Responses to **Urbanization**

Groundwater, Stream Flow, and Lake Level Responses to Urbanization in the Yahara Lakes Basin

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The Yahara lakes drainage basin is one of the most rapidly urbanizing areas within Wisconsin. Multiple hydrological problems are accelerating due to the increase in impervious area (i.e., rooftops, roads, parking lots, driveways, etc.) from urban development. These problems include lowered groundwater levels both in shallow and deep aquifers due to the combination of less rainfall/snowmelt infiltration into the ground, and greater groundwater pumping by municipalities. Lower water tables in the shallow aquifer have led to a decline in the flow of local springs that maintain dry weather baseflow in streams and are a direct source of clean water to the Yahara lakes and nearby wetlands.

The effect of this increased groundwater pumping in the Yahara drainage basin is that most of the pumped water ends up in the sanitary sewer system with the treated effluent discharged outside of the basin. Flow rates of wastewater being treated by the Madison Metropolitan Sewerage District (MMSD) have increased lockstep with this urban development.

Another problem from the greater urban impervious area is the increase in storm water runoff to the lakes – a problem that is exacerbated with the loss of much of the watershed's wetlands in prior years. While current urban design practices have resulted in detention ponds being constructed to reduce runoff peak flow rates, the total volume of runoff has not been affected by the detention systems.

The combined effect of this altered hydrology has led to more frequent and severe flooding in the Yahara lakes and interconnecting river system during wet periods. During drought periods water levels are often too low for recreation, navigation, and fish and aquatic life needs. Flow rates in the Yahara River downstream of Lake Waubesa become very low due to competing needs to maintain lake levels.

This article reviews some important characteristics of the altered hydrology due to urbanization, and provides some options for future management to alleviate these problems. A new hydrologic study and modeling initiative to address these hydrological concerns is also discussed.

Groundwater

Groundwater is an integral part of the water budget of the Yahara River chain of lakes, and the lakes are well connected to the underlying groundwater system. Prior to development and urbanization in the Madison area, the Yahara lakes and associated smaller streams and wetlands were sinks, or discharge areas, for groundwater. Cold-water springs were common features along the lakeshores (Figures 1a, 1b). Today, municipal and industrial groundwater pumping in the Madison metropolitan area has lowered water levels beneath the city and parts of the lakes. Over large areas, the natural flow of groundwater to the lakes has reversed, and the lakes now lose significant amounts of surface water to the groundwater system. Although these declines in groundwater levels have little effect on lake levels, they do influence outflow to the lower Yahara River, particularly in baseflow periods during dry summers. Some lakeshore springs have declined or disappeared entirely, especially along the south shore of Lake Mendota, the north shore of Lake Wingra, and around Lake Monona (Figures 2a, 2b).

Three important aquifers, or water-bearing geologic units, occur throughout south-central Wisconsin, and all these units are present below the Yahara lakes. Near the land surface, glacial deposits along with recent stream sediments form a shallow sand-and-gravel aquifer. Below the sand and gravel a series of dolomite and sandstone formations makes up an upper bedrock aquifer that provides water to shallow domestic wells in rural parts of Dane County. A thin shale-like layer below these rock forms a regional aquitard, or relatively impermeable confining layer, that separates the upper bedrock aquifer from the underlying Mount Simon aquifer (the deep aquifer). The Mount Simon aquifer is composed mostly of well-sorted sandstones and ranges from about 500 to 800 feet thick. It is a prolific regional aquifer and serves as a source for most of the high-capacity municipal and industrial wells in the area.

Groundwater moves both vertically and horizontally through the three aquifers. The water table is the upper surface of the saturated zone and generally occurs within 100 feet of the land surface in central Dane County. The Yahara lakes represent an outcrop of this water table surface with the lakes lying at the base of the groundwater basin in central Dane County. Recharge of groundwater occurs through infiltration of precipitation on the uplands around the lakes. Recharge of the deep aquifer from the upper aquifer occurs because the shale layer is not continuous throughout the region.

