Hydrology of the Driftless Area

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1. The abundant supply of cold water in Driftless Area streams is due to high rates of groundwater recharge.
2. Groundwater recharge rates are highest on the steep hillsides, which receive runoff from the hilltop areas in addition to direct precipitation.
3. Many headwater streams in the Driftless Area have unusually high baseflows as a result of the high recharge rates and the presence of horizontal bedrock layers that are relatively impermeable and divert groundwater to springs.
4. Poor agricultural practices in the first half of the twentieth century resulted in severe runoff and soil erosion, massive sediment deposition on the floodplains, and large increases in peak flows at the expense of baseflows.
5. The adoption of soil conservation practices in the later half of the twentieth century resulted in increased infiltration, a decrease in peak flows, and an increase in baseflows.
6. Future increases in air temperatures due to increases in atmospheric greenhouse gases will gradually increase stream water temperatures, although the impact will be somewhat buffered by the large amount of spring flow to the stream.

Hydrology | Groundwater | Streamflow | Hydrogeology | Temperature

Driftless Area streams generally provide ideal habitat for a coldwater fishery. The headwater portions of these streams are relatively long and include relatively steep reaches. Perennial flow occurs throughout the extent of these streams, including the headwater portions with very small drainage areas. This perennial "baseflow" results from groundwater inflows that enter the stream from numerous discreet springs as well as from diffuse flow through channel bottoms. Because groundwater temperatures about equal the mean annual air temperature, groundwater inflows from springs and the channel bed keep segments of the streams relatively cool in the summer and prevent them from freezing in the winter (1). Groundwater inflows through the channel bottom also provide ideal habitat for fish spawning. Such groundwater inflows provide refuges for coldwater fish species during extended hot periods (2).

This paper begins by using data from the U.S. Geological Survey (USGS) and other researchers to quantify the ideal hydrologic conditions in Driftless Area streams. It then summarizes the adverse hydrologic impacts of agricultural development in the early twentieth century and the subsequent recovery resulting from the adoption of conservation practices. It ends with a discussion of the potential impact of climate change.

Baseflow in the Driftless Area

The most important factor supporting the coldwater fishery in the Driftless Area is occurrence of relatively high baseflow in its streams, especially in the headwater portions. Gebert, et al. (3) provides estimates of the magnitude of baseflow at 1,618 locations in Wisconsin for the period 1970 through 1999. For this paper, the USGS provided a subset of these estimates for the 409 stream locations in the Wisconsin portion of the Driftless Area of the Wisconsin Driftless Area estimates, 61% were made using stream gage data, and 39% were made using 6 to 15 discharge measurements collected during low-flow conditions (Gebert, personal communication, 2018).

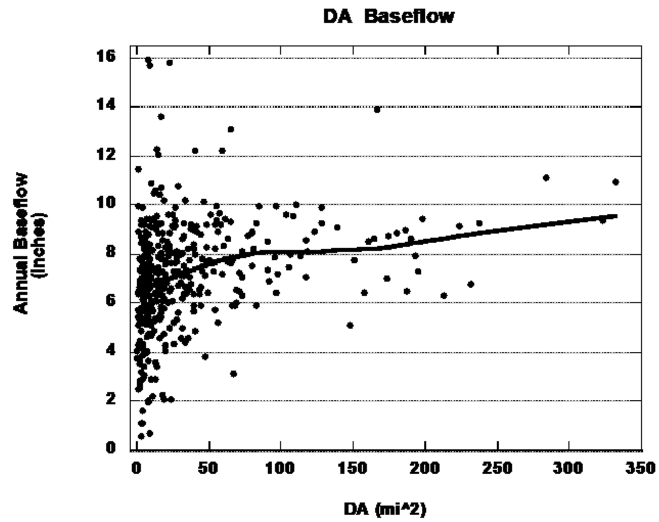

Fig. 1. USGS annual baseflow estimates (per unit of drainage area) as a function of drainage area (DA) for 409 stream locations from 1970-1999.

