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 70-362, 113 p. [PEER REVIEWED]

Keywords: Central Sands, geology, aquifer properties, streams, evapotranspiration, recharge, high capacity wells

In-depth study of hydrology in the Central Sands as relates to potential stream depletion by large-scale conversion to irrigated agriculture. Report includes maps and discussion of bedrock surfaces (including the sandstone/Precambrian contact and major buried bedrock valleys), thickness of the sand and gravel aquifer, and regional water table. Aquifer characteristics are estimated from the results of eight pumping tests in various parts of the Central Sands (K = 130–500 ft/d, typical Sy = 0.2). Glacial sediments are mainly permeable sands (including Lake Wisconsin sediments, outwash, pitted outwash and moraines). Lake clays (New Rome) are also discussed. The paper provides an overview of land use and water use in the region up to 1967 and speculates on future development.

Weeks and Stangland evaluated the hydrologic system for several gaged streams in the Central Sands using water budget and water balance methods. The water budget method provides a composite picture of water movement for the entire watershed (evapotranspiration + Δ soil moisture = precipitation – runoff – Δ groundwater storage – Δ surface water storage – Δ storage as snow). The water balance method calculates recharge and soil moisture changes based on calculation of actual evapotranspiration (ET) per landcover type. In several small gaged stream catchments, annual ET rates for various landcover types were assessed: bare ground, phreatophytic vegetation, forested, grassland, unirrigated cropland, irrigated beans, irrigated potatoes, and irrigated corn. The broad categories include landcovers with different ET profiles. For example, “forest” includes native deciduous and coniferous forests and pine plantations. “Grassland” includes prairie, grain crops, bluegrass, etc. The ET results are therefore applicable to large areas only. Changes in soil moisture storage were measured under irrigated and natural landcovers. Monthly and annual ET were calculated using water budget and water balance methods for five streams and related to potential stream depletion and water table changes.

Groundwater inputs and flow variability in streams were evaluated. Streams gained the most flow in headwaters and the incised reaches near the Wisconsin River. Potential streamflow reductions due to irrigated agriculture were assessed in Big Roche a Cri and upper Tenmile Creek assuming conversion from grassland or forest to irrigation, with predicted reductions of 25–30 percent assuming long-term continuation of estimated 1968 irrigation levels. Greater impacts would occur with changes from grassland to irrigated agriculture than from forest to irrigated agriculture. Habitat impacts could relate to changes in stream depth or temperature. Water table decline of 3 feet at the groundwater divide was predicted for sustained 1968 irrigation levels (5 feet if irrigation were doubled). Qualitative and quantitative estimates were made of the potential impacts from conversion to irrigated agriculture from various natural land covers in the marsh and forested reaches of Central Sands streams.

Weeks, E.P., 1969, Determining the ratio of horizontal to vertical permeability by aquifer-test analysis: Water Resources Research, v. 5, no. 1, p. 196–214. [PEER REVIEWED]

Keywords: Central Sands, aquifer properties

Weeks conducted pumping tests for five partially penetrating wells with observation wells to determine the vertical anisotropy of the sand and gravel aquifer. Additional aquifer parameters (specific yield and transmissivity) were also reported. Results are shown below and have been used for subsequent work in the Central Sands such as Bradbury and others (1992).

Aquifer test results

Well	K_H:K_V	T (ft^2/d)	Sy	b (ft)
Hancock	4.1	22,000	0.17–0.2	120
Bancroft Pt-513	2	11,000		80
Bancroft Pt-544	7	23,000		70
Mosinee	2	21,000		85
Plover	16–25 (avg. 20)	19,000		80

Zheng, C., Bradbury, K.R., and Anderson, M.P., 1988, Role of interceptor ditches in limiting the spread of contaminants in groundwater: Ground Water, v. 26, no. 6, p. 734–742. [PEER REVIEWED]

Keywords: Central Sands, ditches, groundwater model

A 2-D, steady state numerical model was used to investigate a drainage ditch (Ditch 4) in the Buena Vista area of the Central Sands. In this area, 65–150 feet of sand is underlain by impermeable Precambrian bedrock. Model results were compared to head and seepage meter readings for late May 1984 and to head readings for July and August of the same year. A recharge distribution was calibrated to the May measurements. Results showed that the ditch's effectiveness in acting as a hydraulic barrier varies seasonally. In May (high water table), the drainage ditch captured water from most or all of the aquifer thickness, effectively forming a flow barrier. Under lower water table conditions (July and August), the ditch did not capture water from the entire aquifer. In August, the ditch captured only about a third of the aquifer thickness and had significant underflow.

CENTRAL SANDS—GEOLOGY BY COUNTY

ADAMS

Clayton, L. 1987, Pleistocene geology of Adams County, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 59, 14 p., includes map, cross sections, GIS files, https://wgnhs.uwex.edu/pubs/000309/. [PEER REVIEWED]

Keywords: Adams County, Central Sands, glacial geology

Pleistocene sediments in Adams County are underlain by crystalline Precambrian bedrock and Cambrian sandstone. The sandstone surface is irregular, and sandstone crops out in steep-sided hills throughout the county west of the Johnstown Moraine.

Pleistocene materials are generally sandy. Glacial sediments were deposited as till in the Johnstown Moraine, glacial stream sediments (pitted and uncollapsed outwash plain), and offshore lake sediments in glacial Lake Wisconsin, including the Lewiston arm of the lake east of the terminal moraine. Sand was sourced from Cambrian sandstones to the east. Fine-grained lake deposits of the New Rome Member of the Big Flats Formation are present in much of the western part of the county—this formation is relatively continuous and occurs above and below sandy units. The paper provides a chronology for the formation and drainage of glacial Lake Wisconsin and creation of the Wisconsin River. Pleistocene glacial features in Adams County include collapse trenches formed by the melting of ice along the edge of Lake Wisconsin, and ice-wedge polygons indicative of permafrost conditions, visible on air photos.

In the western part of the county, glacial sands are overlain by windblown sand which in places forms large dunes. The thickest of these windblown deposits are found to the northwest.

Hart, D.J., 2015, Using the New Rome Formation as a geologic weighing lysimeter for water management in Wisconsin's sand plain: Final Report for WDNR Project Number 14-HDG-03, 18 p. [NOT PEER REVIEWED]

Keywords: New Rome, Central Sands, aquifer properties, geophysics, pumping test

A site in central Adams County was instrumented to determine aquifer properties of the New Rome Formation (NRF). The NRF is a laterally continuous, fine-grained unit that has been interpreted as deep-water sediment associated with glacial Lake Wisconsin. The study site included both irrigated field and grassland and was within about 1,000 ft of Klein Creek. Geoprobe boring and GPR were used to identify subsurface stratigraphy, including vertical variation within the NRF and clinoforms in the overlying sandy sediments. The clinoforms were interpreted as a recessional/transgressive sequence. The NRF was 10–12.5 ft thick at the site, with a sharp lower contact and gradational upper contact with the surrounding sands. Piezometers were installed at the field and grassland sites and screened above, within, and below the NRF. Water levels from above and below the NRF indicated that it was acting as an aquitard. Vertical gradients varied across the study site. Pumping test results from the deep piezometer also indicated confined conditions. Pumping test results in the shallow aquifer elicited a drawdown response in the NRF monitoring well. Irrigation pumping was not observed to influence water levels in the shallow piezometer or in Klein Creek—no drawdown due to pumping and no increase in water level due to applied irrigation water. The NRF at the site was also tested to determine whether it could be used as a weighing lysimeter, but stresses dissipated too quickly for this to be feasible. The ability of the NRF to act as an aquitard appears to be variable, and there may also be significant lateral groundwater movement. A lower-bound vertical hydraulic conductivity of 2.6×10^{-4} ft/d was determined for the lower, massive, clay using laboratory methods.

MARQUETTE

Ekern, G. I. and Thwaites, F.T., 1930, The Glover Bluff structure: a disturbed area in the Paleozoics of Wisconsin: Transactions of the Wisconsin Academy of Science, Arts and Letters, v. 25, p. 89–97. [PEER REVIEWED]

Keywords: Impact structure, meteorite impact, bedrock

This paper describes Glover Bluff, a highly deformed Ordovician dolomite outlier in northwestern Marquette County. The bluff was formerly an active quarry; folded/faulted bedding is exposed. Rock exposed on the bluff's three hills consist of the upper part of the Tunnel City (Franconia/Mazomanie), the Jordan sandstone, and Prairie du Chien (lower Magnesian). Geologic contacts at Glover Bluff are about 200 feet down-dropped compared to contact elevations at Bald Bluff, approximately 2 miles to the west, which is also capped by Ordovician dolomite. The paper also identifies contact elevations between the Trempealeau and Tunnel City groups at several other nearby locations. Geology and structures observed on each of the three hills are described.

Note: The Glover Bluff structure is located approximately 1 mile southeast of Pleasant Lake. Subsequent to the Ekern and Thwaites paper, the origin of the structure was attributed to a meteor impact following the discovery of shatter cones (Read, 1983) and breccia at the site. However, the structure's origin is not entirely certain, and non-impact provenance has also been proposed for the structure.

PORTAGE

Clayton, L., 1986, Pleistocene geology of Portage County, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 56, 19 p., 2 plates, GIS files, https://wgnhs.uwex.edu/pubs/000306/. [PEER REVIEWED]

Keywords: Portage County, Central Sands, glacial geology

Abstract: "Portage County...is underlain by Precambrian igneous and metamorphic rock, Cambrian sandstone, and a variety of Pleistocene materials. The eastern and southwestern part of the county is underlain by 0 to more than 70 m of till, stream sediment, and lake sediment deposited during the Arnott and Wisconsin Glaciations during the late Pleistocene; this material is included in the Keene and Mapleview Members of the Horicon Formation. In the northwestern part of the county, the Precambrian is overlain by a few meters of hillslope deposits derived from residuum, which formed at least partly during the Pleistocene."

Greenberg, J.K., Brown, B.A., 1986, Bedrock geology of Portage County, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 53, 1 plate, GIS files, https://wgnhs.uwex.edu/pubs/000303/. [PEER REVIEWED]

Keywords: Portage County, Central Sands, bedrock geology, maps, GIS files

Consists of a bedrock geology map of Portage County and related GIS files.

Holt, C.L.R., 1965, Geology and water resources of Portage County, Wisconsin: U.S. Geological Survey Water Supply Paper 1796, 77 p., 2 plates. [PEER REVIEWED]

Keywords: Portage County, Central Sand, water quantity, water quality, glacial geology

Portage County is divided into three provinces: sand plain, drift, and drift-crystalline rock. The CSLS area includes the first two of these provinces, which are characterized by sandy outwash, tills, and post-glacial alluvium, together with some wetland areas. The county averages 31 inches of precipitation, about 21 inches of evapotranspiration, and about 10.6 inches of groundwater recharge annually. Surface water runoff is minimal (0.5–1.5 inches). Table 1 provides a county-wide water budget. As of 1960, irrigated agriculture was beginning to expand (irrigated acres increased from 2,800 acres to 6,900 acres between 1954 and 1960). Figure 4 shows a nice graph of potential evapotranspiration and precipitation through a typical year, explaining the timing of recharge. There is a clear description of season-by-season groundwater/surface water interactions on p. 12–13. Land surface west of the moraine slopes 3–15 ft/mi toward the Wisconsin River. As of 1960, drainage ditches had reduced the wetland area in Portage County from 20 percent to 7 percent. Plate 1 maps Portage County bedrock geology (crystalline in the northwest overlain by sandstone in the southeast). Sandstone mounds protrude through the glacial sands in places, some apparently shaped by glacial ice. Mosquito Mound, for example, is elongated, with gentle slope on the east and steep face on the west. There is also a buried sandstone ridge near the Little Plover River, which influences groundwater flow. Glacial tills are very sandy and can be difficult to distinguish from outwash sediments; thickness in the sand plain averages~100 ft (<10–250 ft); in the drift province sediment thicknesses are <10 to 350 ft. The Arnott moraine has a somewhat different makeup and is the product of a pre-Wisconsinan glaciation event. The Outer and Second (Hancock and Almond) moraines contain many kettle lakes and other collapse features. Specific yield values from pump tests range from 0.15–0.31 (average ~0.2). Soil moisture capacity in Plainfield/Coloma is small at 8–13 percent. Table 3 lists aquifer properties (b, T, s, etc.) from four pumping tests. Specific capacities measured in the sand plain were higher than in the drift area, although both are quite high. Lake levels in seepage lakes dropped 2–6 ft during a 1956–1959 drought. Lake fluctuations are not attributed to groundwater pumping at the time of this report.