Groundwater extracted through municipal and industrial wells in the Madison area – currently totaling about 50 million gallons per day (MGD) or 75 cubic feet per second (cfs) – results in a reduction in groundwater levels in the aquifers beneath Madison. The largest drawdowns (about 60 feet)

Figure 1a. Pheasant Branch Spring in the western part of Lake Mendota's watershed. Photo: R. Lathrop, Wisconsin DNR.

Figure 1b. Pheasant Branch Spring boils. Photo: K. Bradbury, Wis. Geol. Nat. Hist. Survey.

occur in the deep aquifer and form a cone of depression nearly 20 miles in diameter (Figure 3a). These drawdowns propagate upward to cause drawdowns in the shallow aquifers (Figure 3b). The Madison lakes split the cone of depression because the lakes supply water to the groundwater system and tend to mitigate shallow drawdowns near the lakeshores and beneath the lakes.

Pumping and drawdown have caused significant changes in lake groundwater budgets. Table 1 compares the water budgets for the lakes calculated for predevelopment conditions with the water budgets for year 2002 pumping rates. For example, model simulations indicate that Lake Mendota historically received nearly 24 cfs of groundwater input. Today, the lake receives only about 4 cfs – a reduction in groundwater inflow of over 80 percent. Lake Monona historically received about 9 cfs but today *loses* about 1.5 cfs, a net reduction of over 115 percent. Overall, the Yahara lakes have had a reduction of about 19 cfs, or about 66 percent of groundwater inflow.

Groundwater flow modeling results show how these reductions are distributed over the lakes and are dependent on proximity to the cones of depression. Model simulations confirmed with field data (Bradbury and others 1999) indicate the northwestern one-third of Lake Mendota gains groundwater, while the southeastern two-thirds of the lake loses groundwater. All of Lake Monona currently loses water to groundwater.

Urbanization Effects on Stream Flow and Lake Levels

The effects of urbanization on stream flows can be illustrated by a comparison of U.S. Geological Survey discharge records for two area watershed stream systems: Garfoot Creek in western Dane County and Spring Harbor storm sewer in southwestern Madison. Both systems have similar drainage areas, but Garfoot Creek has almost no impervious cover with the watershed being a partially forested agricultural watershed, whereas Spring Harbor experienced traditional residential and commercial urban development in recent decades.

During 1995 in Garfoot Creek, rainfall and snowmelt events produced relatively little runoff as evidenced by small increases in stream discharge; most of the precipitation was infiltrating into the ground replenishing groundwater aquifers that maintain the spring-fed stream's substantial baseflow discharge (Figure 4). In contrast, Spring Harbor in 1995 had very high peak runoff discharges for very short periods of time interposed by almost no dry-weather baseflow. Very little precipitation was infiltrating to support shallow aquifer springs; much of

Figure 2b. Plaque at the Springhaven pagoda commemorating the natural spring water that once existed there. Photo: K. Bradbury, Wis. Geol. Nat. Hist. Survey.

Figure 2a. Pagoda built to protect the Springhaven Springs near Lake Monona, circa 1900. Photo: K. Bradbury, Wis. Geol. Nat. Hist. Survey.

the precipitation was converted to surface runoff conveyed by the storm sewer system even though detention basins were located in the drainage basin.

These stream discharge characteristics for non-urbanized and urbanized watersheds allow a simulation of Lake Mendota's water level responses to two extreme scenarios of watershed development – undeveloped and fully urbanized (Figure 5). Using precipitation records for 1995 to 1998, model simulations indicate three periods of extremely high lake levels and two periods of very low lake levels would have occurred in the fully urbanized watershed scenario. The undeveloped watershed scenario would have had a much more stable lake level record.

The effects of urbanization on Lake Mendota's water levels is also evident in annual maximum lake levels from 1916 to 2000. While other factors such as loss of wetlands and changing climate may also be important, a statistically significant upward trend in maximum lake levels has occurred during the last century. Since 1990, lake levels have been more than one foot above the DNR's summer operating level in many years. Levels were more than two feet higher than the operating level in 1993 and 2000 resulting in extreme flooding conditions throughout the entire Yahara River system.

