Evaluating the Effects of Urbanization and Land-Use Planning Using Ground-Water and Surface-Water Models

Why are the effects of urbanization a concern?

As the city of Middleton, Wisconsin, and its surroundings continue to develop, the Pheasant Branch watershed (fig.1) is expected to undergo urbanization. For the downstream city of Middleton, urbanization in the watershed can mean increased flood peaks, water volume and pollutant loads. More subtly, it may also reduce water that sustains the ground-water system (called "recharge") and adversely affect downstream ecosystems that depend on ground water such as the Pheasant Branch Springs (hereafter referred to as the Springs). The relation of stormwater runoff and reduced ground-water recharge is complex because the surface-water system is coupled to the underlying ground-water system. In many cases there is movement of water from one system to the other that varies seasonally or daily depending on changing conditions. Therefore, it is difficult to reliably determine the effects of urbanization on stream baseflow and spring flows without rigorous investigation. Moreover, mitigating adverse effects after development has occurred can be expensive and administratively difficult. Overlying these concerns are issues such as stewardship of the resource, the rights of the public, and land owners' rights—both of those developing their land and those whose land is affected by this development. With the often-contradictory goals, a scientific basis for assessing effects of urbanization and effectiveness of mitigation measures helps ensure fair and constructive decision-making. The U.S. Geological Survey, in cooperation with the City of Middleton and Wisconsin Department of Natural Resources, completed a study that helps address these issues through modeling of the hydrologic system. This Fact Sheet discusses the results of this work.

Site Description

The Pheasant Branch watershed consists of 24 square miles located on the edge of the Driftless Area in Dane County. The watershed is composed of a South Fork, North Fork and lower system that flows into the Pheasant Branch Marsh (fig. 1). At the marsh (photo inset), streamflow combines with flows from a large spring complex and ground water discharged to the marsh; this combined flow ultimately discharges into Lake Mendota. During present-day development conditions, the streamflow, flow from the Springs, and ground-water discharge elsewhere in the marsh are roughly equal (around 2 ft^3/s each) during conditions not associated with storm events.

The hydrology of the watershed has been appreciably modified over the last 150 years. Prior to the turn of the century, the Pheasant Branch watershed west of Highway 12 drained into a large wetland that occupied the flat-lying land that surrounds the present confluence of the North and South Forks (Maher, 1999). The watershed was closed in most years, but in extremely wet years may have spilled into the Black Earth Creek watershed to the west. In the 1850s the wetland was drained to Lake Mendota. Most of the existing channels in the Pheasant Branch watershed are a result of conversion of the land to agricultural uses. The channel that extends from Highway 12 to the Pheasant Branch Marsh has a steep fall (90 foot drop over 2 miles) resulting in high erosion rates that threaten infrastructure such as bridges and sewer lines. The City of Middleton has spent over 2.3 million dollars in the last 25 years in an attempt to protect these structures from erosion (Gary Huth, City Engineer, personal communication). The Pheasant Branch system also has had an appreciable effect on the larger Lake Mendota watershed, and had the highest sediment load per unit area for all rural streams measured in Dane County (Lathrop and Johnson, 1979). Increased stormwater flows resulting from future development are expected to worsen both the erosion in the stream channel and sediment transport. These issues have become a topic of concern for the citizens of Middleton (North Fork Pheasant Branch Watershed Committee, 1999).

How was the study designed?

The study included all elements of the hydrologic cycle including rainfall, snowmelt, evapotranspiration, interflow, streamflow, baseflow, and ground-water flow. The entire hydrologic system is characterized quantitatively; thus, output from surface-water modeling was coupled to the ground-water model input. This coupling allowed for more realistic scenarios (that is, simulating how urbanization affects surface-water storm flows and ground-water recharge) and provided an additional check for reasonableness.

Figure 1. Location of study area, streamgaging stations, and rain gages, Pheasant Branch watershed near Middleton, Wis.

What the study accomplished

Identifying the source of water to the Springs

The spring system is an important water resource in the Pheasant Branch watershed, and an important source of water for a wild rice community in the Pheasant Branch Marsh. Identifying the source waters for the spring is a first step in ensuring its protection. In this study ground-water-flow modeling and geochemical information was used to identify areas that feed the Springs.