WAUPACA

Berkstresser, C.F., 1964, Ground-water resources of Waupaca County, Wisconsin: U.S. Geological Survey Water Supply Paper 1669-U, 38 p, 4 plates. [PEER REVIEWED]

Keywords: Waupaca County, water resources, water quality

The part of Waupaca County southwest of the Waupaca River is within the CSLS area. Surficial deposits in this part of the county are mainly outwash (maximum thickness: 132 ft) and hummocky till, with some modern alluvial areas/wetlands. These are underlain by impermeable Precambrian rock in the north, Cambrian sandstone in the southeast. As of 1959, average annual precipitation in the county was 29.5 inches. As with other Central Sands counties, recharge mainly occurs at spring snowmelt, with a smaller recharge event in fall. Aquifer properties reported for a pumping test in Sec. 9, T21N, R11E were: Sy = 0.2, T = 13,400 ft^2/d, K = 1300 ft/d.

- Plate 1: Well and spring locations

- Plate 2: Bedrock surface and general bedrock geology [limited accuracy]
- Plate 3: Surficial geology
- Plate 4: 1958–59 water table map

Mode, W.N., Hooyer, T.S., Attig, J.W., and Clayton, L., 2015, Preliminary Quaternary geology of Waupaca County, Wisconsin: Wisconsin Geological and Natural History Survey Open File Report 2015-03, 1 plate, GIS files, https://wgnhs.uwex.edu/pubs/000937/. [NOT PEER REVIEWED]

Keywords: Waupaca County, glacial geology, Quaternary, maps, GIS files

Consists of a map of Quaternary geology map of Waupaca County and related GIS files

WAUSHARA

Conlon, T.D., 1996, Hydrogeology of the sand and gravel aquifer in the vicinity of the Wild Rose State Fish Hatchery, North-Central Waushara County, Wisconsin: U.S. Geological Survey Water-Resources Investigations Report 96-4213, 9 p. plus appendix. [PEER REVIEWED]

Keywords: Waushara County, springs, aquifer properties

This study estimated properties of the sand and gravel aquifer and springs at the Wild Rose State Fish Hatchery. The site is a groundwater discharge area with multiple springs and flowing sand points/wells. Depth to bedrock was estimated using data from three seismic refraction surveys and 14 USGS soil borings. The borings are described in appendix A. The site is underlain by thin to absent sandstone over granite bedrock—estimated elevations are shown in figure 2, estimated sand and gravel thickness is shown in figure 3. An average K value of 18 ft/d was estimated from two slug tests. Annual water level fluctuations in a well at the site were <0.5 ft. in 1995. Based on Homstrom and others (1995), springs and flowing wells at the site were estimated to flow at 3 million gallons/day, with a contributing area extending west to the topographic divide (surface water divide is not coincident with the groundwater divide). The paper also speculates that the Pine River may provide some water to the springs based on its proximity and on relative water elevations.

Summers, W.K., 1965, Geology and ground-water resources of Waushara County, Wisconsin: U.S. Geological Survey Water Supply Paper 1809-B, 32 p., 3 plates. [PEER REVIEWED]

Keywords: Waushara County, Central Sands, bedrock geology, glacial geology, water resources, high capacity wells, recharge, water quality

Waushara County is subdivided into six regions: (1) western outwash plain, (2) outer and second moraine, (3) pitted outwash plain (between the Hancock and Almond Moraines), (4) well-drained hills and kettles (east of Almond Moraine), (5) drumlins, moraines, sand plains, bedrock mounds, and marshes (east/central Waushara), and (6) glacial lake plain (east). The sediments of each region and their water-bearing capacities are described. Impermeable crystalline bedrock (Precambrian) underlies the entire county, mainly at depths around 400 ft. The Precambrian outcrops near Redgranite. The Precambrian surface slopes southeast at ~20 ft/mi [Note: very few wells encounter Precambrian rock]. Sandstone overlies Precambrian bedrock; the maximum observed thickness of sandstone was 280 ft, and the unit generally thickens to the south. Well yields in sandstone may be high, especially where overlain by sand and gravel. The upper bedrock surface generally slopes southeast at ~10–15 ft/mi.

Based on baseflow for the Fox and Waupaca Rivers, annual recharge for Waushara County is estimated to be 9–10 in/yr in the west, 6–7 in/yr in the east. Flowing wells (eastern Waushara), stream flow, springs, and water levels in wells are discussed. The section on springs includes specific flows for Mecan and Mill Pond springs (p. B17). Fluctuations in the water table are minimized because "if recharge is above normal, discharge to streams increases; and conversely, if recharge is below normal, discharge to streams decreases, and the balance is maintained." (i.e., the main impact of changing recharge amounts is on stream flows). Water quality is also assessed, and the quality was generally good, except for hardness and high iron in some areas.

Note: Report has three plates: a July 1957 water table map, a bedrock surface map, and a surficial geology map.

WOOD

Batten, W.G., 1989, Hydrogeology of Wood County, Wisconsin: U.S. Geological Survey Information Circular 603, 31 p. + maps [Plate 1, water table map]. [PEER REVIEWED]

Keywords: Wood County, Central Sands, aquifer properties, glacial geology, bedrock geology, water table map

Wood County is divided into three physiographic areas: rolling uplands in the northern two-thirds of the county, marshy areas with poorly drained soils west of the Wisconsin River, and sand plains in the southeast, including the Wisconsin River floodplain (CSLS area). The majority of the county is underlain by low-permeability Precambrian rocks. Cambrian sandstone is also present in about half the county, including most of the sand plain area (fig. 4); sandstone is typically 20–40 ft thick (maximum thickness 180 ft). The bedrock surface slopes gently to the southeast. The sand and gravel aquifer consists of lacustrine sands of glacial Lake Wisconsin, 40 ft thick near the Wisconsin River and 60–80 ft thick at the eastern border of the county (fig. 6). The sands contain a layer of clayey silt 5–10 ft thick at a depth of 10–20 ft (New Rome, see note). The hydraulic conductivity of the sand and gravel aquifer ranges from 155–280 ft/d, with an average of 210 ft/d. Average rainfall is 31 in/yr. Recharge estimates include Weeks and Stangland (1971), 11–12 in/yr and Holt (1965), 6.8 in (dry year) – 10.3 in (wet year). Few irrigation wells were active in Wood County in 1985. Twenty wells pumped an estimated 1.08 million gallons per day. Water quality was generally good, other than elevated hardness, iron, and manganese in some areas. Only 3 percent of 124 samples had nitrate concentrations above the drinking water standard.

Note: WDNR investigations related to the Golden Sands Dairy environmental impact study suggest that the New Rome Member is likely discontinuous in Wood County and more continuous in Adams County.

Brown, B.A., Greenberg, J.K., 1986, Bedrock geology of Wood County: Wisconsin Geological and Natural History Survey Information Circular 54, 1 plate, https://wgnhs.uwex.edu/pubs/000304/. [PEER REVIEWED]

Keywords: Wood County, Central Sands, bedrock geology, maps, GIS files

Consists of a bedrock map of Wood County and related GIS files.

Clayton, L, 1991, Pleistocene geology of Wood County, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 68, 18 p., 2 plates (map and cross sections), GIS files, https://wgnhs.uwex.edu/pubs/000318/. [PEER REVIEWED]

Keywords: Wood County, Central Sands, Pleistocene geology, glacial geology, maps, GIS files

Pleistocene deposits in Wood County are derived from several glacial episodes and post-glacial sources. The northern part of the county has glacial materials from at least three separate pre-Wisconsinan glacial advances. The Marshfield moraine in the northwest part of the county formed during one of these glaciations. Sediments in the northern part of the county are characterized by poorly sorted hillslope sediments derived from underlying bedrock; in the east, these generally overlie crystalline Precambrian rock.

Sediments in the southern part of Wood County, including the part within the CSLS area, are typically sandy offshore deposits from meltwater streams associated with the Green Bay Lobe in Portage, Marathon, and Langlade Counties, and with Glacial Lake Wisconsin. The fine-grained New Rome Member is mapped as generally continuous in much of the lake plain. It has a typical thickness of 1 m but over 3 m in some places. Sand of the Love Terrace is found adjacent to the Wisconsin River. These sands were deposited after the draining of Lake Wisconsin; they occur above the level of the modern floodplain but are downcut several meters below the adjacent glacial sands. In many places, offshore deposits and river terrace sediments are covered with 0.5 m or more of windblown sand. Sand dune orientation indicates a wind direction from the west-northwest.

Note: Based on a review of geologic and well driller logs (Golden Sands Dairy review), the New Rome Member appears to be sporadically present but generally thin and discontinuous in Wood County.

CENTRAL SANDS—GENERAL

Bradbury, K.R., Kraft, G.J., Drought, J., Fienen, M.N., Hunt, R.J. and Hart, D.J., 2017, Groundwater quantity fundamentals in Wisconsin's Central Sands regions: Report prepared for the Wisconsin Food, Land, and Water Project Groundwater Quantity Work Group, 7 p. [NOT PEER REVIEWED]

Bussan, A.J., Kraft, G., Isherwood, J., eds., 2011, Walking on water: Essays for the Central Sands: University of Wisconsin–Extension Publication A3961, 58 p. [NOT PEER REVIEWED]

Kraft, G.J., Kucharik, C.J., and Greb, S.R., 2011, Climate change influences on Wisconsin Central Sands hydrology and aquatic ecosystems—Central Sands Hydrology Working Group Report to the WICCI adaptive assessment report: Wisconsin Initiative on Climate Change Impacts, 20 p., https://www.wicci.wisc.edu/report/Central-Sands-Hydrology.pdf. [NOT PEER REVIEWED]

Miller, N. 2012, Vanishing waters?: Grow—Wisconsin's Magazine for the Life Sciences, vol. 5, issue 2, p. 20–27. [NOT PEER REVIEWED]

LAKE WATER BUDGETS, GROUNDWATER-SURFACE WATER INTERACTIONS

Anderson, M.P., and Pint, C.D., 2002, Groundwater-lake interaction: response to climate change, Vilas County, Wisconsin: Final report to the Water Resources Institute, University of Wisconsin, 16 p. [NOT PEER REVIEWED]

Keywords: Lakes, groundwater models, surface water-groundwater interactions

Regional-scale steady state and transient groundwater models were created for the Trout Lake Basin in northern Wisconsin. The model was used to delineate lake capture areas and assess the effects of wet vs. dry climate conditions on groundwater-lake interactions. The lakes within the model were simulated in MODFLOW using the LAK3 package. Flowpaths were delineated, with travel time of 20–200 years for different lakes in the system. Underflow was common, highlighting the importance of conducting simulations in three dimensions. Lake levels in seepage lakes were sensitive to changes in recharge in the "dry" and "wet" scenarios, with the lake nearest the groundwater divide showing the greatest effects. Capture zone sizes decreased under "wet" conditions, while groundwater discharge rates increased.

