A Model for Estimating the Phosphorus in Runoff from Shoreland Development

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1. Overview and Example

Phosphorus in runoff from development on the shore can lead to an increase in aquatic plants and algae in a lake. Estimating this impact and designing to minimize it was the purpose of developing the modeling approach described in this report. This approach uses a continuous simulation model to estimate the phosphorus transferred from a home or cabin to a lake along with benefits of mitigation through buffers, raingardens and infiltration trenches.

This approach uses the EPA Stormwater Management Model (SWMM). This is a relatively general model that allows different configurations of impervious surfaces, infiltration practices and soil properties to be incorporated. Of course, the movement of water and phosphorus on the shore is very complicated and the model is a simplified representation of the process. To demonstrate the approach that was developed and provide a tool that can be used to estimate phosphorus transfer from the shore, this report describes the results of modeling with a simplified lot configuration and assumptions about water movement and phosphorus concentrations.

Figure 1 shows the elements of the simplified lot configuration that was employed in the EPA SWMM model to characterize a shoreland lot.

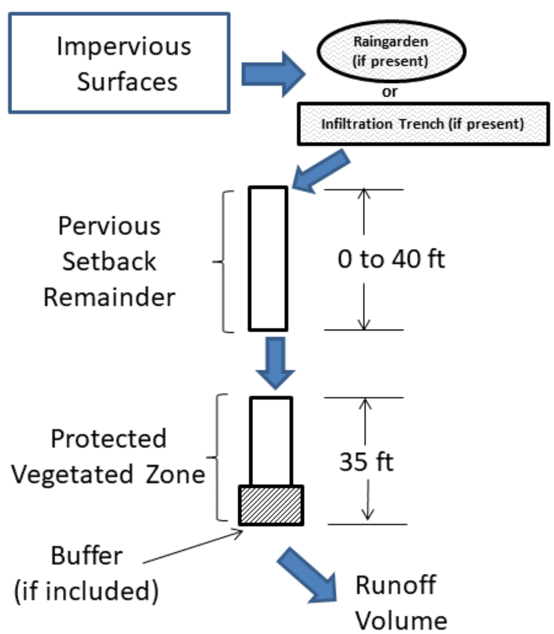

Figure 1. Simplified lot configuration used as a model for estimating the runoff volume from the shore. The impervious runoff is assumed to be directed to a portion of the setback from the lake with a width that varies with slope. Infiltration devices (raingarden or infiltration trench) are assumed to be before the setback. Buffer depth is distance from the lake and its addition reduces the depth of the protected vegetated zone. Total phosphorus is calculated by multiplying the runoff volume from each impervious surface area by the flow-weighted mean concentration of 0.5 mg/l phosphorus and then summed for the parcel.

The average runoff volume per year from a multi-year simulation is multiplied by an assumed flow-weighted mean concentration of 0.5 mg/l to calculate the average annual phosphorus in pounds/year from each impervious surface. The total phosphorus from the parcel is the sum of the phosphorus from all the impervious surfaces.

Users can estimate the annual phosphorus from the impervious surfaces and explore the benefit of adding infiltration practices with model. The EPA SWMM model can be used directly (example files and precipitation/temperature files for Wisconsin can be provided and a User Guide is being developed) or, if appropriate, solution tables provided in this report can be used. These solution tables were obtained by running the model for a range of possible conditions and then summarizing the results. These all assume the general parcel layout shown in Figure 1 with impervious surfaces 35 to 75 feet from the lake.

The results from the model are presented as pounds of phosphorus per year (lb P/yr) which is the average annual phosphorus over the period of the simulation. For example, the baseline model table solutions in Appendix A used a thirty-six year simulation period (1960-1995). The resulting average annual model results range from 0.000 lb P/yr (for 500 ft^2 of impervious on high infiltration rate soils and low slope) to 0.128 lb P/yr (for 2000 ft^2 of impervious on low infiltration rate soils with steeper slopes). Although the absolute value of these model results reflect assumptions that are incorporated in the model, they are in the general range of monitoring results from Graczyk et al. (2003) who found phosphorus transfer from 0.01 to 0.08 lb P/acre-yr in shoreland monitoring of lawns. The results of the monitoring here only describe the developed portion of a lot near the lake, which may be approximately 0.1 acres of total land area. If the model results from the developed portion of the lot are converted to a per-acre transfer, it would range from 0 to 1.28 lb/acre-year. That is also near the range reported for turf runoff studies of Bierman et al. (2010) in Minnesota or Steinke et al. (2007) in Wisconsin. Both of those studies found runoff in frozen conditions was at least as important as the non-frozen conditions, a condition which will need more evaluation in the shoreland model here which leads to most of the runoff during the non-frozen periods of the year. These studies also found total phosphorus concentrations that were consistently higher than the 0.5 mg/l used in the shoreland model developed here and were closer to 1 mg/l overall.

The model results can also be compared to phosphorus transfer rates from undeveloped conditions as a way to set goals for developed areas. An example of phosphorus export rates for undeveloped land in Wisconsin is the “low to most likely” range of 0.04-0.08 lb/acre-year for forested watersheds described by Panuska and Lillie (1995) which if adjusted for the approximately 0.1 acre of the modeled area in the baseline modeling performed here, would correspond to 0.004-0.008 lb/year. The Panuska and Lillie export rate would also include the groundwater contribution which could be 0.02-0.04 lb/acre-year (assuming 10 to 20 ug/l for the groundwater P concentration) or approximately half of the export rate. Consequently, a target range for developed shoreland could be in the range of 0.001 to 0.01 lb P/year.