Another significant indicator to the effects of urbanization is Lake Mendota's water level response to very large rainfall events. For six-inch rainfall events occurring within individual decades, the 1930s through the 1950s had estimated lake level increases of about six

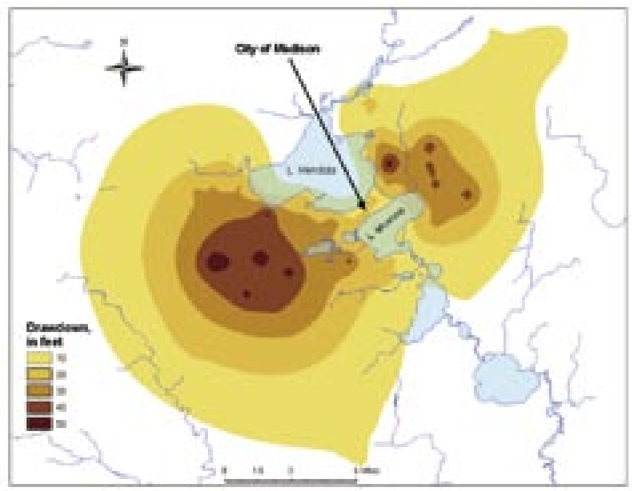

Figure 3a. Drawdown of deep aquifer near Madison. Graph: K. Bradbury, Wis. Geol. Nat. Hist. Survey.

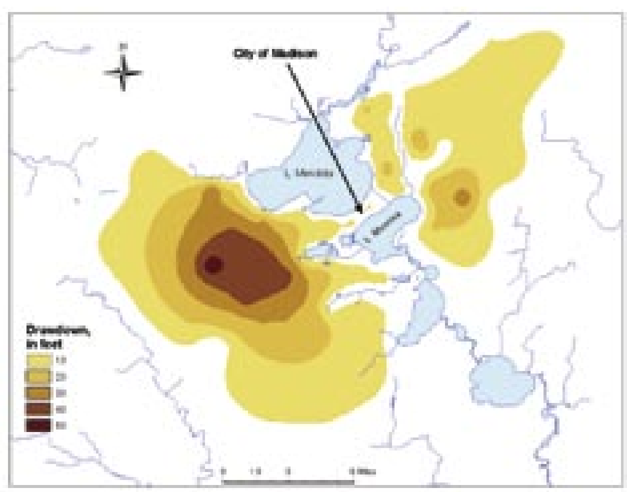

Figure 3b. Drawdown in the shallow aquifer near Madison. Graph: K. Bradbury, Wis. Geol. Nat. Hist. Survey.

Table 1. Simulated groundwater inflow to the Madison Lakes. *Historic* flows represent a simulation with no groundwater pumping; *current* rates assume pumping at year 2002 pumping rates. Source: K. Bradbury, Wis. Geol. Nat. Hist. Survey.

Lake	*Historic (cfs)*	*Current (cfs)*	*Change (cfs)*	*Pct Change*
Mendota	23.9	4.4	-19.5	-82%
Monona	8.7	-1.5	-10.2	-117%
Waubesa	10.3	6.5	-3.8	-37%
Kegonsa	10.2	8.8	-1.4	-14%
Wingra	3.3	1.2	-2.1	-64%
Total	56.4	19.4	-37.0	-66%