Farnsworth, R.K., Thompson, E.S., and Peck, E.L., 1982, Evaporation atlas for the contiguous 48 United States: National Oceanic and Atmospheric Administration Technical Report NWS 33, 24 p. [PEER REVIEWED]

Keywords: Evaporation

The atlas provides pan evaporation rates and free water surface conversion rates for the entire United States. Free water surface evaporation is not equivalent to lake evaporation because it does not account for heat storage. However, the values given are used in many papers as a point for comparison to more detailed evaporation studies. For a shallow lake like Plainfield, free water surface evaporation may provide a decent estimate of evaporation.

Finch, J., and Calver, A., 2008, Methods for the quantification of evaporation from lakes: Report to the World Meteorological Organization's Commission for Hydrology, 41 p., http://nora.nerc.ac.uk/id/eprint/14359/1/wmoevap_271008.pdf. [PEER REVIEWED]

Keywords: Lake water balance, methods, evaporation

Provides an overview of methods used to estimate evaporation from lakes. Evaporation amounts depend on (1) the available energy from net radiation at the water body surface and heat stored in the water and (2) the ease of vapor diffusion to from the lake to the atmosphere. In temperate climates like Wisconsin, there is a seasonal offset between the period of greatest energy input (summer solstice) and period of greatest evaporation (late fall). The offset is due to heat storage in the water body and increases with increases water body depth. Shallow waters, <0.5 m deep, experience virtually no offset, while deeper water bodies may experience maximum evaporation 4 months after the solstice. Lake stratification is also a complicating factor for lake evaporation models.

Summaries are provided for several different evaporation estimation methods: pan evaporation, mass balance, energy budget, bulk transfer, physically based combination equations (Priestley-Taylor, Penman-Monteith), equilibrium temperature method, and empirical approaches. Each section includes the data needs for the method, together with underlying assumptions, degree of accuracy, and drawbacks. The energy balance method is generally considered the most accurate of the methods listed, but has high data needs and is expensive. Combination equations such as Penman-Monteith have good accuracy, rely on meteorological data that are more readily measured, and can be modified to account for water body heat storage. Accounting for seasonal lake stratification remains a challenge.

Hennings, R.G., 1978, The hydrogeology of a sand plain seepage lake, Portage County, Wisconsin: University of Wisconsin, M.S. thesis, 70 p. [REVIEWED BY GRADUATE COMMITTEE]

Keywords: Central Sands, lake water budget, hydrogeology, water quality

This thesis studies the hydrogeology and nutrient loading of Pickerel Lake in southeastern Portage County. Pickerel Lake is a 45-acre seepage lake in the pitted outwash plain between the Elderon and Second (Almond) moraines. Pickerel Lake has a maximum depth of 15 ft and lakebed sediment thickness of up to 55 ft. Lakebed sediment is >12 ft thick everywhere outside of the shore zone. Boring logs record mainly medium-coarse sand. Clays and silts are present in some, but not all, logs. Subsurface temperature and lakebed/onshore piezometers were used to characterize groundwater inflow and outflow. Vertical and horizontal flow nets were constructed, together with a lake water budget. Hennings calculated a lake volume replacement rate of 1.2 years, with groundwater flows making up over three quarters of the lake's water budget. Generalized K values were used for calculations. Hennings recommended piezometer placement through lakebed sediments in order to better estimate that thickness of the aquifer that is in communication with the lake.

A second section of the thesis includes a nutrient budget for phosphorus. This concluded that Pickerel Lake is naturally eutrophic, with some anthropogenic contribution from nonpoint sources.

Note: Like Long and Plainfield Lakes, Pickerel Lake is located within a tunnel channel.

Hunt, R.J., Haitjema, H.H., Krohelski, J.T., and Feinstein, D.T., 2003, Simulating ground water-lake interaction: approaches and insights: Ground Water, v. 41, no. 2, p. 227–237. [PEER REVIEWED]

Keywords: Lakes, groundwater models, MODFLOW, LAK package

Lakes may be represented in MODFLOW as areas of specified head, as high-K zones, or using the LAK package. The LAK package allows the most detailed representation of a lake, but in some cases, simpler representations are appropriate. High-K lakes may be used for seepage lakes with no surface inflows or outlets (still true?) and gave similar results to the LAK package in the test case. 2-D analytical tools help conceptualize lake/groundwater interaction. A lake's vertical capture zone depends on its length relative to the aquifer thickness (small lakes capture about half the aquifer thickness, large lakes capture the entire thickness); horizontal capture zones are about twice the lake's width. (These generalizations may not hold true depending on the precipitation/evaporation ratio and the presence of surface water inlets/outlets.) Two-dimensional groundwater models may be appropriate if the lake is larger than the characteristic length (L), where $L=5*(k_h/k_v)^{0.5}$ * aquifer thickness, and where there are no surface water features at a distance less than L. Model grid spacing was shown to be important to surface inflow/outflow results (less so for groundwater/lake interaction). Ideal grid spacing is between 0.1λ and λ, where $\lambda = (Tc)^{0.5}$; T is transmissivity and c is the resistance to flow between the lake and aquifer (thickness of resistance layer / K_v).

Karnauskas, R.J., 1977, The hydrogeology of the Nepco Lake watershed in central Wisconsin with a discussion of management implications: University of Wisconsin, M.S. thesis, 248 p. [REVIEWED BY GRADUATE COMMITTEE]

Keywords: Central Sands, Nepco Lake, water budgets, water quality, hydrogeology

Thesis describes the hydrogeology and water quality of the Nepco Lake watershed in Wood and Portage Counties (water quality is outside the scope of this review). Upper bedrock is crystalline to the west, sandstone to the east. Bedrock is overlain by sandy moraine and outwash sediments. Specific capacities of sandstone wells are three times lower than wells penetrating the outwash. Near Nepco Lake, deeper wells encounter a reddish-brown silty sand with different hydraulic properties and water quality from the overlying clean sands. Reddish-brown clay loam overlies crystalline bedrock. Table 5 summarizes hydraulic characteristics of the outwash as determined from 8 aquifer tests. Near Wisconsin Rapids, K averaged 1540 gallons/day/ft^2, and the average coefficient of storage was 0.23. Laboratory values for specific yield were 0.21–0.31.

The Nepco Lake watershed was characterized using 146 monitoring wells, including 18 piezometer nests. Water levels in drainage ditches were within 0.05 ft of the water table elevation and were also used as monitoring points. Aquifer storage changes were calculated based on water levels. For 1976–1977 (dry year) aquifer storage declined July–January and regained 85 percent of the lost storage during spring thaw.

Monthly hydrologic budgets were calculated for the 1976–1977 water year. Direct groundwater inputs made up only 0.8–4 percent of the lakes budget but was an important component of surface inflow to the lake. For example, Fourmile Creek [Buena Vista] is a groundwater discharge area and gained 4.5–8 MGD (8.4–14.9 cfs) of flow between Wazeecha Lake and Nepco Lake.

The effects of current and future development land use on groundwater levels, stream flows, and water quality were assessed. Karnauskas concluded that groundwater availability was unlikely to be significantly impacted, water quality was likely to be locally affected in areas of urban and agricultural development, and that streamflow reduction was likely to be a result of additional groundwater pumping.

Krabbenhoft, D.P., Bowser, C.J., Anderson, M.P., and Valley, J.W., 1990, Estimating groundwater exchange with lakes 1. The stable isotope mass balance method: Water Resources Research, v. 26, no. 10, p. 2445–2453. [PEER REVIEWED]

Keywords: Lakes, stable isotopes, water budget

Stable isotopes of oxygen were used to evaluate the groundwater inflow component of a lake water budget in northern Wisconsin. Lake water is enriched in heavier oxygen (^{18}O) and hydrogen (^{2}H) isotopes due to preferential evaporation of the lighter isotopes. A network of shallow and deep piezometers and seepage meters were sampled, together with lake water. Lake samples were taken during periods when the lake was well mixed (fall). Lake water exhibited the heaviest isotope ratios, while upgradient deep groundwater isotopes were the lightest (values close to average precipitation). Isotopes taken from deep groundwater downgradient of the lake reflected mixing of lake water and groundwater (see fig. 2). [**Note**: This type of analysis would likely be helpful to identify groundwater withdrawal/lake interactions in the CSLS field study.] Isotope ratios in shallow groundwater were fairly constant at sampling points all around the lake.

The annual groundwater inflow amount was calculated (eq. 4) using the inflow/outflow rate and isotopic composition of precipitation, surface inflow and evaporation, and the isotopic composition of the lake. Lake evaporation was estimated using nearby pan evaporation data, and precipitation was derived from nearby weather stations. Because the lake had no surface water inlet or outlet and runoff was minimal, groundwater outflow was calculated as the residual of the water budget. Evaporation was the largest source of error in the water budget calculation. Inflow and outflow results agreed well with a numerical model calibrated to the observed $\delta^{18}O$ distribution.

Note: $\delta^{18}O$ is the deviation of the sample isotope ratio from the standard ratio, given in permille (explanation at http://www.iceandclimate.nbi.ku.dk/research/past_atmos/past_temperature_moisture/isotopes_delta_notation).

Lee, T.M., and Swancar, A., 1997, Influence of evaporation, ground water, and uncertainty in the hydrologic budget of Lake Lucerne, a seepage lake in Polk County, Florida: U.S. Geological Survey Water Supply Paper 2439, 61 p. [PEER REVIEWED]

Keywords: Seepage lakes, water budget, evaporation, energy balance, flow net

A water budget was created for a central Florida seepage lake using energy budget methods. The lake is situated in a sand aquifer overlying the Upper Floridan (karst) aquifer and is the result of sinkhole collapse in the limestone. Groundwater flows to the lake from all sides and exits through the lake bottom (sinkhole appears to be a preferential flow path). There is typically a confining clay at the top of the carbonate aquifer. As with Central Sands seepage lakes, groundwater inflow and outflow and evaporation were the dominant components of the water budget.

An energy budget was constructed to determine daily evaporation rates. The rates determined from the energy budget varied from calculated pan evaporation rates by 10–35 percent.

Monthly groundwater inflow rates were determined using flow net methods. Water levels were collected from 36 monitoring wells. A single K value was used. The potential error of this method was calculated to be high due to uncertainties in hydraulic conductivity and transient effects. Leakage from the lake bottom was calculated from the hydrologic budget for a 3-week period and then estimated using a simplified flow net. An estimated 22 percent increase in lake leakage over natural conditions was attributed to nearby groundwater pumping for citrus irrigation. This estimate was based on average predevelopment water table heads (possibly not a very accurate method, especially as the water budget was calculated during a dry year). Error analysis of the water budget results suggested that groundwater leakage and inflow rates were both underestimated; inflow rates were shown to be as much as 2.2 times the original calculation (23.6 in. vs. 10.5 in.)

A 2-D, steady-state groundwater model was used to evaluate the effects of heterogeneity on groundwater inflow and leakage. Results showed that breaks in the confining unit at the top of bedrock (vs. continuous clay) caused only the upper part of the aquifer to be captured by the lake, increased the percent of the lake area where leakage occurred, and decreased the area of inflow. The amount of anisotropy simulated strongly affected the amount of vertical leakage but had little impact on (mainly horizontal) inflow. The effect of decreasing the vertical conductivity of lake sediments was to redistribute leakage to higher conductivity areas, but total leakage did not change significantly.