Fig. 1 is a plot of the estimates of annual baseflow discharge per unit drainage (watershed) area vs. drainage area. The area weighted mean is 8.0-in (20-cm), a value that is higher than average baseflow in Wisconsin (Gebert, personal communication, 2018). For headwater sites with very small drainage areas, the baseflow discharges vary greatly, ranging from below 1-in (2.5-cm) to just below 16-in (40.5-cm). The fact that

Statement of Interest

The coldwater fishery in Driftless Area streams is excellent because of unusually high inflows of relatively cold groundwater, especially in the headwaters. The high inflows of cold water are largely a result of unusually high rates of groundwater recharge, especially on the steep hillslopes. However, in the first half of the twentieth century, groundwater inflows to the streams were much lower as a result of poor agricultural practices. Subsequent adoption of conservation practices largely reversed this impact, although there is no guarantee that conservation practices will persist. Expected increases in air temperatures also threaten the persistence of cold-water conditions.

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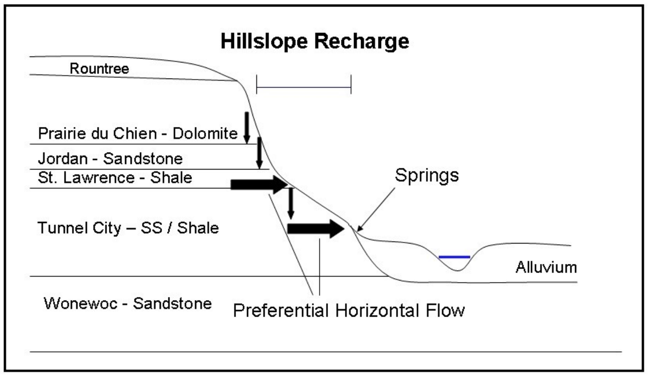

Fig. 2. Diagram of geologic units and groundwater flow in headwaters near study sites. Larger arrows indicate larger groundwater discharges. Figure from Schuster (4), adapted from Clayton and Attig (5) and Juckem (6).

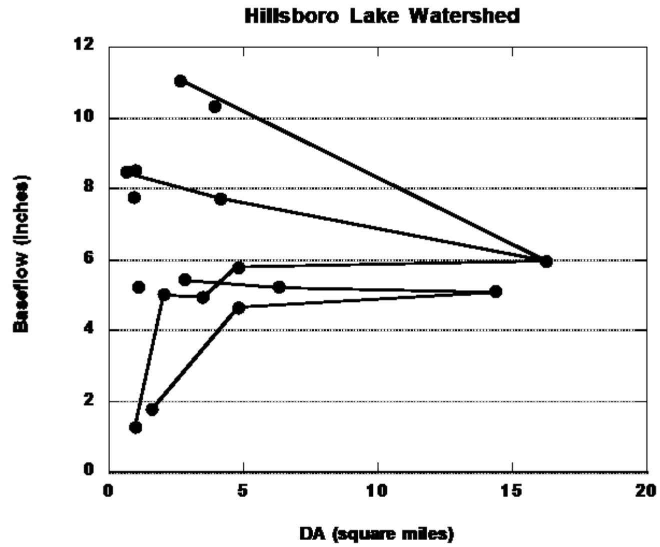

Fig. 3. Baseflow estimates for locations in the headwaters of the West Branch Baraboo River and the adjacent Kickapoo River. The connecting lines indicate flow paths.

many sites have baseflow discharges below the regional mean is not unusual, as streambeds high in a watershed are commonly above the local water table. However, it is unusual for small headwater watersheds to have baseflow discharges that are significantly larger than the regional mean.

There are two possible reasons for the unusually high estimates of mean baseflow discharge in the headwater watersheds. First, it is possible that the land area contributing to groundwater is greater than the area contributing to surface water. This would result in an upwardly biased estimate of the annual depth of baseflow, as the drainage area is used to convert discharges from volume per unit time (e.g., cubic feet per second) to volume per unit area/time (e.g, inches per year). In such a case the estimates are simply incorrect.