A mathematical flow model of ground water of the area was constructed using the computer program MODFLOW (McDonald and Harbaugh, 1988) by adding more detail to a specific area of an available ground-water flow model constructed for the entire county (Krohelski and others, 2000). Information entered into the model included the amount of rain and snow that recharges the ground-water system (as determined by the surface-water modeling described below) and the amount of water pumped from area wells. In addition, the locations of streams, Lake Mendota, and geological properties were entered into the model. The ground-water model was run using average conditions and the simulated water levels and streamflows were compared to available water levels and measured streamflows to check the model accuracy. Using a recently developed automated approach, the various model inputs were varied until the model closely approximated the average conditions measured in the hydrologic system. During this process it was noted that parameters that gave the "best fit" were different than the parameters that fit the larger, county-scale model. A statistical technique (Monte Carlo analysis) was used to evaluate the different combination of parameters on the simulated capture zone of the Springs. The models were used to trace mathematical water particles to see where the ground water goes (if we track forward in time) or where it came from (if we track backward in time). This approach was used to define the recharge, or "capture", area that supplies ground water to the Springs (fig. 2). The probability of capture shown in figure 2 represents the uncertainty in the model parameters that are included in the ground-water model computations. Geochemical sampling of the springs also supported the location of the simulated recharge area (Hunt and Steuer, 2000).

Springs have not always been valued as an important water resource, as shown by this discarded 55-gallon drum (foreground) among the many sand boils of the Pheasant Branch Springs.

This work shows two important findings. First, the Springs capture water outside of the immediate areas surrounding the spring. Waters that infiltrate into the ground in the North Fork watershed, and even north of that watershed, flow to the Springs (fig. 2). Moreover, the ground-water system does not spatially coincide with the surface-watershed (the divides that define the basin in fig. 2) and ground water flows across topographic and political boundaries. Or put another way, the North Fork watershed of the Pheasant Branch and areas outside of the North Fork watershed are linked by the ground-water system. Therefore, urbanization in the North Fork watershed that affects the ground-water system will change the Springs, even though the urbanization is not in the immediate vicinity of the Springs! It should be noted that the location of this capture area depends on the conditions in the surrounding hydrologic system. If the system were sufficiently changed (for example, by drilling additional high-capacity wells near the capture area) the shape and extent of the capture zone would change. Secondly, the work demonstrates that spring flow is made up of young and old water (hundreds to thousands of years old). The young water has short flowpaths from where it enters the ground to where it resurfaces again at the Springs. The older ground water has traveled from more distant areas to the Springs.

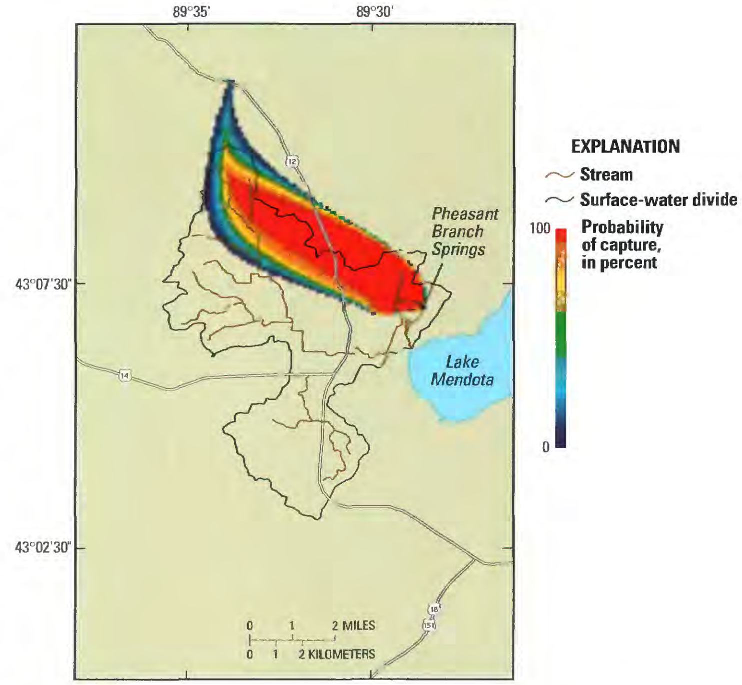

Figure 2. Simulated capture zone in the lower bedrock for Pheasant Branch Springs, Dane County, Wis. (from Hunt and Steuer, 2000).

These longer flowpaths result in a "lag time" between the time that changes occur on the distant land surface and the time these changes are seen at the Springs. Accurate long-term estimates of the effects of changing land use need to account for this lag.