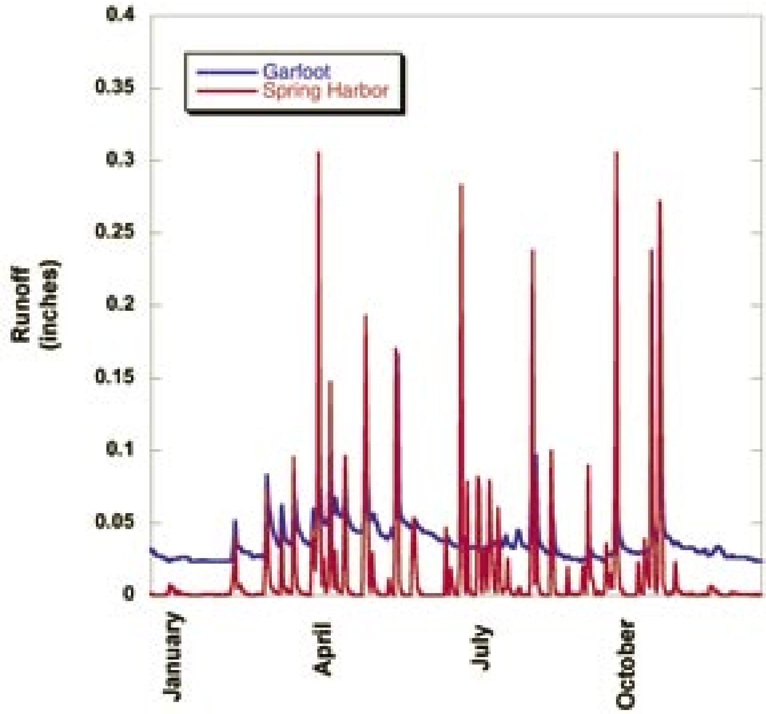

Figure 4. Water discharge from Garfoot Creek and Spring Harbor storm sewer in 1995. Graph: K. Potter, UW-Madison.

to seven inches (Figure 6); discharges through Mendota's outlet dam were able to keep up with runoff inputs from the watershed. By the 1990s, lake levels were estimated to increase about 10 inches; outlet discharges could not compensate for the increased volume of runoff rapidly entering the lake.

New Tools for Lake Level and River Fow Management

Recognizing that better tools were needed for managing lake levels and river flows, the Dane County Department of Land and Water Resources (LWRD) has contracted with Baird & Associates to develop a coupled hydrologic and hydraulic model to provide a means of objectively quantifying the effects of a wide range of systemic changes that affect the hydrology of the Yahara watershed, and the resulting river and lake levels. This decision support tool will enable the LWRD to reliably predict the outcome of watershed, infrastructure and operational changes so that these issues can be evaluated on their own merits, rather than the likelihood of perceived changes. Ideally, the model could be used to optimize the decision-making processes. The decisions facing the watershed managers range from policy issues, such as riparian and wetland zoning, to lake level management, biological and environmental concerns, and infrastructure management, such as the replacement of the dams and locks. These decisions have implications that are often contentious among watershed stakeholder groups.

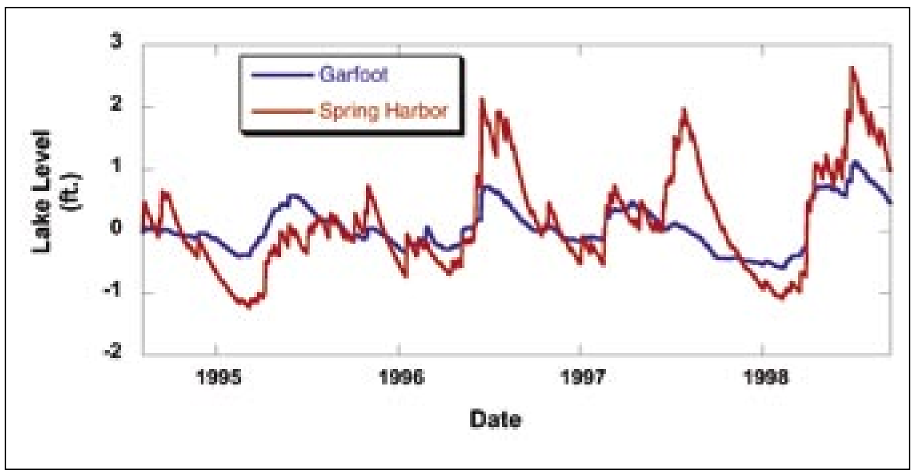

Figure 5. Lake Mendota water levels simulated for natural (Garfoot Creek) and totally developed (Spring Harbor) watershed land use scenarios. Graph: K. Potter, UW-Madison.