However, the high baseflow discharges at headwater locations could also result from the nature of bedrock, which consists of nearly horizontal layers of sandstone, carbonates, and shales. These layers have widely varying capacities to store and transmit water. When water seeping downward reaches a relatively impermeable layer, some or even all of it moves laterally. This lateral flow of water is likely to reach the channel, either via springs that flow overland to the channel or groundwater flow directly into the channel bottom. When a relatively impermeable layer is high in the watershed, it will produce anomalously high baseflow discharges in the headwater streams. Fig. 2 illustrates the geology of the region, and indicates the strata that produce high groundwater discharge.

Fig. 3 is a plot of estimates of mean annual baseflow discharge per unit area vs. drainage area for 14 locations in the portion of the West Branch Baraboo River watershed upstream of Hillsboro Lake, as well as for four sites from the headwaters of the adjacent Kickapoo River. Ten of the estimates were published in Potter and Gaffield (7), and were based on four to five synoptic streamflow measurements at each site made between May 1995 and July 1999. The remaining 7 estimates, including the four estimates in Kickapoo watershed, were based on three synoptic measurements at each site made between July, 2013 and May, 2015 (4). In both cases the method developed by Potter (8) was used to estimate mean annual baseflow from the synoptic baseflow measurements. The lines connecting the mean baseflow estimates indicate the flow path in the West Branch Baraboo watershed. The four sites in the adjacent Kickapoo watershed were chosen to determine whether the high baseflow values in the headwaters of the West Branch Baraboo River were biased as a result of the groundwater watershed being larger than the surface watershed. The fact that three of the four baseflow estimates in the upper Kickapoo watershed are also relatively large strongly suggests that the surface water and groundwater watersheds do not differ significantly. As in the case of the overall Driftless Area, the headwater baseflow values in the West Branch Baraboo River vary widely. The high baseflow headwater sites 11, 12, 13, and 14 are likely receiving groundwater discharge from the St. Lawrence formation (Fig. 2).

Groundwater Recharge

Groundwater recharge rates vary widely in the Driftless Area, but are less variable when considered in the context of the three major landscapes units that exist there - the ridgetops, hillslopes, and the valley bottoms. The ridgetops are rolling uplands. The hillslopes are generally steep, and valley bottoms contain the river floodplains. Fig. 4 delineates these landscape units in the portion of the West Branch Baraboo River watershed upstream of Hillsboro Lake.

Olson (9) monitored spring runoff from a ridgetop/hillside complex in the Garfoot Creek watershed during the spring snowmelt periods of 1993 and 1994 and found that during the event 6-in (15-cm) infiltrated the hillside, while only 3-in (7.5-cm) infiltrated the hilltop.

Juckem (6) conducted a series of infiltration tests at 15 sites in the Coon Creek watershed, 4 on the ridgetop, 4 on the hillside, and 7 on the valley bottom. The results indicated that infiltration rates on the ridgetop were higher than on the valley bottom, and that the infiltration rates on the hillside were 2 to 10 times higher than on the ridgetop and valley bottom.

Water Temperatures

The geology and geomorphology of the Driftless Area and the resulting impact on baseflows result in large spatial variations