Quantifying how urbanization might affect the surface-water and ground-water systems

A model similar to the ground-water model also was used to simulate the surface-water system (Steuer and Hunt, 2001). The surface-water model accounts for all the sources and sinks of water such as the amount evaporated, used by plants, infiltrated into the ground, or moved over the surface after a snowmelt or rainstorm to Pheasant Branch. The average water movements from 1993 to 1998 for the Pheasant Branch watershed are shown in figure 3. Notice that much of the annual 35 inches of precipitation (snow and rainfall) that fell on the watershed went back into the air by evaporation or plant transpiration. The amount of water that soaked into the ground and made it past the root system is used as recharge

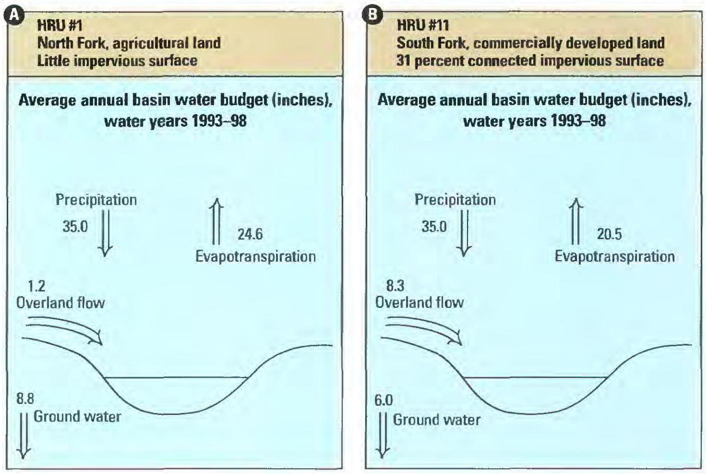

Figure 3. Average annual water budget for two hydrologic response units (HRUs) in the Pheasant Branch watershed (budget not balanced because of change in ground-water storage).

for the ground-water model. This water becomes local ground-water that sustains the creek, or the larger Lake Mendota regional system. Results of the study indicate that much of the recharge occurred during the spring snowmelt period. During the summer months, when the plants are active, much of the water infiltrating into the soil is intercepted within the plant root zone.

The surface-water model computations also show that the amount of recharge to the ground-water system differed between areas (fig. 4). The model divides the watershed into representative areas called "hydrologic response units" (HRUs). HRUs with large amounts of pavement, rooftops, or other impervious surfaces had less recharge, whereas wooded areas or land with soils suitable for infiltration had greater recharge. One notable result of the fieldwork conducted during this study is that farmland enrolled in the Conservation Reserve Program (CRP) had appreciably higher infiltration than when the same soil was actively farmed (Steuer and Hunt, 2001).

As discussed above, changing the land use by development or different agricultural practices can change how water moves through the system. Once the hydrologic models are constructed and calibrated they can be used to assess how changes in land use can affect the hydrologic system. Two aerial photographs that show the substantial development in the southern and middle portions of the Pheasant Branch watershed from 1974 to 1995 are shown in figure 5. The models were used to calculate what water movement would be like in the future if the northern watershed were to be developed to the same degree as the highlighted areas in the 1995 photograph.

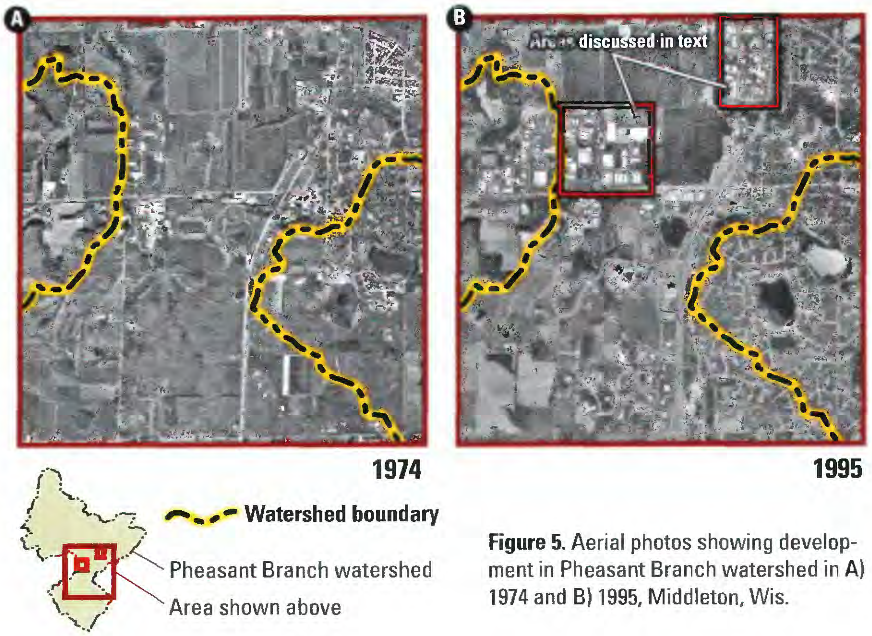

Figure 5. Aerial photos showing development in Pheasant Branch watershed in A) 1974 and B) 1995, Middleton, Wis.

