 feet thick. In places the sand and gravel aquifer is underlain by a sandstone aquifer, and in other places the sand and gravel is interrupted by a clayey layer called the New Rome Formation. With the exception of some very small isolated locations, groundwater in the central sands flows through a connected large system that receives recharge from local precipitation. Groundwater naturally flows to streams where it discharges and leaves the watershed.

Why relevant: The groundwater flow system is well connected, wide-ranging, and the aquifer stores and transmits water to surface water and to wells.

2. **Concept: Groundwater and surface water are directly connected throughout the central sands.**

   Details: Surface waters (lakes, streams, wetlands) in the region occur at places where the water table intersects the land surface. Streams in central Wisconsin are supplied by groundwater discharge. Lakes and wetlands, depending on their location in the landscape, can be groundwater discharge points or flow-through features.

   Why relevant: Groundwater and surface water are well connected and should be thought of as a single resource. Groundwater discharge is the source of baseflow in streams. Groundwater controls lake levels. Changes to the groundwater system affect surface water and changes to surface water affect groundwater.

3. **Concept: Pumping wells affect groundwater levels**

   Details: A basic principle of well hydraulics is that removing water from a well always reduces total hydraulic pressure, or head, in the aquifer near the well. This pressure change results in a lowering of groundwater levels near the well, known as drawdown. The amount of drawdown is directly related to the pumping rate, aquifer transmissivity, aquifer storativity, and distance from the well and can be predicted by well-established equations. The three-dimensional extent of drawdown is generally cone-shaped and is called the cone of depression; this cone grows larger the longer a well is pumped. A typical cone of depression for a high-capacity well in the central sands is measurable for a half a mile or more around a well. While a distinct cone of depression comes and goes as a well cycles on and off, it is important to realize there is always less water in the aquifer, and thus lower water levels, for a short period after a well is pumped. The complete recovery of the water table can take months or longer.

   Why relevant: The effect of each well pumping is a reduction in groundwater levels. The distance, timing, and magnitude of the reduction depends on the properties of the aquifer and the amount, duration, and location of pumping.

4. **Concept: Pumping wells divert water from streams**

   Details: Streams in the central sands are natural areas of groundwater discharge, and this groundwater discharge sustains streamflow throughout the year. By removing groundwater from the aquifer, well pumping modifies and interrupts natural groundwater flow and thus reduces the volume of groundwater discharge to streams. This reduction is called “diversion,” because water that would have discharged to a stream under natural conditions is diverted away from the stream. If a well is close enough to a stream or lake, it can also induce water directly from that surface-water feature. The amount of diversion caused by a well depends on the pumping rate, pumping period, distance from a stream, and local geology.

Why relevant: Each pumping well in the Central Sands impacts streams by diverting groundwater discharge and reducing streamflows. Even wells outside the surface-water basin of a particular stream can divert water away from the stream.

5. **Concept: Cumulative impacts matter.**

   Details: Whenever a well is pumped, discharge is diverted from streams and water levels in an aquifer, lakes, and wetlands are lowered. Cumulative impacts refer to the additive effects as impacts from numerous wells in the same area overlap. When many wells in a region are being pumped, water level declines and streamflow diversions add to each other. So even though a single well may cause only a small decline or diversion, the additive effects of many wells can significantly impact lakes and streams.

   Why relevant: Unless located immediately adjacent to a surface water feature or another well, any single well typically has modest impacts on water levels or streamflow. However, when many wells are located in the same area the cumulative impacts of all these wells can become significant.

6. **Concept: When crops are irrigated using groundwater, there is a net loss to the groundwater system.**

   Details: Irrigation replenishes soil moisture to maximize plant growth. Ideally, irrigation amounts would exactly match plant consumption (defined as water incorporated into the plant biomass, transpired through the plant, directly evaporated from plant surfaces and the ground or a small amount that evaporates while the water is sprayed through the air). In practice this is difficult to achieve. An estimated 70-90% of irrigation water is removed from the aquifer, while 10-30% may return to the aquifer, and this returned water is called irrigation return flow. The absolute amount of return flow varies from field to field, from crop to crop, and from year to year, and depends on many variables including soil type, crop type, crop maturity, irrigation rate, antecedent soil moisture, and weather patterns. Every current method for estimating return flow in the central sands contains significant uncertainty.

   Why relevant: Understanding where the irrigation water goes is important for understanding the water balance of the central sands region. Averaged over the irrigated region, between 70% and 90% of the applied irrigation water is removed from the aquifer—lost from the groundwater system either by being released to the atmosphere through evapotranspiration or incorporated into the crops—while between 10% and 30% is returned to the groundwater system. Improving estimates of consumptive use is a recommended topic for continued research.