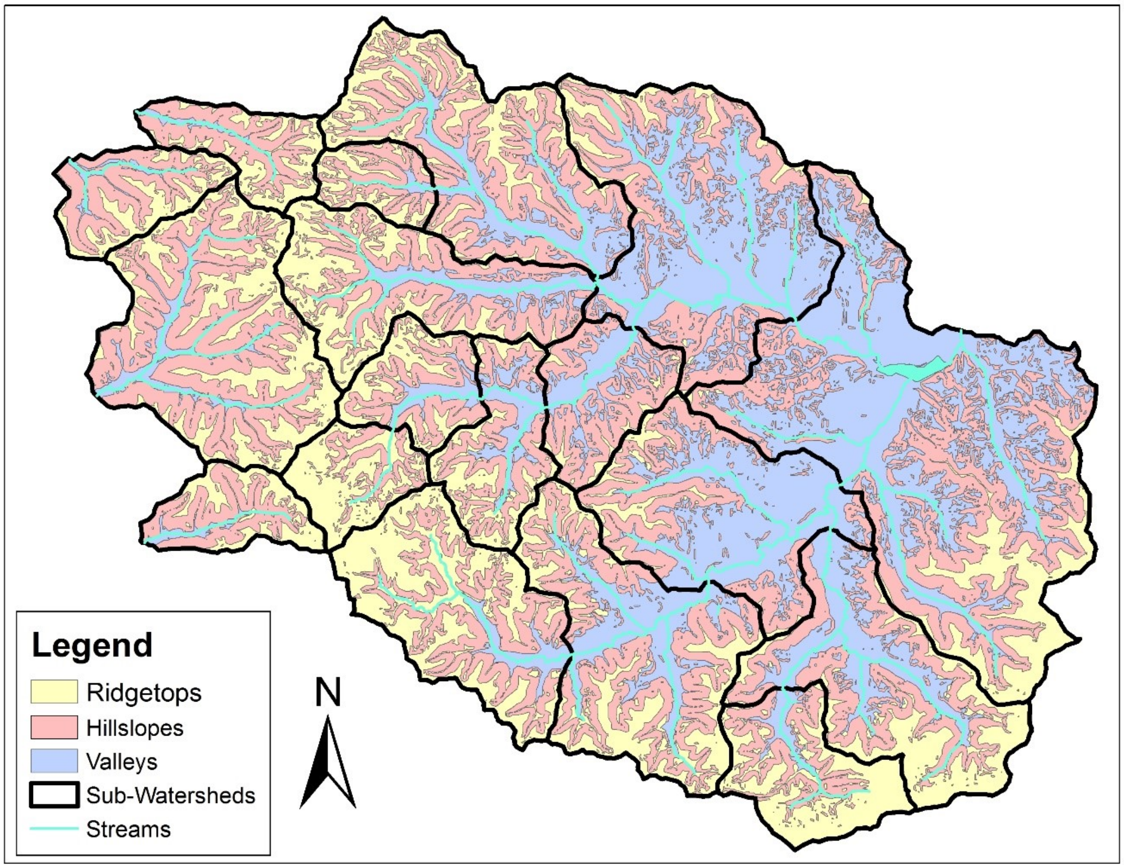

Fig. 4. Landscape units in the West Branch of the Baraboo River above Hillsboro Lake.

in water temperatures, particularly in headwater streams. This is illustrated in Figs. 5, 6, which provide daily maximum water temperatures measured in the summer of 1999 at multiple locations in two small headwater streams, Joos Creek and Eagle Creek (10). Each stream was sampled over a distance of about 2.2-mi (3.6-km). In Joos Creek, the coolest location is at the most upstream location (J7), which is just below the location of spring inflow. Water temperatures steadily increase downstream to the location at which it joins Eagle Creek. In the case of Eagle Creek, the coolest location is also at the most upstream location (E7). However, the second coolest location is just above the point at which it joins Joos Creek (E3). At all sites on both streams the daily maximum temperatures during the period from June 15 through August 14 range from 59-68°F (15-20°C). The maximum difference between the stream temperatures was 59°F (15°C) on Joos Creek and 60°F (15.6°C) on Eagle Creek.

Clearly inflows of relatively cold groundwater explain most of the spatial variability in summer water temperatures in the Driftless Area. However, another significant factor is shading by trees, particularly in headwater streams. Shading dampens the increase in temperatures in stream water that is cooler because of nearby upstream inflows of groundwater. However, the impact of shading on water temperature clearly decreases with increasing stream width. And, trees or large tree branches that fall into streams can cause significant channel widening (11).