How water movement, under the hypothetical development scenario, would change from present-day conditions is shown in figure 6. Model simulations project that streamflow peaks during rainstorms or snowmelt would increase by more than 450 percent. Moreover, Pheasant Branch is expected to be dry between storms—a notable change from the present-day baseflow conditions. Recharge to the ground-water system from the Pheasant Branch watershed also would decrease by 57 percent, and the flow from the Pheasant Branch Springs would decrease by 26 percent. It should be noted that the reductions in spring flow would be expected to be greater if additional ground-water pumping also was associated with the development.

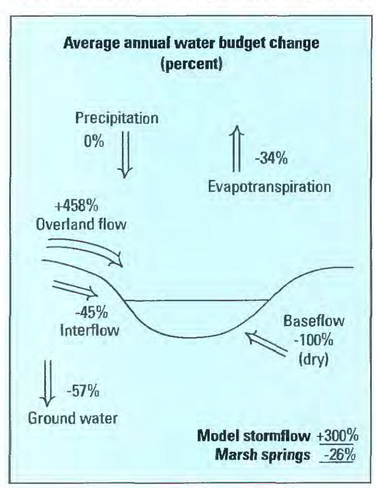

Figure 6. Changes from present-day conditions to the average annual water budget after hypothetical development.

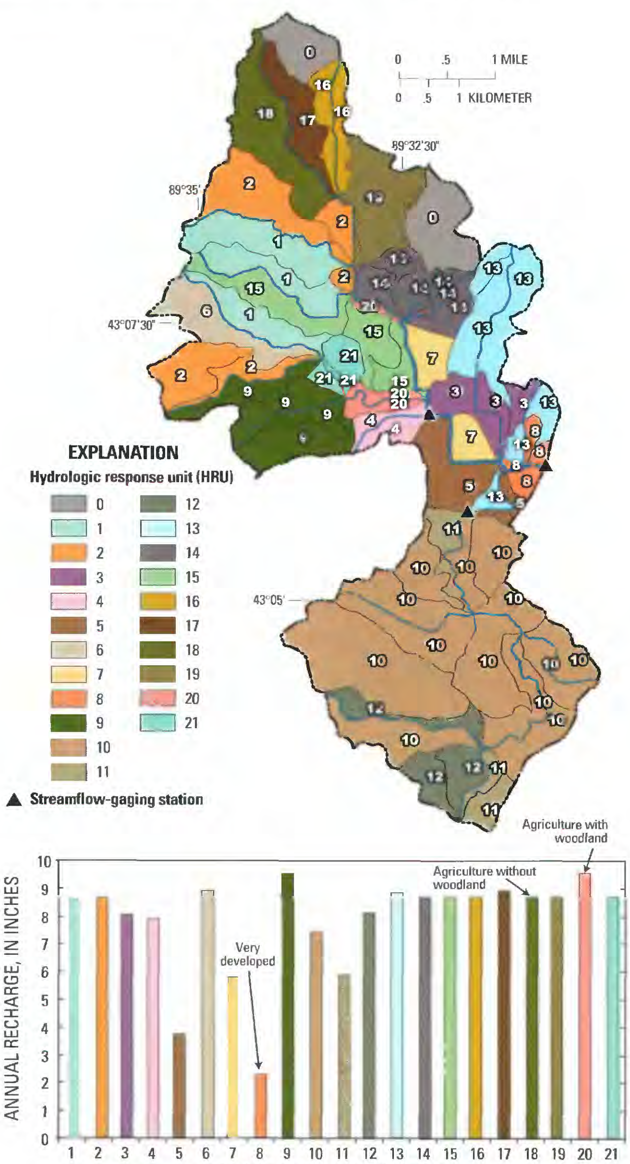

Figure 4. Location of the hydrologic response units (HRUs) and resulting simulated recharge for each HRU.