Munter, J.A., and Anderson, M.P., 1981, The use of ground-water flow models for estimating lake seepage rates: Groundwater, v. 19, no. 6, p. 608–616. [PEER REVIEWED]

Keywords: Central Sands, groundwater-surface water interactions, modeling

Numerical modeling of groundwater-lake interactions was developed for two Wisconsin lakes: Bass Lake, a seepage lake in St. Croix County and Nepco Lake, an impoundment in the Central Sands (Wood County). A steady-state 2-D profile model developed for Bass Lake highlighted the influence of the horizontal to vertical hydraulic conductivity ratio (Kh/Kv) on the magnitude and distribution of groundwater inflow and outflow. Smaller values of Kh/Kv resulted in smaller vertical gradients. Conversely, vertical gradients could be used to estimate Kh/Kv in model calibration. Kh/Kv also impacted the flow distribution to the lake, with low Kh/Kv resulting in near shore seepage and high Kh/Kv resulting in seepage occurring much farther offshore. Fine-grained sediments in the littoral zone were are shown to impact seepage rates much more than similar sediments located offshore. At Nepco Lake, 2-D and 3-D models were used in an attempt to recreate observed conditions. Downward gradients were observed at all parts of the lake due to the effects of the earthen dam impounding the lake. The 2-D profile model was unable to recreate field conditions, while the 3-D model, which included neighboring stream geometry, was able to simulate observed heads and stream flow.

Parkhurst, R.S., Winter, T.C., Rosenberry, D.O., and Sturrock, A.M., 1998, Evaporation from a small prairie wetland in the Cottonwood Lake Area, North Dakota—an energy-budget study: Wetlands, v. 18, no. 2, p. 272–287. [PEER REVIEWED]

Keywords: Evaporation, energy-budget, water budget, wetlands

An energy-budget study determined evaporation rates from a prairie wetland in central North Dakota. Prairie wetlands are small, shallow surface water bodies; the study wetland had an area of 2 ha (5 acres) and a maximum depth of 1 m. The lake was instrumented with thermistors above and below the water level and in the underlying sediments Weather data were also collected. Of the components of the energy budget (equation 1), long-wave radiation into and out of the lake contributed the greatest energy flux. Groundwater-related heat fluxes were calculated using the segment method (see Rosenberry and others, 2008, chap. 2). Groundwater fluxes were found to be small (low-K tills) and had very little effect on overall evaporation. A key finding of the study was that evaporation rates from small water bodies are extremely responsive to solar radiation (as compared to lake temperature for larger water bodies) and will therefore reflect the degree of cloudiness for a given time period. Because of this, evaporation rates did not show a consistent increase-decrease pattern over the open-water season.

Note: Some findings of this study may be relevant to Plainfield Lake, although groundwater flux is likely a more important factor at Plainfield Lake. Also note that the Parkhurst study was of a shallow lake in North Dakota, where evaporation exceeds annual precipitation, while in Wisconsin the reverse may be true. The study does not address transpiration.

Possin, B.N., 1972, The hydrogeology of Mirror and Shadow Lakes in Waupaca, Wisconsin: University of Wisconsin, M.S. thesis, 83 p. [REVIEWED BY GRADUATE COMMITTEE]

Keywords: Central Sands, lake water budget, hydrogeology, water quality

This thesis studies the hydrogeology and nutrient loading of Mirror and Shadow Lakes in Waupaca County. The lakes form a chain with an outlet to the Crystal River but no surface inflow. They are located in a pitted outwash plain (stratified sand) underlain by glacial till. Forty-five monitoring wells, including four piezometer nests, were used to characterize groundwater flow into and out of the lake. Possin notes that additional piezometer nests would have been desirable to characterize vertical groundwater movement. Inflow and outflow areas varied seasonally. Marl and peat act to seal the lakes from groundwater flow. At Mirror Lake, about half of the groundwater flowing toward the lake is calculated to flow beneath or around rather than through it. A hydrologic budget was constructed, using simplifying assumptions where data gaps existed, and lake volume replacement rates were calculated. Groundwater flow was estimated to make up 20–40 percent of the lakes' inflow and 2–16 percent of their outflow.

A second section of the thesis includes a nutrient budget for phosphorus and nitrogen, which were present at problematic levels. The study concluded that storm sewer diversion and aeration could be used to reduce phosphorus levels.

Rosenberry, D.O., Briggs, M.A., Delin, G., and Hare, D.K., 2016, Combined use of thermal methods and seepage meters to efficiently locate, quantify, and monitor focused groundwater discharge to a sand-bed stream: Water Resources Research, v. 52, p. 4486–4503, doi: 10.1002/2016WR018808. [PEER REVIEWED]

Keywords: Temperature profiling, groundwater-surface water interaction, methods, seepage

Groundwater discharge points in a stream were located and assessed using fiber-optic distributed temperature sensing (FO-DTS), seepage meters, and vertical temperature profiling. The stream substrate was relatively uniform glacial outwash sand and gravel, yet groundwater inflow was not homogeneous. FO-DTS cables deployed along the stream bed successfully located areas of focused groundwater upwelling the majority of the time (confirmed by seepage meter results). Relatively fast streamflow and hyporheic advection did not offset the cold temperature anomalies downstream from areas of high seepage. Groundwater inflow was separately estimated using the diurnal vertical temperature profile in the stream bed (VFLUX2 model); results agreed very well with seepage meter results in the same location and did not appear to respond strongly to precipitation events. The model is sensitive to streambed thermal diffusivity, especially in areas of upward flow, and a site-specific value is needed for this parameter.

Notes: The methods described here could also be applicable to seepage lakes. A relatively uniform bed is needed to obtain good-quality of the results, as the cable needs to rest directly on the bed.

Rosenberry, D.O., and LaBaugh, J.W., 2008, Field techniques for estimating water fluxes between surface water and ground water: U.S. Geological Survey Techniques and Methods 4–D2, 128 p. [PEER REVIEWED]

Keywords: Groundwater-surface water interactions, field techniques, temperature

Chapter 1: Provides an overview of concepts in groundwater-surface water interactions and briefly describes various methods of qualitative and quantitative assessments techniques. Also provides examples of studies where the techniques have been used in various types of settings. Methods described include: rainfall-runoff models, stream discharge measurements, numerical groundwater flow modeling, measurement of hydraulic properties using wells, infrared imagery analysis, dye and tracer tests (including solute tracers, naturally occurring chemical tracers, and stable isotopes), temperature profiling (surface probes and vertical profiles), specific conductance probes, electrical resistivity profiling, mini-piezometers, seepage meters, and biological indicators of groundwater inflow.

Chapter 2: Describes methods, applicability (table 4), and common pitfalls for three methods of quantifying groundwater-surface water flows: (1) use of monitoring well data with the Darcy equation to calculate flow, (2) hydraulic gradient measurement using mini-piezometers, and (3) direct flow measurement using seepage meters. **Darcy approach:** Two methods are described to calculate whole-lake flows: the segmented approach and flow-net analysis. In each case, results improve with a higher number of monitoring points (wells). A homogeneous, isotropic aquifer under steady-state conditions is assumed. Uncertainties in K and b (thickness of aquifer for which water enters the lake) are the greatest sources for error in these methods. **Mini-piezometers:** Hydraulic potentiomanometers (or mini-piezometers) can identify gradients into and out of surface waters by simultaneously measuring lake and shallow groundwater levels. Typical construction of the device and some variants are described. This device works best in sediments that are fine sand or coarser. Transects parallel and perpendicular to the shoreline can identify special variability in gradients, and inserting the probe to different depths can test vertical hydraulic head distribution. Potential sources of measurement error are identified. **Seepage meters:** Seepage meters provide a direct measurement of inflow or outflow. They may also be used in combination with mini-piezometers to obtain a local value for K. The chapter describes the seepage meter apparatus and offers tips and troubleshooting suggestions to obtain more accurate seepage measurements. Sources of error such as improper attachment of tubing and bags, timing and accuracy of measurements are discussed.

Chapter 3: Describes methods typically used in karst settings—not relevant to the CSLS.

Chapter 4: Describes the use of temperature as a tracer of groundwater movement in stream beds. Temperature can be a useful tracer because it is a “robust” property to monitor and does not require lab analysis. Heat is transferred in the subsurface by conduction, convection, and advection. Advection dominates where near-saturated conditions exist but other transfer methods should not be ignored for fluxes less than 8 x 10^{-8} m/s (clay-textured beds, low hydraulic gradients). Higher groundwater inflow rates result in increased lag time and decreased temperature extremes in the bed relative to surface temperatures patterns. Equations are given for using temperature to determine hydraulic conductivity and groundwater fluxes. Measurement techniques and proper monitoring point placement, and the potential issues with direct and indirect measurements are discussed. Indirect measurements (wells) are shown to give good temperature results.

Sacks, L.A., Lee, T.M., and Swancar, A., 2014, The suitability of a simplified isotope-balance approach to quantify transient groundwater-lake interactions over a decade with climatic extremes: Journal of Hydrology, v. 519, p. 3042–3053. [PEER REVIEWED]

Keywords: Lakes, stable isotopes, water budget, transient

Oxygen isotopes were used to assess temporal changes in groundwater flow into a central Florida lake over a 10-year period. A biannual time-step was used, and results were compared to an existing water budget for the lake (Lee and Swancar, 1997). Groundwater inflow was calculated for each period using the method described in Krabbenhoft and others (1990). The resulting groundwater inflow estimates varied over time, and more than half of the isotope-based estimates fell within the previously computed water budget’s margin of error. During periods of very high precipitation (e.g., years with multiple hurricanes) or severe drought, isotope-derived groundwater inflow results did not match groundwater inflow calculated by the water budget. The calculation assumed the isotopic composition of precipitation and atmospheric moisture to be constant, while they actually varied due to the climate extremes. [This effect may be less dramatic in Wisconsin given Midwestern weather patterns—no hurricanes.] Groundwater inflow results were most sensitive to uncertainties in relative humidity, evaporation, and the isotopic composition of lake water.

Stauffer, R.E., 1985, Use of solute tracers released by weathering to estimate groundwater inflow to seepage lakes: Environmental Science and Technology, v. 19, no. 5, p. 405–411. [PEER REVIEWED]

Keywords: Lakes, water budget, water chemistry, Wisconsin, Central Sands, groundwater

Stauffer estimated the average groundwater inflow to seepage lakes, including nine lakes in the Central Sands region, using relative magnesium (Mg) concentrations in groundwater and lake water. Several potential chemical tracers were considered (including calcium, magnesium, and silicon), and magnesium was chosen as the most conservative/ least reactive. After substitutions and assumptions, the equation for steady state groundwater inflow is given as $Q_i = (X_pC_o - PC_p) / (C_i - C_o)$, where Q_i is the groundwater inflow, X_p is the excess precipitation (precipitation – evaporation), P is direct precipitation, C_p is the tracer concentration in precipitation, C_o is the concentration in lake water, and C_i is the concentration in groundwater. Annual average precipitation and evaporation were estimated from regional values. Baseflow chemistry in nearby streams was used as a proxy for groundwater concentrations. Two water chemistry samples were taken from the majority of the study lakes. Improved estimates of evaporation, precipitation, additional lake water samples, and direct groundwater sampling would improve results of this method. Concurrent use of multiple tracers to confirm results would also be helpful.

Note: (1) Wood Lake, east of Pleasant Lake, was one of the lakes evaluated in this study. The calculated steady state groundwater inflow was 0.5 m/yr. (2) The variables in the equations in this paper are not always clearly defined.

Watras, C.J., Read, J.S., Holman, K.D., Liu, Z. Song, Y.-Y., Watras, A.J., Morgan, S., and Stanley, E.H., 2014, Decadal oscillation of lakes and aquifers in the upper Great Lakes region of North America: Hydroclimatic implications: Geophysical Research Letters, v. 41, no. 2, p. 456–462. [PEER REVIEWED]

Keywords: Lakes, water levels, Wisconsin

This report evaluates water level trends in lake level and groundwater level data in northern Wisconsin. A consistent 13-year water level oscillation is observed from 1940 to 1998. The oscillation is related to atmospheric water flux (precipitation – evaporation) and to stage-dependent outflows. In 1998, a declining water level trend was observed, overprinting the ongoing 13-year cycle. The long-term trends are observed at multiple scales: in small northern Wisconsin lakes, in groundwater, and in the Great Lakes. The appearance of these patterns in such hydrologically different settings indicates large-scale drivers. Watras and others suggest a possible relationship to North Pacific atmospheric oscillations.