The hydrologic modeling components of the model will include the ability to change the degree of urbanization in portions of the watershed to determine the effect of this change. This will be useful in determining the long-range effects of urban development in the watershed.

Other aspects of the model include an analysis of various conveyance (or water movement) issues of the Yahara River system that have played a role in several high-water events in recent history. The minor elevation difference between the lakes and the low slope of the river does not afford the system much ability to rapidly convey large amounts of water. When this lack of slope is combined with the flow-choking effects of weed growth in the river, the conveyance is reduced further. The portion of the river between Lake Waubesa and Lake Kegonsa is a key "bottleneck" for the system due to this combination. There are many times during the summer that the backwater caused by weed growth controls the outflow from Lake Waubesa even more than the outlet structure itself (Figure 7). The flow during the late spring of 2005 is

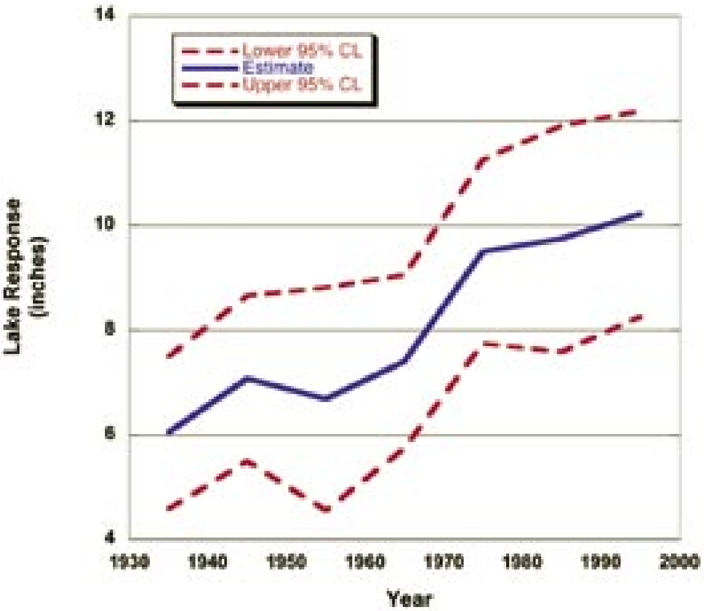

Figure 6. Decadal trends of Mendota's lake level response to six-inch rainfall events. Graph: M. Wegener and K. Potter, UW-Madison.

an example. The model will include the capability to simulate the flow resistance caused by weeds and other factors, so that the impacts of remedial actions can be predicted.

One of the most critical, and often contentious, aspects of the management of the lakes and river is the operation of the controlling structures. Although the target lake levels have already been determined, the management decisions preceding and during high-flow events remains a challenging task. The model will include the ability to simulate many types of "what-if" scenarios regarding the lake level management. When high-flow events occur, the key management issues include the optimization of the drawdown of each lake such that the flow released does not exacerbate the flooding on the next downstream lake. For these types of decisions, the model will provide an estimate of the impacts of decisions before they are implemented.

Other aspects of the modeling system will include a means of quantifying the net effect of best management practices (BMPs) on a subwatershed level and its relative impact on the hydrologic response. This will provide a basis for the determining the most effective BMP for a given situation.

The management decisions and issues facing the watershed managers of the upper Yahara River and lakes Mendota, Monona, Waubesa and Kegonsa are complex, and will become even more complex, given the growth trends in the watershed. The impacts of these growth trends can potentially cause the lakes to rise to high levels more often, and to higher levels than ever before, and requiring longer periods to return to desirable levels. These hydrologic and hydraulic models will provide the watershed managers with a means of evaluating a variety of mitigation measures in a more proactive and objective manner.