Investigating what can be done to minimize the effects of development

The project results also can be used to evaluate the effects of land-use planning practices. Certain areas have larger effects on the hydrologic system than others because of soil type, location, or land use. For example, some areas in the watershed can infiltrate appreciable quantities of water and are valuable for ground-water recharge (fig. 7). Ideally, these areas could be managed to retain or enhance their capability to infiltrate water into the ground-water system. Additionally, other areas have high storage and detention values for mitigating adverse effects of urbanization on surface-water resources. The model was used to evaluate an array of detention basins within the North Fork watershed to assess the effectiveness of this traditional stormwater control practice (fig. 8). Generally, the

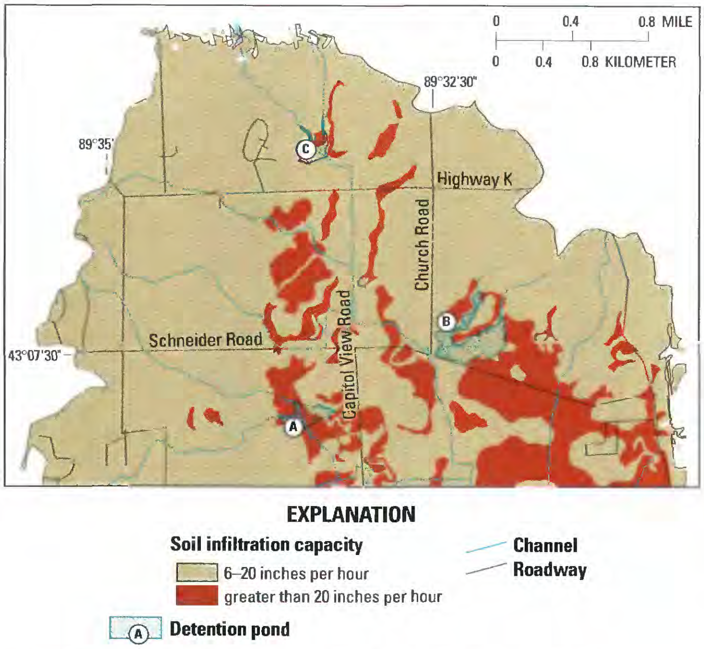

Figure 7. Location of high-infiltration-rate soils as determined by project fieldwork. Three reservoirs used in the example application (fig. 8) also are shown.

results indicate that these measures might mitigate some adverse effects of development if properly located and the degree of development was not too high. These simulations help quantify the potential benefits of such measures, and allow the local municipalities to weigh the cost of implementing the measures against the benefits gained.

Other smaller-scale options also are available to minimize the effects of development. Researchers at the University of Wisconsin, Wisconsin Department of Natural Resources, and at the U.S. Geological Survey are examining the possibility of increasing infiltration at individual developments or even at specific home sites rather than collecting water runoff from large developed areas and managing it downstream in the watershed.

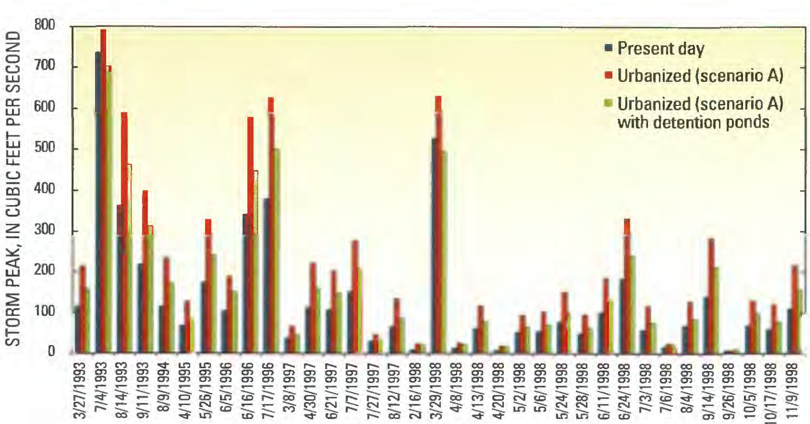

Figure 8. Simulated Pheasant Branch Creek flow peaks for present-day conditions, a relatively low degree of additional urbanization (scenario A), and additional urbanization tempered with three detention ponds (shown in figure 7).

How the City of Middleton uses the study to influence development

- A new development in the recharge area of the Springs was required to include methods for preserving infiltration and minimizing stormwater runoff, as well as the monitoring of the effectiveness of these practices.
- Future development in the North Fork watershed will be planned to produce runoff conditions similar to figure 8 to protect the watershed and help ensure that the conditions shown in figure 6 don't occur. Three detention basins (such as those shown in figure 7) will be sited and formally preserved by placing them on the city's official development map, by plan review, or possibly by purchase.
- The city also will identify high-infiltration areas in the North Fork watershed as desirable green space for parks, trails, and other recreational uses.

This work examines infiltrating potential stormwater on-site by using rain gardens or a combination of water-quality and infiltration basins. Future work will use the models described here to simulate the effect of these practices on the larger Pheasant Branch streamflow, ground-water system, and the Springs.

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