Note: Lake level trends observed in Northern Wisconsin by Watras and others appear to correlate to some of the groundwater-surface water level changes observed in Central Wisconsin in the past few decades. Causative relationships are yet to be determined.

Winter, T.C., 1995, Hydrological processes and the water budget of lakes, *in* Lerman, A., Imboden, D.M., and Gat, J.R., eds., Physics and chemistry of lakes: Springer, Berlin, Heidelberg, p. 37–62. [PEER REVIEWED]

Keywords: Lakes, water budgets, groundwater-surface water interactions

Provides an overview of lake hydrology and water budget components (precipitation, overland runoff, groundwater inflow, evaporation, groundwater outflow, surface water outflow). Available measurement/calculation methods are briefly discussed, with potential difficulties.

Local precipitation measurement is important to ensure accuracy of the lake budget. Evaporation is most accurately determined by an energy budget, but this may be prohibitively expensive. Eleven empirical evaporation methods were assessed by comparison to energy budget results: the Penman, DeBruin-Keijman and Priestly-Taylor methods gave the most comparable results. In one study, wind speed measurements in the lake center varied from shoreline measurements by 20–40 percent. The chapter reviews concepts in runoff production and surface water flow measurement. Lake interactions with the groundwater system are discussed at length, including the effect of anisotropy and transient changes in water table level, which can lead to flow reversals on the up- and down-gradient side of flow-through lakes. Winter emphasizes the importance of a whole-watershed conceptual approach to assessing lake/groundwater interactions, as monitoring networks are discrete in space and time and are unlikely to capture all important aspects of the system.

Note: (1) Relevant to the Plainfield/Long Lake area, “for lakes enclosed by a groundwater divide, areas of seepage from a lake can occur offshore that would not be detectable with any number of water-table wells placed within the lake’s groundwater watershed.” (p. 51) (2) Numerical modeling tools available have changed somewhat since 1995.

LITTLE PLOVER RIVER (LPR)

Bradbury, K.R., Fienen, M.N., Kniffin, M.L., Krause, J.J., Westenbroek, S.M., Leaf, A.T., and Barlow, P.M., 2017, A groundwater flow model for the Little Plover River basin in Wisconsin’s Central Sands: Wisconsin Geological and Natural History Survey Bulletin 111, 82 p., https://wgnhs.uwex.edu/pubs/b111/. [PEER REVIEWED]

Keywords: Central Sands, Little Plover River, MODFLOW, groundwater model

Report summarizes the work done to model groundwater and surface water flow in the Little Plover River (LPR) basin in the northern part of the Central Sands (central Portage County). It includes a brief description of water quantity issues and regional hydrogeology and describes methods to determine geologic layering, water use, groundwater levels (head targets), streamflows (flux targets), hydraulic conductivity, and recharge. A significant portion of the report is devoted to recharge estimation methods using the soil-water balance model. The report also provides details of model construction (grid and layering, boundary conditions, parameterization and calibration, time steps for transient model). Many aspects of CSLS model construction and execution are expected be similar to those used in the LPR study.

The report presents stream depletion results for various groundwater pumping scenarios under steady state and transient conditions. Model results show the stream to be well-connected to groundwater and to be influenced by groundwater pumping. Optimization modeling was used to test management scenarios such as removal of pumping wells near the stream.

Bradbury, K.R., Fehling, A.C., and Parsen, M.J., 2017, A groundwater flow model for the Little Plover River basin in Wisconsin’s Central Sands—user’s manual: Wisconsin Geological and Natural History Survey Bulletin 111–Supplement, 30 p. [PEER REVIEWED]

Keywords: Central Sands, Little Plover River, MODFLOW, groundwater model

The user’s manual gives instructions for running the LPR model in steady state and transient mode and for running scenarios.

Browne, B. A., and Guldan, N.M., 2005, Understanding long-term baseflow water quality trends using a synoptic survey of the ground water–surface water interface, central Wisconsin: Journal of Environmental Quality, v. 34, no. 3, p. 825–835. [PEER REVIEWED]

Keywords: Central Sands, Little Plover River, groundwater age, nitrate, recharge

This study established relationships between groundwater recharge date and nitrate concentration. Mini-piezometers (n=145) were installed to a depth of 60 cm in the LPR thalweg and sampled for components including chlorofluorocarbons (CFCs), nitrate, and N_2. Hydraulic conductivity was estimated using a Hvorslev falling head test at each sample site, and groundwater seepage was calculated using Darcy's law. The Little Plover River gains flow from groundwater in most of its ditched headwater area, loses flow in its midsection, and gains significant flow in the downstream reach approaching the Wisconsin River (fig. 2). Calculated discharge amounts were summed and agreed well with measured stream flows (fig. 3); this was attributed to isotropic conditions, low variability of K, and the large number of sample points. CFC concentrations were used to derive recharge ages for water at each sample point. Recharge ages ranged from 50 to 0 years, with a weighted mean of 23.7± 7 years. Age data were used to reconstruct nitrate concentrations in groundwater through the period 1950–2000, and future concentrations were predicted under three input scenarios.

Clancy, K., Kraft, G.J., and Mechenich, D.J., 2009, Knowledge development for groundwater withdrawal management around the Little Plover River, Portage County Wisconsin, A report to the Wisconsin Department of Natural Resources: Center for Watershed Science and Education, College of Natural Resources, University of Wisconsin–Stevens Point, 50 p. [Report to WDNR—NOT PEER REVIEWED]

Keywords: Central Sands, Little Plover River, precipitation, statistical analysis, groundwater model, high capacity wells

Assessment of Little Plover River following the early 2000s dry-ups. Uses statistical methods and numerical modeling to assess flow depletion in the LPR. Describes LPR historical flow record, the history of groundwater withdrawals in the LPR basin, and past precipitation records. Assesses pumping diversion amounts associated with the Village of Plover municipal wells, industrial uses, irrigation wells, etc. Statistical tests indicate decreased flow starting in the early 1970s. Transient groundwater modeling indicates 3–5 cfs of flow depletion from the LPR related to groundwater pumping.

Note: Data from this study were used to inform the Little Plover River groundwater model (Bradbury and others, 2017).

Fienen, M.N., Bradbury, K.R., Kniffin, M., and Barlow, P.M., 2018, Depletion mapping and constrained optimization to support managing groundwater extraction: Groundwater, v.56, no. 1, p. 18–31. [PEER REVIEWED]

Keywords: Central Sands, Little Plover River, groundwater model, management tools

The Little Plover River groundwater model (Bradbury and others, 2017) was developed in the context of a changing regulatory landscape and the potential need for withdrawal management tools. A Public Rights Flow has been set for the LPR and was used as a target flow when investigating management options. The contributing area for the LPR was mapped at steady state under non-pumping and 2013 pumping conditions, as were the contributing areas for nearby high capacity wells. Stream depletion is the result of three mechanisms: direct capture from the stream, interception of groundwater that would otherwise have flowed into the stream, and diversion of water to other water bodies due to alterations in the flow field. The depletion potential of nearby wells was assessed, and some wells outside the stream's contributing area were found to have high depletion potential. The most influential factor on depletion potential was distance from the stream. Turning off pumping in the 12 wells with the highest depletion potential brought streamflows near the target flow. Management options were explored using optimization modeling in MODFLOW-GWM. Wells were grouped by location and depletion potential into 20 or 50 groups, and pumping was decreased to reach the target flow in the LPR. Table 1 summarizes the total reductions in pumping modeled under several different scenarios, including a scenario in which the maximum pumping reduction was limited to 35 percent and one in which wells were allowed to shut off completely. One limitation of the analysis, described in the paper, is that recharge rates were not able to be tied to changing pumping rates. In the context of irrigated agriculture, these two values are interdependent and will affect real impact amounts.

Weeks, E.P., Erickson, D.W., and Holt, C.L.R., Jr., 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., 6 plates [PEER REVIEWED]

Keywords: Central Sands, Little Plover River, stream flow, high capacity wells

Weeks and others conducted an in-depth study of hydrology and surface water/groundwater interactions in the Little Plover River basin. The hydrogeology of the basin is described. Aquifer and stream bed parameters and water budget components were derived from field studies, where possible. The study assessed the impacts of groundwater withdrawals on streamflow by measuring flow at several locations while pumping a well 300 feet from the stream. Significant amounts of depletion were observed during the test. The paper discusses potential impacts of increased pumping on stream flow, temperature, and fish populations. The Little Plover River pump test video was a product of this study and shows field techniques and results.

RECHARGE ESTIMATION

Bradbury, K.R., 1991, Tritium as an indicator of ground-water age in central Wisconsin: Ground Water, v. 29, no. 3 p. 398–404. [PEER REVIEWED]

Keywords: Central Sands, aquifer properties, recharge

This data is used and discussed further in Bradbury and others (1992). Groundwater travel times calculated using tritium concentrations are on average longer in discharge areas and shorter in recharge areas. The paper notes that groundwater travel times in the moraine areas are longer than elsewhere, even though this is a recharge area. This could indicate that moraine sediments experience slower infiltration than outwash plain sediments, although both are mainly composed of sand and gravel.

Bradbury, K.R., Faustini, J.M., and Stoertz, M.W., 1992, Groundwater flow systems and recharge in the Buena Vista Basin, Portage and Wood Counties, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 72, 31 p., https://wgnhs.uwex.edu/pubs/ic72/. [PEER REVIEWED]

Keywords: Central Sands, aquifer properties, recharge, groundwater model

Report describes the hydrogeology and groundwater recharge of the Buena Vista Basin in the northern Central Sands. The sand and gravel aquifer in underlain by Precambrian crystalline bedrock in the north part of the basin and by Cambrian sandstone in the south. Sediments are generally sand and gravel, including on the moraines. Continuous clays are found only in the southwest corner of the basin. On the east end of the basin, the groundwater divide occurs between the Hancock and Almond moraines. Hydraulic conductivity in the sand and gravel aquifer on the order of 10^{-4} m/s based on a variety of aquifer tests (table 1). Results of individual slug tests conducted for this study are listed in an appendix.

Water level measurements from piezometer nest, tritium sampling and simple numerical groundwater modeling were used to determine recharge and discharge areas in the basin. Results of the different methods were generally in agreement, with the strongest recharge areas near the east, north and south basin divides and discharge areas in the lower reaches of streams and in wetland areas at the base of the moraine. (Results from tritium sampling showed longer flow paths in discharge areas than recharge areas, although there samples did have a large standard deviation.) Flow paths are short (5 km) relative to the length of the basin (30 km).

Gebert, W.A., Walker, J.F., and Kennedy, J.L., 2011, Estimating 1970–99 average annual groundwater recharge in Wisconsin using streamflow data: U.S. Geological Survey Open-File Report 2009–1210, 14 p. plus appendixes, https://pubs.usgs.gov/ofr/2009/1210/. [PEER REVIEWED]

Keywords: Baseflow, streams, recharge, Wisconsin

Stream baseflow was calculated for continuous-record and partial-record stations covering ~72 percent of the state of Wisconsin for the period of 1970–1999. Baseflow is approximately equal to recharge when averaged over a long period. The baseflow index (annual baseflow volume / annual runoff volume) was calculated for 123 continuous gaging stations; this was divided by the surface watershed area to determine inches of recharge per year. For partial record sites, available flow measurements were related to nearby gage data either graphically or using a regression equation to determine annual average baseflow. Baseflow and recharge estimates are tabulated for numerous small watersheds within the CSLS area (Central Wisconsin River Basin and Fox-Wolf River Basin, appendices 7 and 8). Results were generally reasonable, except where the areas of the surface and groundwater basins were poorly matched.