7. **Concept: Groundwater, surface water, evapotranspiration, and high-capacity well use in the central sands have important transient components, meaning that conditions continually vary through time.**

   Details: The dynamics of the groundwater-surface water system vary seasonally. Natural groundwater recharge usually occurs mostly in the spring and fall, with little recharge in the summer or winter. Surface-water features respond to this pattern, with highest streamflows in the spring and fall and lowest streamflows during the dry summer months and into the fall. Native vegetation typically follows a similar pattern with higher evapotranspiration taking place in the spring and fall when more water is available. Irrigation pumping follows an opposite pattern, with almost no irrigation during the spring, fall, or winter and maximum irrigation during the dry summer months. In addition, there are often significant time lags on the order of months or years between pumping and the effects of pumping on lakes and streams. This lag time depends primarily on the distance from the pumping well.

Why relevant: The lack of synchronization between recharge, pumping, and streamflow means that annual averages, such as annual water budgets or annual pumping volumes, can be misleading and should be used with caution. A water budget that nearly balances at the end of a calendar year can be seriously out of balance during July through October, when the streams are most stressed and require sufficient groundwater inflow to support the fishery.

8. **Concept: Groundwater levels have declined in parts of the central sands where a higher density of high-capacity wells occurs.**

Details: Over the past several decades, groundwater levels have consistently declined in parts of central Wisconsin where larger numbers of high capacity wells occur, but these declines are subtle and are difficult to document without considering long water-level records and statistical analyses. In places where monitoring has occurred, long-term records document these water-level reductions. Groundwater levels measured by the USGS at a site (PT-23/08E/26-1464 and two previous wells at the same location) near Plover, for instance, with nearly 70 years of record, have declined below historical record lows previously only associated with extreme drought.

Why relevant: Groundwater levels in the central sands typically fluctuate by two to three feet annually in response to seasonal weather and pumping patterns. Accordingly, evaluation of possible long-term trends requires long-term water-level records. Evaluations of these records show declines in water levels near areas of multiple irrigation wells.

9. **Concept: Streamflow and lake levels have declined in parts of the central sands where a higher density of high-capacity wells occurs.**

Details: Streamflows and lake levels have declined in parts of central Wisconsin where large numbers of high capacity wells occur. For instance, recent flows in the early 2000s in the Little Plover River were below its 1959-1987 historic low, a period that contained some of the driest years on record. Lakes in the vicinity of large numbers of high-capacity wells are anomalously low. In places where water level or flow data do not exist, visual observations reveal declining water levels. For instance, for some lakes, beaches are wider than the historic norm and boat landings no longer reach the water even during modestly dry to wet years. Conversely, streamflows and lake levels have remained steady or have even increased in areas of the central sands having less groundwater pumping.

Why relevant: Stream baseflow is a key measure of groundwater discharge, and reductions in stream baseflow indicate that the basin's groundwater budget has changed. Likewise, lakes in the central sands reflect groundwater levels, and long-term lake-level declines are a symptom of lower groundwater levels. Observations that water bodies outside the more heavily irrigated areas oscillate over time but do not trend downward are consistent with the conclusion that pumping has caused stressed water conditions.

10. **Concept: Results of numerical groundwater flow models are consistent with observations of declines in streamflow and groundwater levels in areas of numerous high-capacity wells.**

    Details: Groundwater-flow models combine the equations describing groundwater movement and well hydraulics with geology and boundary conditions to simulate groundwater movement and groundwater-surface water exchange in complex settings under both steady-state and transient conditions. Output of such models includes simulated groundwater levels, stream baseflows, lake levels, and a water budget that accounts for how groundwater moves through the system. Multiple recent independent models for the Little Plover River area suggest that high-capacity well pumping has reduced local groundwater levels by up to 5 feet and reduced Little Plover baseflow by up to 4.5 cubic feet per second.

    Why relevant: Numerical groundwater modeling is the accepted state of professional practice for addressing complex groundwater problems. The ability to reproduce field observations with calculations based on fundamental hydraulic and hydrogeologic principles is a key test of the validity of hypotheses and a predictive tool that helps use past observations to predict future conditions.