Historical Impacts of Agriculture on Driftless Area Streams

The Driftless Area of today is much different from the one experienced by the early European settlers, largely because of the impact of agricultural development. Though many of the settlers were familiar with farming in steep terrain, most were not accustomed to the intense summer rainfalls that occur there. As a result, pre-conservation agriculture in North America significantly increased the amount and rate of stormwater runoff, causing a cascading set of destructive environmental impacts that still persist today, even after the adoption of conservation practices in the later half of the twentieth century (Vondracek, page 8).

Knox (12) estimated that pre-conservation agriculture increased the magnitude of 10-year floods discharges in the Platte River by a factor of three to five. Similar increases occurred throughout the Driftless Area. This increased surface runoff caused massive soil erosion and created thousands of gullies, both on the hilltops and in the steep hillsides. The hilltop gullies have mostly been filled, but virtually all of the hillside gullies remain today. Fraczek (13) mapped hundreds of large gullies in the 142-mi^2 (368-km^2) Coon Creek watershed. These gullies have a combined length of 243-mi (391-km), which is over 10 times the main channel length. In addition to increasing the downstream peak flows, the gullies cause runoff from the hilltops to bypass the highly permeable hillslopes, reducing groundwater recharge.

Most of the soil eroded from the uplands and hillsides was deposited on floodplains. Knox (12) estimated that deposition

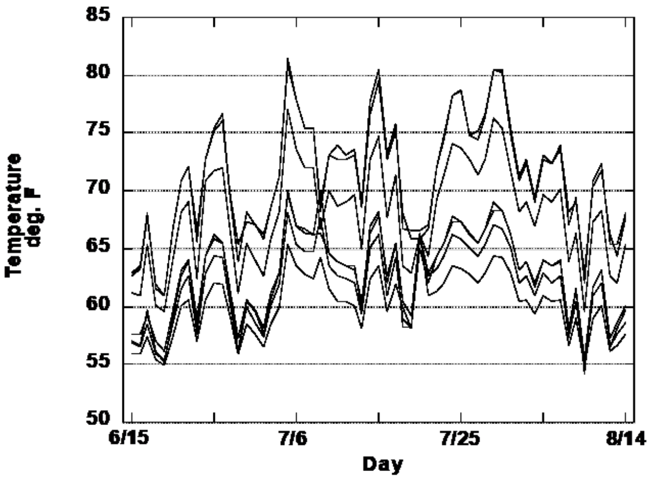

Fig. 5. Daily maximum temperature for Joos Creek.

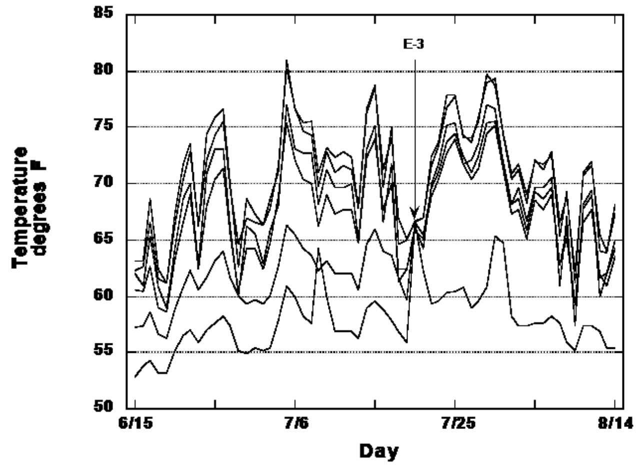

Fig. 6. Daily maximum temperature for Eagle Creek. Note sharp increase in temperature at station E3 about July 20, which is likely to represent a data collection error.

rates on Midwest floodplains during this period were 10 to 100 times larger than the pre-settlement rates. As a result, the elevation of the land adjacent to streams increased by about a half to several meters (1 to 10+ ft) (12), resulting in widespread loss of riparian wetlands (These lands are commonly referred to as terraces, as they are at higher elevations than the active floodplain). For example, based on field surveying and hydraulic modeling, Woltemade and Potter (14) determined that the modern terrace of the low-order tributaries in the Grant River watershed is generally not inundated by the two-year flood, and in some cases, is not inundated by the ten-year flood. In undisturbed watersheds, alluvial floodplains are typically inundated by floods that occur every one to two years (15).