Hart, D.J., and Schoephoester, P.R., 2014, Groundwater recharge in Menominee, Shawano, Waupaca, and Waushara Counties, Wisconsin, estimated by a GIS-based water-balance model: Wisconsin Geological and Natural History Survey Open-File Report 2014-02, 22 p., https://wgnhs.uwex.edu/pubs/wofr201402/. [PEER REVIEWED]

Keywords: Recharge, Waushara County, soil-water balance

A regional recharge model was constructed for a four-county area in east-central Wisconsin using the soil-water balance (SWB) model. Recharge varies spatially with land use, soils, geology, and topography and temporally with seasonal and climatic variations. These factors (except geology) are inputs to the SWB model. SWB operates on a grid and is governed by the equation: Recharge = precipitation – interception – runoff – evapotranspiration – (total soil moisture – antecedent soil moisture). Western Waushara County, where the CSLS is focused, is characterized by low-runoff soils, low available water storage, and a mix of agricultural and open/forested land use. The SWB model has several limitations: it does not account for precipitation intensity, recharge in closed depressions can be unrealistically elevated, snowmelt timing was difficult to estimate, K is assumed to be horizontally and vertically homogeneous for hydrologic soil groups, evapotranspiration (ET) values are dependent on rooting depth assumptions, and shallow water tables within the root zone underestimate ET.

Recharge rates correlate with geology (high recharge in outwash areas, low recharge in areas of fine glacial lake sediments). Springs were associated with high-recharge, hilly areas. Western Waushara County was modeled to be a high-recharge area (>12–15 in/yr). Waushara also has the highest concentration of large springs in the four-county area modeled. In 2005, irrigation rates were estimated to be 14 percent of recharge rates for Waushara County. The impact of irrigation on net recharge was estimated cause between 3.2 and 5.9 in/yr of recharge reduction. (Estimates used generic crop ET rates that did not vary through the growing season likely overestimating impacts from irrigation.)

Radatz. A., Lowery, B., Bland, W., Naber, M., and Weisenberger, D., 2010, Disappearing lakes: groundwater levels in central Wisconsin, *in* Proceedings of the 2010 Wisconsin Crop Management Conference, v. 49, p. 126–131. [NOT PEER REVIEWED]

Keywords: Central Sands, recharge, groundwater monitoring, high capacity wells

Brief discussion of groundwater monitoring data results for wells on several different land use types in the Central Sands (irrigated and non-irrigated agriculture, prairie with trees (pine) and grassland). Water levels and precipitation data were monitored continuously at 8 wells for an 18-month period (2008–2009). Observations included: agricultural fields did not allow winter infiltration, pine forest had high interception rates and did not show groundwater responses to rain events, water levels beneath irrigated fields dropped more quickly than the prairie site. Discussion also considered landscape position, concluding that irrigated crops high in the landscape could cause more reduction in recharge versus dry land crops or natural landscapes than would those in discharge areas. This assumes that the water table in discharge areas is in the root zone and available to plants (not always the case).

Note: No information about well construction is provided in this paper.

Stoertz, M.W., 1985, Evaluation of groundwater recharge in the Central Sand Plain of Wisconsin: University of Wisconsin–Madison, M.S. thesis, 159 p. [REVIEWED BY GRADUATE COMMITTEE]

Keywords: Recharge, Central Sands, numerical model

Temporal and spatial recharge patterns in the Buena Vista Basin of the Central Sands were investigated using field instrumentation at two sites and a steady-state 2-D groundwater model. Vertical gradients and soil moisture profiles were used to characterize groundwater movement in the vadose and saturated zones. Horizons of slightly finer grain size/lower conductivity than the typical well-sorted sands were found to be important factors in moisture retention and the timing of groundwater recharge. A 0.5-m silt layer 7.3 m below ground surface (New Rome) at the discharge site caused a significant dampening and time delay in the effect of individual rainfall events on groundwater levels.

Stoertz also examined seasonal recharge patterns. Following a late December thaw and rainfall event, an increase in soil moisture was observed in frozen soil, suggesting that infiltration can happen during the winter, depending on the amount of moisture (as ice) blocking soil pores. Summer recharge patterns were different at the two field sites: at the site with shallow groundwater (defined as the water table at 2 m below ground surface) rainfall events continued to result in water table rise throughout the summer, while at the site with deep groundwater (defined as water table at 10 m below ground surface) the water table declined from mid-July through fall. Groundwater modeling showed recharge and discharge areas in the Buena Vista Basin to be laterally and longitudinally variable, with strong recharge and discharge locations often adjacent to one another.

Note: K values from grain-size and permeameter tests for the field sites are shown in table 1 and 2. K values are one the order of 10^{-4} to 10^{-5} m/s.

Stoertz, M.W., 1989, A new method for mapping groundwater recharge areas and for zoning recharge areas for an inverse model: University of Wisconsin, Ph.D. thesis, 178 p. [REVIEWED BY GRADUATE COMMITTEE]

Keywords: Recharge, Central Sands, numerical model

Inverse analytical element modeling was used to map recharge zonation in the Buena Vista Basin of the Central Sands. A 2-D mass balance method in MODFLOW was used to derive recharge zonation, which was ground-truthed against a previously derived recharged map. Results were more sensitive to fluxes (i.e., stream discharge) than to hydraulic conductivity, which ranged from 7.2 x 10^{-4} m/s (south, west) to 9.6 x 10^{-4} m/s (northeast); K only varied by 25 percent throughout the test area. Maps of soil association, soil drainage, surficial geology, and depth to water were compared to the mass-balance recharge distribution. Although some aspects of recharge and discharge areas could be identified, none of these features alone was reflective of the overall recharge/discharge pattern.

Stoertz, M.W., Anderson, M.P., and Bradbury, K.R., 1991, Field investigations and numerical studies of groundwater recharge through unsaturated sand: a methodology applied to central Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 71, 52 p., https://wgnhs.uwex.edu/pubs/ic71/. [PEER REVIEWED]

Keywords: Recharge, unsaturated zone, Central Sands, model

Field methods and computer modeling were used to estimate deep drainage (as a recharge surrogate) through bare sandy soils in the Buena Vista area, Wisconsin Central Sands. The soil profile at the study site was mainly sand, except for a 0.5 m silty layer at a depth of 7.3 m. Depth to crystalline bedrock was estimated to be 19 m. Water movement through the unsaturated zone is controlled by soil properties (including hydraulic conductivity and inhomogeneities), soil moisture content, and soil tension. These were measured by an instantaneous profile test, tensiometer, and neutron scatter logging, respectively. During the instantaneous profile test, soils drained rapidly (with the exception of the fine-grained layer), within 72 hours. A numerical model was constructed to simulate water movement through a homogeneous soil profile. Changes in water table depth, drainage lag times, and the effects of storm intensity were evaluated. Soil drainage times for simulated storms were significantly longer than indicated by the instantaneous profile test (7–20 days for sandy soil). The calculations used in this study neglected hysteresis effects and lateral movement of water, which are likely be important factors in deep drainage. One study conclusion was that recharge estimation could be more efficiently estimated using a groundwater perspective rather than an unsaturated zone perspective due to the high data needs and potentially unrealistic simplifying assumptions of unsaturated zone calculations used here.

Stoertz, M.W., and Bradbury, K.R., 1989, Mapping recharge areas using a ground-water flow model—a case study: Ground Water, v. 27, no. 2, p. 220–228. [PEER REVIEWED]

Keywords: Recharge, Central Sands, numerical model

This paper estimates groundwater recharge and discharge patterns in the Buena Vista Basin using a 2-D groundwater model. Cell-by-cell fluxes were calculated while the water table surface was held constant. Differences between cell inflow and outflow were interpreted as groundwater recharge or discharge. Recharge/discharge patterns generally agreed with field-mapped zones. Recharge areas occurred on the east end of the basin and north and south of the stream on the west end. Discharge areas occurred near streams and in the marshy area west of the moraine. The model grid was not fine enough to accurately represent the ditched area or other basin details. The magnitude of recharge was sensitive to K values and grid size, and the absolute magnitudes of recharge are probably not very accurate. The basin K value was estimated to be $3x10^{-3}$ ft/s based on aquifer test data and fitting recharge results (loosely) to stream discharges.

STREAMS

(See also Little Plover River section)

Bolha, D., 2015, Water quality assessment report for headwater streams in the Eastern Central Sands area in Central Wisconsin, December 2015 report: WDNR, 20 p. [NOT PEER REVIEWED]

Keywords: Central Sands, streams, water quality, habitat

Fish and macroinvertebrate populations, qualitative habitat data, and water temperatures were sampled in 2014 at sixteen headwater streams in the Central Sands. Sampling locations included Chaffee and Tagatz Creeks near Pleasant Lake, the South Branch of Wedde Creek, and Schmudlack Creek. Average and maximum monthly temperatures are reported. Natural communities were assessed.

Gebert, W.A., 1982, Low-flow characteristics of streams in the central Wisconsin River basin: Wisconsin, U.S. Geological Survey Open-File Report 81-495, 99 p., 2 plates. [PEER REVIEWED]

Keywords: Streamflow, baseflow, regressions, streams

Presents low-flow calculations for the Wisconsin River basin, including the Central Sands region. Pages 7–11 provide a good summary of different commonly used low flow statistics and how they are defined. Low-flow characteristics were determined directly from available data for gage stations with >10 years of monitoring (standard error 17 percent). Low flow characteristics at partial-record stations (locations with 8–20 baseflow measurements) and miscellaneous sites (3–8 measurements) were determined by establishing a linear relationship with a nearby gage site. Standard error for partial record sites was 22 percent; standard error for miscellaneous site was 32 percent. Flow at ungaged sites was determined using multiple-regression analysis; flows were found to be most dependent on drainage area, hydraulic conductivity, soil-infiltration capacity, forest cover, baseflow index (a ratio including baseflow per drainage area), and drift thickness. Regression equations are presented for the four regions studied. In the Central Sand Plain, low flow was found to be mainly dependent on drainage area and baseflow index.

Gebert, W.A., Garn, H.S., and Rose, W.J., 2016, Changes in streamflow characteristics in Wisconsin as related to precipitation and land use: U.S. Geological Survey Scientific Investigations Report 2015-5140, 25 p. [PEER REVIEWED]

Keywords: Streamflow, climate, land use, Wisconsin

Streamflow characteristics were compared for 15 long-term gaging stations in Wisconsin for the periods 1915–1968 and 1969–2008. Observed low flows were higher during the more recent time period in streams with dominantly agricultural land use. Forested stream low flows also increased slightly. Peak flows decreased in many streams throughout the state. These changes coincided with increased annual precipitation and changes in the monthly distribution of precipitation. The study attributes baseflow increases in agricultural streams to changes in agricultural land use practices and increased precipitation.

Notes: (1) One of the streams whose streamflow characteristics were analyzed for this study is the Fox River at Berlin, whose watershed overlaps the CSLS area. (2) Watersheds are divided into agricultural and forested categories for the purposed of this study, and changes are attributed to the different land uses. However, the two groups of sites are also geographically divided (agricultural in the south, forested in the north), so regional climate differences may also account for the differences between the two groups.