11. **Concept: Evapotranspiration is related to land cover and influences water levels and streamflows.**

    Details: Evapotranspiration refers to evaporation off plants, open water, bare ground and transpiration from plants. In the Central Sands transpiration is larger than evaporation. Plants remove water from the soil using their roots and pass it as vapor through stomata into the atmosphere; this flux can be appreciable on the basin scale. The amount of water transpired by plants is a function of the type, density, and size of the vegetation as well as amount of water available in the root zone and time of year. Native plants and trees typically transpire for more of the season than shallow rooted plants and irrigated crops. Evapotranspiration rates are related to plant type, where some wetland plants have appreciably higher rates than upland plants. Regardless of plant type, the highest rates of evapotranspiration occur during the summer months. Peer-reviewed research as well as empirical observations indicate that evapotranspiration is greatest under irrigated land cover, with differences among the various irrigated crops, followed by forest, non-irrigated agriculture, and grassland. Groundwater recharge follows an opposite continuum. Understanding the relative transpiration of native vegetation and irrigated crops is an active area of interest to stakeholders and thus merits greater study.

    Why relevant: All landscapes lose water to evapotranspiration. The effect of adding irrigation to a landscape increases evapotranspiration relative to the pre-existing land cover.

12. **Concept: Proposed causes other than groundwater pumping have been unable to fully explain observed patterns of normal and depressed water levels and streamflows.**

Details: Consideration has been (and should continue to be) given to other proposed causes of stressed groundwater and surface water conditions in the central sands. Common potential causes include drought, climate change, forestation, and the construction of drainage ditches. When examined, each of these potential causes has failed to fully explain observed conditions. For instance, weather has become wetter, not drier, in recent times, areas with more forest frequently have higher, not lower, water levels, and drainage ditches were in place for many years before currently-observed hydrologic stresses.

Why relevant: No mechanism other than groundwater pumping has been shown to align well with the locations, magnitude, and timing of observed changes in groundwater levels and surface-water flows.

Key references

Among the numerous peer-reviewed scientific and technical papers that address various aspects of central sands water issues we recommend the following, and references therein, for accessible and understandable discussions of the region's water resources.

Barlow, P.M., and Leake, S.A., 2012, Streamflow depletion by wells—Understanding and managing the effects of groundwater pumping on streamflow: U.S. Geological Survey Circular 1376, 84 p. (A summary of how groundwater wells interact with streams; available here: https://pubs.usgs.gov/circ/1376/).

Bredehoeft, J.D., 2002, The water budget myth revisited: Why hydrogeologists model: Ground Water, v. 40, no. 4, p. 340-345. (Discussion of the need to use models that consider full accounting of the water budget to calculate the interaction of wells with streams).

Bradbury, K.R., Fienen, M.N., Kniffin, Maribeth, Krause, Jacob, Westenbroek, S.M., Leaf, A.T., and Barlow, P.M., in press, Groundwater flow model for the Little Plover River basin in Wisconsin's Central Sand Plain: Wisconsin Geological and Natural History Survey Bulletin. (Recently-completed groundwater flow model focused on the Little Plover River area).

Hunt, Randy. 2003. A water science primer. Wisconsin Academy of Sciences Transactions, Volume 90. P 11-21. (A succinct summary of groundwater and surface water in Wisconsin, pointing out common misconceptions and misunderstandings; available here: http://wi.water.usgs.gov/gwcomp/learn/hunt_water%20_primer_was_transactions_90.pdf

Kniffin, M., K. Potter, A.J. Bussan, J. Colquhoun, and K. Bradbury, 2014, Sustaining central sands water resources: State of the science 2014: UW-Extension, publication # G4058, 102 p. (As stated on the UWEX web site, this publication "…provides a common framework and language for scientists to communicate within and across disciplines regarding water resource management in the Central Sands region of Wisconsin.").

Kraft, G. J., Clancy, K., Mechenich, D. J., and Haucke, J., 2012, Irrigation Effects in the Northern Lake States: Wisconsin Central Sands Revisited: Ground Water, v. 50, no. 2, p. 308-318. (Journal publication documenting impacts from irrigation pumping in the central sands).

Weeks, E. P., Ericson, D. W., and Holt, C. L. R. J., 1965, Hydrology of the Little Plover River basin, Portage County, Wisconsin, and the Effects of Water Resource development: U.S. Geological Survey, Water-Supply paper 1811, 78 p. (USGS report on the Little Plover River and potential impacts of irrigation pumping. A movie was produced illustrating field experiments from this work and can be viewed online at https://youtu.be/GW9cYdIT8iM).

Weeks, E. P., and Stangland, H. G., 1971, Effects of irrigation on streamflow in the central sand plain of Wisconsin: U S Geological Survey, Open-File Report 1970-362, 113 p., 4 plates. (USGS study focused on impacts of irrigation on central sands' streamflows in the 1960s-70s).