Aldo Leopold (16), provided the following assessment of the impact of agriculture on the Driftless Area: *"...gone is the humus of the old prairie which until recently enabled the upland ridges to take on the rains as they came... Every rain pours off the ridges as from a roof. The ravines of the grazed slopes are the gutters. In their pastured condition they cannot resist the abrasion of the silt-laden torrents. Great gashing gullies are torn out of the hillside. Each gulley dumps its load of hillslope rocks upon the fields of the creek bottom and its muddy waters into the already swollen streams."*

After the creation of the Soil Conservation Service (now the Natural Resource Conservation Service) and the adoption of conservation practices through most of the Driftless Area, hydrological conditions greatly improved. Argabright, et al. (17) estimated that soil erosion rates on agricultural lands in five Driftless Area counties decreased by 58% between 1930 and 1982. And based on USGS streamflow data, Potter (18) demonstrated that annual peak flows and winter/spring flood volumes of the South Fork of the Pecatonica River decreased significantly during the period 1940 through 1986, while the contribution of winter/spring snowmelt to baseflow increased. Gebert and Krug (19), McCabe and Wolock (20), and Juckem, et al. (21) have documented increases in baseflow in the Driftless Area.

However, both legacy and current impacts of agriculture exist today. For example, Knox (12) estimated that flood peaks that would have been 5 to 6 times the pre-settlement values were reduced to 3 to 4 times by better land management. As previously mentioned, the hillside gullies are still present and reduce the amount of groundwater recharge. The other major legacy of pre-conservation agricultural is the sedimentation of floodplains and the concomitant loss of floodplain wetlands. Also, the high banks shed large amounts of sediment as the channels migrate laterally (Melchior, page 20).

Threats to Driftless Area Streams

Unless there are major interventions, water temperatures in Driftless Area streams will generally increase in the future as a result of increasing global greenhouse gas emissions. Based on flow and temperature modeling, Stewart, et al. (22) estimated the impacts of climate changes for the state of Wisconsin. For the Driftless Area, Stewart, et al. (22) estimated that the number of miles of Driftless Area streams with cold-water conditions will decrease by 47% by the mid-21st century. While these modeling results are instructive, they constitute a rough approximation and are likely overly pessimistic. The results are only based on 371 temperature sites, about a fifth of which were in the Driftless Area. The limited temperature data used in the study does not begin to capture the spatial heterogeneity in stream temperature that results from groundwater inflows, as demonstrated by the data from Joos and Eagle Creek (Figs. 5, 6). As previously mentioned, coldwater discharges into streams can provide refuges for cold-water species during extreme summer temperatures (2). These refuges will likely delay the loss of coldwater fishery. An additional delay will result from the fact that a large proportion of groundwater recharge results from the infiltration of snowmelt. Most climate change models predict an increase in the winter/spring precipitation. Furthermore, a large proportion of groundwater recharge results from melting snow and ice. For this reason, the increase in groundwater temperatures will lag that of air temperatures. Using an infiltration model and the output from four climate models, Murdoch (23) estimated that the amount and temperature of percolating water of a depth of 15-ft (5-m) would increase by about 50%, and the temperature would increased by about 67% of the increase in air temperature.

Regarding agriculture, there is no guarantee that that the all of conservation practices that were adopted in the Driftless Area will continue to be maintained. During the period 2006 to 2011, grasslands in the U.S. Corn Belt were converted to corn and soybean cropping at an annual rate of 1.0 to 5.4%, largely as a result of a doubling of commodity prices (24). Data on grassland conversions are not available for Wisconsin, although it is not unreasonable to speculate that grasslands have been converted to cropland as well. Any significant conversion of grasslands to agricultural lands would result in significant losses in groundwater recharge and hence baseflow, unless the agricultural practices employed the most progressive conservation practices.

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