Gebert, W.A., Radloff, M.J., Considine, E.J., and Kennedy, J.L., 2007, Use of streamflow data to estimate base flow / ground-water recharge for Wisconsin: Journal of the American Water Resources Association, v. 43, no. 1, p. 220–236. [PEER REVIEWED]

Keywords: Streamflow, baseflow, regression, streams, recharge

This study investigates baseflow values and trends for gaged Wisconsin streams and used multiple regression analysis to develop regression equations for partial-record and other ungauged streams in Wisconsin. Baseflow and recharge were assumed to be identical for this study, and surface watersheds were used as a surrogate for groundwatersheds. Increasing baseflow trends were observed for the period 1970–1999 in most streams in agricultural areas (southern two-thirds of Wisconsin). Total flow (baseflow + runoff) typically exhibited no trend during the period. Calculated average annual baseflows for 118 Wisconsin streams are shown (fig. 4). Regression equations for baseflow had a minimum standard error of 9.5 percent.

The most influential factors for determining streamflow were baseflow factor (Q90/watershed area), drainage area, and soil infiltration. Base showed more spatial variability for small watersheds than large watersheds. In some cases, discrepancies between surface water and groundwater drainage areas resulted in unreasonable baseflow results.

Kraft, G.J., Clancy, K., and Mechenich, D.J., 2008, A survey of baseflow discharges in the western Fox-Wolf Watershed: Center for Watershed Science and Education, College of Natural Resources, University of Wisconsin–Stevens Point, 33 p. [Report to WDNR—NOT PEER REVIEWED]

Keywords: Central Sands, stream flow, baseflow, Fox-Wolf Watershed

Survey of low-flow characteristics of streams in the Fox-Wolf Watershed (eastern Central Sands). Study used existing data from USGS gages and USGS spot measurements and also collected additional data, monitoring baseflow at 304 headwater sites in 2005–2006. These water years were slightly dryer than average. USGS and Kraft and others spot measurements generally agreed well. These and other UWSP flow measurements may be used for the CSLS model to inform flux targets. Based on the Q_{50} of the larger gage station sites in the watershed, stream baseflow averaged 0.83 cfs/mi^2, for an average groundwater recharge rate of 11.2 in.

STUDY LAKES

HISTORICAL DATA AVAILABLE FOR PLAINFIELD LAKE

Bathymetry Map: July 2, 1941 (WPA Lake Survey Project)

USGS Gage 05401067 operated 5/20/1978–11/27/1979

LONG LAKE STUDIES

Cason, C., and Chikowski, A., 2004, Long Lake comprehensive survey results: Aquatic Biologists, Inc., 58 p. plus appendices (118 p. total). [NOT PEER REVIEWED]

Keywords: Long Lake, lake studies, Central Sands, water quantity, water quality

This planning study addresses water quantity, water quality, and nuisance algae blooms. The study included the creation of a lake bathymetry map based on 80 survey points, installation and water level monitoring of 18 shallow piezometers, and an estimate of lake area. A water budget was also completed but lacks details of how each piece was calculated. Some parts of the report indicate that the writers did not have a good understanding of groundwater movement. The study also included fish and aquatic life surveys, water chemistry sampling, and creation of temperature profiles.

Kniffin, M., 2014, A hydrogeological investigation of Long Lake–Oasis, Waushara County, Wisconsin, a report prepared for the National Conservation Resource Service: CIG Grant Report, 22 p. [NOT PEER REVIEWED]

Keywords: Long Lake, lake studies, Central Sands, GPR

This study examined the geology and groundwater movement near Long Lake. Existing well logs were located and assessed for coarse/fine grained materials. Field work included sediment coring in the lake bed, installation and monitoring of piezometers north, south, east and west of the lake, and a ground-penetrating radar (GPR) transect along the west shore. Water levels in wells were collected on six dates in 2012–2014; most nests had downward vertical gradients and no upward gradients were observed during the study. Sediment cores and GPR results showed that fine sediments (silt and clay) are common within the tunnel channel but do not appear to be laterally continuous. Well construction reports within the tunnel channel also tend to include fine-grained sediment (figs. 8 and 9).

Notes: The report does not include a map of the GPR transect location, table of measured water levels, or detailed boring logs. If these items are available, they would be useful for the CSLS. The report mentions that groundwater flowed to the southwest during the study, but a water table map is not provided.

Krueger, R., and Martens, R., 1980, Limnological study of Long Lake, Waushara County, November 1979 through October 1980: Crandon, Wisc., Northern Lake Service, Inc., 38 p. [NOT PEER REVIEWED]

Keywords: Long Lake, lake studies, Central Sands, water quantity, water quality

This report details results of a 12-month study, consisting of groundwater and in-lake data collection. Report concludes little connection between the lake and groundwater based on water levels in observation wells that were significantly below lake levels and miniscule amounts of observed seepage on the north side of the lake. The following data were collected and are included with the report:

- Monthly **water level measurements** for 11 wells: 3 USGS piezometer nests and 1 shallow USGS well, and 1 piezometer nest and 2 additional shallow wells installed for this study
- Tables of monthly **water chemistry** samples for the shallow wells
- **Boring logs** for the Northern wells on the western end of Long Lake
- **Seepage meter** data for two locations near the boat landing.
- Monthly **lake elevation** measurements and **chemistry data** (surface and bottom)
- Monthly **dissolved oxygen and temperature** profiles (difficult to read)
- Contour maps of **lake bathymetry** and depth to hard bottom
- Percent organic matter, nitrogen, and phosphorus from three **sediment cores**
- **Aquatic life** survey data

HISTORICAL DATA AVAILABLE FOR LONG LAKE

Lake bathymetry 1941 (max depth 14 ft.)

Krueger and Martens (1980) includes a bathymetry map from 1979–1980 (max depth ~5.5 ft)

USGS Gage 05401065 operated 11/5/1976–11/27/1979 on Long Lake (gage height)

PLEASANT LAKE STUDIES

Butterfield, B., Hoyman, T., Heath, E., and Cibulka, D., 2014, Pleasant Lake supplemental lake management planning project, Waushara County, Wisconsin, Onterra, LLC: Report to Pleasant Lake Management District and Wisconsin Dept. of Natural Resources, 51 p. plus appendices. [NOT PEER REVIEWED]

Keywords: Central Sands, Pleasant Lake, water quality, water quantity, lake study

This planning document reports the results of a study of Pleasant Lake. Includes surveys of aquatic plants and littoral habitat, fish populations, and invasive species distribution. Substrate is assessed. A relationship between littoral area and water level is shown in figure 2.3-1 and map 5. Assessment work included the creation of a bathymetric map. Appendices include a survey of littoral areas and associated wetland habitat in Turtle Bay and two other small wetland areas (including indicators of groundwater inflow) and lake user survey results.

University of Wisconsin–Stevens Point Center for Watershed Science and Education, 2015, Pleasant Lake, Waushara County, Wisconsin, lake management plan, 61 p. plus appendices (total 261 p.) [NOT PEER REVIEWED]

Keywords: Central Sands, Pleasant Lake, water quality, water quantity, lake study

Planning document describing studies of Pleasant Lake, Waushara County. Topics include watershed land use, lake water quantity and quality, habitat for aquatic flora and fauna, fish community, native and invasive species, shoreland ecosystems, and human use.

Note: Additional information for Pleasant Lake that may be useful includes wetland assessments, fish surveys, etc. conducted in connection with the Richfield Dairy Contested Case Hearing. Written hearing testimony may also be valuable in some cases.

HISTORICAL DATA AVAILABLE FOR PLEASANT LAKE

July 1964: Wisconsin Conservation Department Bathymetric map

2013: Onterra bathymetric map (acoustic survey) reported in Onterra, 2014, Pleasant Lake Supplemental Lake Management Planning Project, Waushara County, Wisconsin, July 2014 (mentioned p. 4)

TUNNEL CHANNELS AND VALLEYS

Notes: There is disagreement on the formation mechanisms of tunnel channels and valleys. Differences between valley characteristics in different regions suggest that different mechanisms may have had different relative importance in their formation. In the CSLS area, tunnel channels have outlets at the terminal moraine and outwash fans containing very coarse material (boulders up to several meters in size). These factors indicate that they were formed at the glacial maximum by high-energy flows. Catastrophic outflows of subglacial meltwater impounded behind a frozen glacier bed offers a good explanation for observed morphology. The tunnels may have been pathways for single or multiple flood events.

Several studies indicate that after the last significant flow of water through Wisconsin tunnel channels, ice movement was probably sluggish or short-lived (receding glacier). This is supported by channels' termination at glacial maximum ice margins and by outwash fan configuration. Cross-cutting relationships between different generations of tunnel valleys, which have been observed in Michigan, northern Europe, and elsewhere are absent from the Central Sands tunnel channels.

Ice that collapsed into abandoned tunnel channels and was buried with sediment could have remained in place for hundreds to thousands of years (Attig and Rawling, 2017). The near-surface sediments overlying former tunnel channels are likely composed of collapsed sediments deposited after the tunnel channel was no longer active. Possible valley-fill sediments include:

- Collapsed till – sandy in the Central Sands region
- Supraglacial lake sediments (lake(s) formed on ice surface over collapsed portion of tunnel) – fine to coarse
- Outwash – coarse, sandy
- Proglacial stream – coarse +/- fine
- Small proglacial lake – fine to coarse

Atkinson, N., Andriashek, L.D., and Slattery, S.R., 2013, Morphological analysis and evolution of buried tunnel valleys in northeast Alberta, Canada: Quaternary Science Reviews, v. 65, p. 53–72. [PEER REVIEWED]

Keywords: Tunnel valleys, tunnel channels, glacial geology, sedimentology, morphology

Researchers studied infill sediments in six buried tunnel valleys in Alberta, Canada. Boring logs and descriptions of exposed sections in outcrop were used to create longitudinal and transverse cross sections of the valleys. The tunnel valleys are cut into underlying bedrock and exhibit undulating longitudinal profiles and high depth to width ratios. Coarse-grained sediment packages grading to sands and silts, interpreted as jökulhlaup deposits, were found to be interbedded with fine-grained tills. In some valleys, infill was cut by oblique channels filled with silty material. "Basal meltwater is inferred to have been released as episodic jökulhlaups beneath the ice sheet, which at times re-used existing valley systems, which were spatially and temporally stable features, and at other times incised new valleys."

Note: A more in-depth look at this paper may be warranted, as valley infill sediments are assessed in some detail.

Attig, J.W., Mickelson, D.M., and Clayton, L., 1989, Late Wisconsin landform distribution and glacier-bed conditions in Wisconsin: Sedimentary Geology, v. 62, no. 2–4, p. 399–405. [PEER REVIEWED]

Keywords: Tunnel channels, glacial geology, Wisconsin

The presence of ice wedges, lack of radiocarbon dates from trees between 26,000–13,000 years before present, and thick sequences of glacial sediments along the glacial margins in Wisconsin indicate persistent frozen bed conditions. The width of the permafrost ranged from 5 km in southern Wisconsin to 20 km in the north. Typical Wisconsin tunnel channel dimensions are 0.5 km wide and up to 40 km long, and longitudinal profile often slope up to the ice margin. Tunnel channels catastrophically drained the interior, melted bed, portions of the glacier; interior areas are indicated by the presence of drumlins/eskers.