Potential for Reuse of Treated Sewage Effluent Water

Madison Metropolitan Sewerage District (Madison, Wisconsin) receives and treats wastewater from a 175-square-mile service area, spanning two watersheds (Yahara River watershed and the Sugar River watershed to the west). Wastewater is pumped to a centralized treatment facility, and effluent resulting from wastewater treatment (42 MGD) is diverted around the Madison lake system.

Effluent diversion around the Madison lake system began in 1958. Diversion facilities were constructed in response to a 1949 state law that required diversion unless advanced treatment techniques were employed that would accomplish substantially the same result in eliminating nuisance conditions as would be accomplished by diversion.

Groundwater quantity concerns in Dane County have placed increased focus on the effluent diversion. The Dane County Hydrologic Study (initiated in 1992) was a cooperative study of the hydrogeology of Dane County conducted to increase the understanding of groundwater/surface water relationships, and in particular, the effects that groundwater withdrawals have on surface waters. The study concluded that the combination of groundwater pumping and effluent diversion has reduced stream baseflows in localized areas within the Yahara and Sugar River watersheds. Impacts on the water balance in wetlands have also been noted.

Figure 7. Lake Waubesa outlet structure. Note the stoplogs below the walkway barely produce a ripple in the water surface. Photo: B. Halverson, Baird & Associates.

In recent years MMSD has initiated three projects to address some of these water loss concerns. The Badger Mill Creek effluent return project mitigates the impact of water diversion from the Sugar River Basin resulting from wastewater treatment. MMSD worked cooperatively with multiple partners to implement an overall solution that addressed both wastewater treatment needs and water balance issues. Specifically, provisions were made to return highly treated effluent to the Sugar River watershed, improving the fishery potential by removing base flow as a limiting condition. Public support for this project was high, with effluent return commencing in 1998.

MMSD's second mitigation began in 2004 as a demonstration project by using treated effluent to irrigate a portion of the City of Fitchburg's Nine Springs Golf Course. Data generated to date indicate that the effluent can be an effective source of water for turf grass production. Additional benefits include reduced groundwater pumping from the shallow aquifer.

MMSD's third mitigation is another demonstration project where a 140-acre wildlife observation area was created in a lagoon system previously used for biosolids storage (Figure 8). Water levels are managed throughout the year to create conditions that are conducive for use by migratory shorebirds and other wildlife, with effluent being used as the source water. Over 200 species of birds have been documented at the site, some of which are rarely seen in Wisconsin.

Opportunities and Challenges to Effluent Reuse

There are many opportunities for using effluent to address water quantity issues within the Yahara and Sugar River basins. These include, but are not limited to:

- Wetland restoration
- Irrigation
- Infiltration
- Flow augmentation
- Industrial uses (e.g., cooling tower use)

Factors that need to be examined during the project evaluation phase include infrastructure requirements, economics, water quality considerations, potential human health and environmental quality impacts, and public information/education requirements. Finding the appropriate balance between some of these factors is challenging, and requires that projects be evaluated using a "net environmental benefit" approach.

Several challenges to successfully implementing an effluent reuse project are:

1. *Effluent quality*: The required effluent quality will be a function of the end use being considered. Accurately defining effluent quality is important because it will impact treatment considerations, economics and perhaps the project viability.
2. *Infrastructure*: In many cases, the infrastructure necessary to support an effluent reuse project is not in place. For example, new conveyance and delivery systems may need to be constructed. In addition to traditional "brick and mortar" infrastructure, the lack of a mature regulatory infrastructure regarding beneficial reuse of effluent in Wisconsin may make it challenging to implement effluent reuse projects.
3. *Economics*: Effluent quality and infrastructure considerations are primary economic drivers. Producing a higher-quality effluent typically results in increased treatment costs. In many cases, new or different treatment technology may need to be installed to produce the necessary effluent quality, and the cost impact can be dramatic. Thus, accurately determining the effluent quality needed to support the end use being considered is critical.
4. *Public information/education*: Complex scientific and technical issues may arise when evaluating effluent reuse alternatives. Helping interested parties understand these issues so they can make informed decisions based on a "net environmental benefit" concept requires significant effort in the areas of public information and education.

Infiltration Practices to Mitigate the Hydrologic Impacts of Urbanization

Perhaps one of the most challenging aspects of urbanization is to mitigate the impacts of impervious surfaces that cause groundwater infiltration rates to decline while surface runoff volumes to surface waters increase. Low-impact urban

Figure 8. Madison Metropolitan Sewerage District's treatment plant and part of their former biosolids storage lagoon system that was recently converted into a wildlife observation area. Photo: R. Lathrop, Wis. DNR.

development practices can achieve that end:

- Preserve natural areas with highly permeable soils (cluster development).
- Minimize soil compaction during development.
- Restore permeability of disturbed soils.
- Use permeable hardscapes.
- Route runoff from impervious surfaces to infiltration practices.

The last point is worthy of further discussion as bioretention facilities (e.g., rain gardens, Figure 9) capture surface runoff for concentrated infiltration and allow soil and plants to remove contaminants in appropriate settings. Modeling indicates that with a garden to impervious area ratio of 0.10, over 90 percent of the annual runoff is infiltrated into the ground (Figure 10) (Dussaillant and others 2004). Interestingly, infiltration rates from rain gardens can greatly exceed infiltration rates that would result if the watershed were not urbanized because of evapotranspiration by plants in the undeveloped landscape. Other practices such as grass swales have great potential to infiltrate water.

The combination of all infiltration practices outlined above presents the greatest challenge for urban development, both existing and future, but these practices are essential if the hydrologic impacts from urbanization are to be reversed for the future of Dane County's waters. Recent legislation at both the state and county level requiring infiltration practices in urban development is a good start, although some fine tuning to eliminate some of the exceptions may be needed.

Figure 9. Rain garden. Photo: S. Jones, Dane Co. Land and Water Resources Dept.

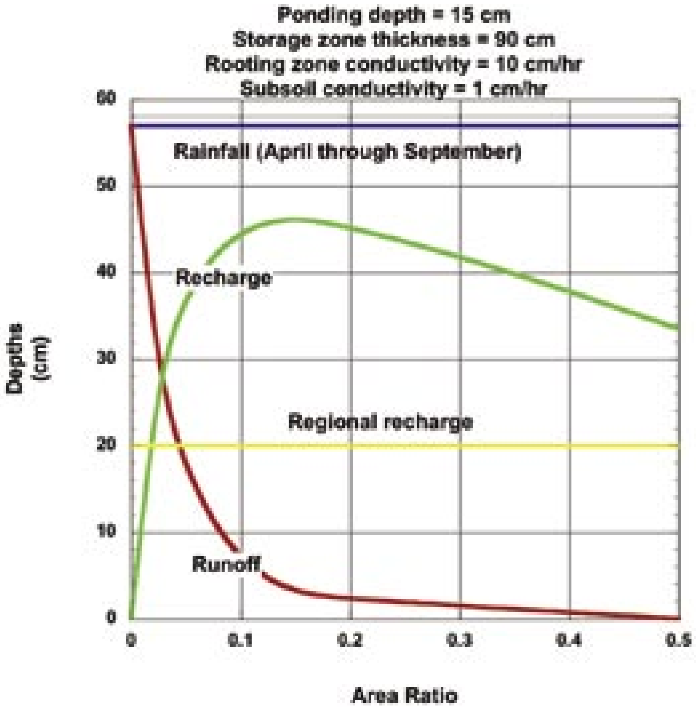

Figure 10. Rain garden simulation, 1992-1997 (from Dussaillant et al. 2004).

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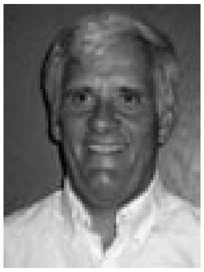
Richard Lathrop is a lake researcher for DNR. He has researched the Madison Lakes for 30 years, and has an honorary appointment with the UW Center for Limnology. He was the Program Chair for the NALMS 25th symposium held in Madison on November 9-11, 2005.



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