Clayton, L., Attig, J.W., and Mickelson, D.M., 1999, Tunnel channels formed in Wisconsin during the last glaciation, *in* Mickelson, D.M. and Attig, J.W., eds., Glacial processes past and present: Boulder, Colorado, Geological Society of America Special Paper 337, p. 69–82. [PEER REVIEWED]

Keywords: Tunnel channels, tunnel valleys, glacial geology, Plainfield, Wisconsin

This paper provides an overview of tunnel channel formation. Typical tunnel channel dimensions in central Wisconsin are 0.15–0.45 km wide, 2–7 km long, and 5–30 m deep. The Plainfield-Huron Tunnel Channel is used as an example channel (see fig. 6). Clayton and others contend that the tunnel channels of the Green Bay Lobe in Wisconsin were formed by periodic catastrophic releases of water from subglacial lakes flowing over a frozen bed. Because the tunnel channels terminate at the outermost moraine, they were formed during the glacial maximum. Tunnel channel features are contrasted with the spillways of proglacial lakes and with tunnel valleys, defined as a subglacial tunnel in which water did not fill the entire channel width (discounted for Wisconsin due to tunnel channel size and channel-like shape). Modern-day expression of the tunnel channels is attributed to collapse of infill sediments. Paper does not discuss the type or deposition of infill sediments.

Cutler, P.M., Colgan, P.M., and Mickelson, D.M., 2002, Sedimentologic evidence for outburst floods from the Laurentide Ice Sheet margin in Wisconsin, USA: implications for tunnel-channel formation: Quaternary International, v. 90, p. 23–40. [PEER REVIEWED]

Keywords: Tunnel channels, tunnel valleys, sedimentology, glacial geology, Wisconsin, outwash

Investigates outwash-fan sediments at the mouths of tunnel channels at three Wisconsin sites (none in the Central Sands). Sediments found at each site, including clast-supported facies with large boulders of up to 2 m, indicate a high-energy depositional environment. Outburst floods are posited as the most likely sediment source. The outbursts do not appear to have created the tunnels, but enlarged previously exists drainage pathways (as shown by underlying sediment). Previous work by Cutler and others suggested a large permafrost wedge existed at the glacial margin during the glacial maximum, and impounded subglacial meltwater is proposed as the most likely source of water for the outburst flood. At each field site, the high-energy flood was the last major depositional event on the outwash fan.

Gibling, M.R., 2006, Width and thickness of fluvial channel bodies and valley fills in the geological record: a literature compilation and classification: Journal of Sedimentary Research, v. 76, p. 731–770. [PEER REVIEWED]

Keywords: Tunnel valley, tunnel channel, fluvial sediments

Reviews geometry of various types of fluvial and valley fill structures/sediments. Subglacial tunnel valleys are typically narrow; their width to depth ratio is as low as 2.5 due to incision from catastrophic meltwater flows.

Hooke, R.LeB., and Jennings, C.E., 2006, On the formation of the tunnel channels of the southern Laurentide ice sheet: Quaternary Science Reviews, v. 25, 1364–1372. [PEER REVIEWED]

Keywords: Tunnel channel, tunnel valley, glacial geology

Authors subscribe to the theory of multiple catastrophic releases of subglacial meltwater impounded behind a permafrost wedge as the means of tunnel valley formation in Wisconsin and Minnesota. They also theorize that tunnel initiation was through piping (subsurface sediment failure and slumping). Others (see Kehew and others, 2012) dispute this mechanism based on lack of evidence for slumping at tunnel valley margins. Paper also mentions that the average spacing of tunnel valleys in central Wisconsin is 3.5 km.

Jorgensen, F., Sandersen, P.B.E., and Bakker, M., 2006, Buried valleys—nature and groundwater interests, *in* Kirsch, R., Rumpel, H., Scheer, W., and Wiederhold, H., eds., Groundwater resources in buried valleys: a challenge for geosciences: Hannover, Germany, Liebniz Institute for Applied Geosciences, p. 11–18. [PEER REVIEWED]

Keywords: buried valleys, tunnel channels, glacial geology

Discusses the origin and groundwater implications (water supply and contaminant transport) of buried valleys in northern Europe. Posits multiple modes of valley formation with both subglacial meltwater erosion and direct glacial erosion. Valley formation was by catastrophic flow, fill with ice/debris, followed by meltwater flow through channels along the valley floor. Northern European buried valleys involve multiple glaciations and cross-cutting relationships (not found in the Central Sands tunnel channels). Valley floors are irregular [product of post-deposition ice collapse, preglacial topography, or both]. Hydraulic barriers within valleys are typically longitudinal. Valley infill is discussed as being variable and complex. Infill sediments were observed through seismic and electromagnetic surveys.

Kehew, A.E., and Kozlowski, A.L., 2007, Tunnel channels of the Saginaw Lobe, Michigan, USA, in Johannsson, P., and Sarala, P., eds., Applied Quaternary research in the central part of glaciated terrain: Geological Survey of Finland, Special Paper 46, p. 69–77. [PEER REVIEWED]

Keywords: Tunnel channels, glacial geology, Michigan

Provides an overview of controversies regarding tunnel channel formation. Describes five types of tunnel channels found in Michigan's southern peninsula. (Type I) large, unburied channels – well-defined modern valley, (Type II) channel overprinted by subsequent ice re-advance – partially buried modern valley present, cuts across later moraine (Type III) channel with extensive infilling not near moraine – little or no surface valley, identified by linear chain of lakes, (Type IV) tunnel channel in cross-cutting relationship with subsequent glacial features of a different glacial lobe, and Type (V) unburied or partially buried tunnel channels containing eskers. To create observed relationships, buried ice would need to remain in place for hundreds to thousands of years before melting/collapsing. Presence of eskers in some channels indicates that they remained open through a depositional phase following the erosional phase.

Kehew, A.E., and Kozlowski, A.L., 2016, Tunnel channels of the Saginaw Lobe, Michigan, USA: Northfield, Minn., Carleton College, Science Education Resource Center Vignettes, https://serc.carleton.edu/37573. [NOT PEER REVIEWED]

Keywords: Tunnel channels, glacial geology, factsheet

Online factsheet discussing southern Michigan tunnel channels.

Kehew, A.E., Piotrowski, J.A., and Jørgensen, F., 2012, Tunnel valleys: Concepts and controversies—a review: Earth-Science Reviews, v. 113, no. 1–2, p. 33–58. [PEER REVIEWED]

Keywords: Tunnel valleys, tunnel channels, glacial geology

This lengthy review provides an overview of various genetic models for tunnel valley formation and discusses valley morphology with a focus on research in northern Europe and the southern margin of the North American Laurentide Ice Sheet. The paper summarizes the role of groundwater flow systems in draining glacial meltwater. Kehew and others also discuss recent advances in the identification and study of tunnel valleys using enhanced imaging techniques (TEM), numerical modeling, and field instrumentation to study subglacial hydrology and drainage patterns.

Subglacial flow features such as tunnel valleys form because groundwater flow alone cannot account for the entire volume of basal meltwater and maintain ice bed meltwater pore pressures below ice flotation levels. Proposed mechanisms for tunnel valley formation include (1) gradual formation by sediment deformation under steady state conditions with subsequent transport by meltwater to the ice margin, (2) time-transgressive formation along a retreating ice margin by (a) drainage of surface meltwater or (b) catastrophic release of impounded meltwater behind a marginal permafrost wedge, and (3) rapid erosion during widespread, catastrophic basal sheetflood events. Those who favor catastrophic drainage of impounded basal meltwater (as Clayton and others in Wisconsin) assume that valley width reflects the width of the flow. The discovery of hundreds of subglacial lakes beneath the Antarctic Ice Sheet provides support for a source of water for those advocating catastrophic formation for tunnel valleys.

Cross-cutting tunnel valleys have been linked to multiple glacial advances. In northern Europe, valleys and networks of valleys on land and on the sea bed, some totally buried, have been linked to three or more glaciations. Danish tunnel valley networks have been related to specific ice margins developed during ice retreat. In Michigan, cross cutting tunnel valleys have been used to define re-advances during a single glaciation. [Tunnel valleys/channels in central Wisconsin do not appear to exhibit these types of relationships.]

Mooers, H.D., 1989, On the formation of tunnel valleys of the Superior Lobe, central Minnesota: Quaternary Research, v. 32, p. 24–35. [PEER REVIEWED]

Keywords: Glacial geology, tunnel valleys, tunnel channels, Minnesota

Tunnel valleys in central Minnesota exhibit some characteristics different from tunnel channels in central Wisconsin. Valleys terminate at several recessional ice margin positions in addition to the glacial maximum. Eskers within tunnel valleys are also more common. This paper takes the position that the tunnel valleys were formed during ice retreat and that the main water source was seasonal meltwater from the glacier surface. Valley continuity is interpreted to be a result of headward migration of the drainage system as ice retreated.

Ó Cofaigh, C., 1996, Tunnel valley genesis: Progress in Physical Geography, v. 20, no. 1, p 1–19. [PEER REVIEWED]

Keywords: Tunnel valleys, tunnel channels, glacial geology, review

Review of the various proposed methods of tunnel valley formation: subglacial sediment deformation, time transgressive formation close to the glacial margin, and catastrophic subglacial meltwater floods. The paper identifies strengths and weaknesses in each. In general, the conclusion is that it is likely that tunnel valleys form through a combination of processes, with different processes dominating in different systems.

Shaver, R.B., and Pusc, S.W., 1992, Hydraulic barriers in Pleistocene buried-valley aquifers: Ground Water, v. 30, no. 1, p. 21–28. [PEER REVIEWED]

Keywords: Glacial geology; tunnel valleys; tunnel channels, hydrogeology; flow barriers

Investigation of two types of flow barriers within buried valleys in North Dakota—longitudinal and transverse. Longitudinal barriers to groundwater flow consist of narrow, resistant ridges of bedrock or glacial drift. These types of barriers occur in buried valleys with anastamosing channel patterns. Transverse hydraulic barriers may occur as a result of a stream or spillway that forms at an oblique angle to the buried valley and down-cuts through the valley, depositing fine-grained sediments. The entire package may be subsequently buried during glacial re-advance. Both longitudinal and transverse hydraulic barriers are characterized by significant head changes across the barrier.

Notes: Longitudinal hydraulic barriers are unlikely given that the Central Sands tunnel channels are relatively narrow and straight. Transverse hydraulic barriers may exist within the Central Sands tunnel valleys, but would not be very relevant to lake studies, as the lakes and pumping wells are situated on the overlying aquifer sediments. (Both buried valley aquifers studied in this paper were aquifers under confined conditions.)

WATER-TABLE MAPS

Batten, W.G., 1989, Hydrogeology of Wood County, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 60, https://wgnhs.uwex.edu/pubs/ic60/. [Plate: Altitude of water table in Wood County] [PEER REVIEWED]

Berkstresser, C.F., 1964, Ground-water resources of Waupaca County, Wisconsin: U.S. Geological Survey Water Supply Paper 1669-U. [Plate 4] [PEER REVIEWED]

Devaul, R.W., and Green, J.H., 1971, Water resources of Wisconsin – central Wisconsin River basin: U.S. Geological Survey Hydrologic Atlas 367. [Plate 3] [PEER REVIEWED]

Lippelt, I.D., Hennings, R.G. 1981, Irrigable lands inventory – Phase I groundwater and related information: Wisconsin Geological and Natural History Survey MP81-1, 13 p., 11 plates, https://wgnhs.uwex.edu/pubs/000467/. [PEER REVIEWED]

- Plate 1: Water Table Map of Adams County (1981)
- Plate 5: Water Table Map of Marquette County (1981)
- Plate 7: Water Table Map of Portage County (1981)
- Plate 8: Water Table Map of Waupaca County (1981)
- Plate 9: Water Table Map of Waushara County (1981)
- Plate 10: Water Table Map of Wood County (1981)

Olcott, P.G., 1968, Water resources of Wisconsin, Fox-Wolf River basin: U.S. Geological Survey Hydrologic Atlas 321. [Plate 2] [PEER REVIEWED]

Summers, W.K., 1965, Geology and ground-water resources of Waushara County, Wisconsin: U.S. Geological Survey Water Supply Paper 1809-B. [Plate 2] [PEER REVIEWED]

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 70-362. [Water Table Map: Figure 9] [PEER REVIEWED]