Example

- *2000 ft² impervious area 75' from the lake*
- *All the runoff from the impervious area drains to a 100 ft² raingarden that is 8 inches deep. Overflow from the raingarden is directed to a pervious area that has sparse vegetation, is used for some storage and experiences foot traffic and other activity.*
- *Between the impervious surface and the lake, the ground surface has been disturbed through activity and includes a trail and storage. There is a 10' deep vegetative buffer at the edge of the lake. The 10' buffer has relatively thick vegetative ground cover.*
- *Soils are coarse textured described as "sandy" with slope approximately 10% in the 75' setback*

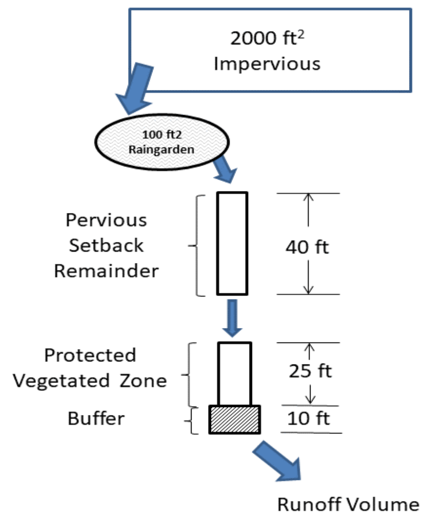

Figure 2. Schematic of model example showing a raingarden following an impervious surface with overflow moving through the setback to the lake

To model the shoreland, the phosphorus estimated for the impervious surface after passage through the raingarden and setback is calculated. This can be calculated using the model or using the table solutions. The table solution approach is used here:

Because the soils are sandy but disturbed, we will use a table for "Medium" infiltration rate in the setback area. Table R2.1.2 in Appendix A provides solutions for a medium infiltration rate with impervious surfaces draining to a raingarden, a seventy-five foot setback and a ten-foot buffer. The phosphorus from the impervious surface without a raingarden and buffer is 0.063 lb/yr (Table R2.1.1). With a 100 ft2 raingarden and a 10 foot buffer, the modeled phosphorus transfer is 0.029 lb/yr (Table R2.1.2), or a reduction of 0.034 lb/yr. The table shows that by increasing the size of the raingarden, the annual phosphorus can be reduced further. For example, a larger, 200 ft² raingarden would reduce this to 0.016 lb/yr.

The model results project that the addition of the raingarden and buffer reduce the phosphorus from the impervious surface by approximately fifty percent. The model results also show how the total phosphorus from the lot could be reduced to 0.01 lb/yr or lower with increased buffer width and additional raingarden area.

2. Introduction

Development on a lake increases the amount of overland runoff and phosphorus moving to the lake (Graczyk et al., 2003). As more phosphorus enters a lake, more algae and plants grow in the lake. The increase in near-shore runoff can alter near-shore water quality and ultimately changes in phosphorus cycling and biological growth rates throughout the lake. These impacts propagate through aquatic food webs and change the plant and animal communities in the lake.

Quantifying the impacts of shoreland development and the designs to mitigate them is challenging. Changes to near-shore hydrology reflect characteristics of an individual lot. Water flow and phosphorus transport are determined by topography and infiltration characteristics both of which are different on each lot and are modified by development. This report describes a method to estimate the impact of riparian development on phosphorus transfer to lakes and to estimate how infiltration practices can mitigate this transfer. This approach was developed to assist homeowners, resource professionals and designers establish development practices that reduce the impact of land change on the water body.

This report was prepared by Paul McGinley, UW-Stevens Point and a project team that included Dave Ferris and Paul Cook, Emily Moore and Shawn O'Connell, Burnett County Land and Water Conservation Department; Cheryl Clemens, Harmony Environmental; and Carolyn Scholl, Vilas County Land and Water Conservation Department. Comments are appreciated and can be emailed to paul.mcginley@uwsp.edu.

3. Background

The land adjacent to a lake contains large quantities of phosphorus in soil and vegetation (Yanai, 1992). Every year, some of this phosphorus is transferred to the lake. Some is transferred by wind, for example as leaves, pollen and dust, and by water, and some is transferred when precipitation becomes groundwater and runoff and conveys sediment, organic matter or dissolved phosphorus to the lake. This is an important source of phosphorus to lakes as it provides this essential element; however, if the amount of phosphorus transferred is increased, such as through shoreland development, it will increase the growth of algae and plants.

Phosphorus transport from land can increase with changes that redirect precipitation into surface runoff pathways that convey greater quantities of phosphorus to the lake. Previous research has shown surface runoff phosphorus concentrations are between 0.3 and 5 mg/l (Graczyk et al., 2003; Zopp et al., 2019). These concentrations are more than thirty times the typical Wisconsin groundwater phosphorus concentrations (McGinley et al., 2016). When these higher concentrations are combined with increased runoff volumes, it leads to more phosphorus movement to lakes. Research in northern Wisconsin showed developed areas of lakeshore lots can have more water movement across the surface than undeveloped wooded areas (Graczyk et al., 2003). As the runoff volume increases, the amount of phosphorus transferred increases proportionally. Figure 1 summarizes the results of runoff events from Graczyk et al. (2003) showing the runoff phosphorus concentrations were typically between 0.3 and 3 mg/l, but that the amount of phosphorus transported in different runoff events (expressed here as pounds of phosphorus per acre), can vary more than a thousand-fold. This wide range in phosphorus transported reflects the wide range in the volume of runoff between events. They concluded that the most important factor that controlled how much phosphorus was transferred was the amount of runoff volume generated.

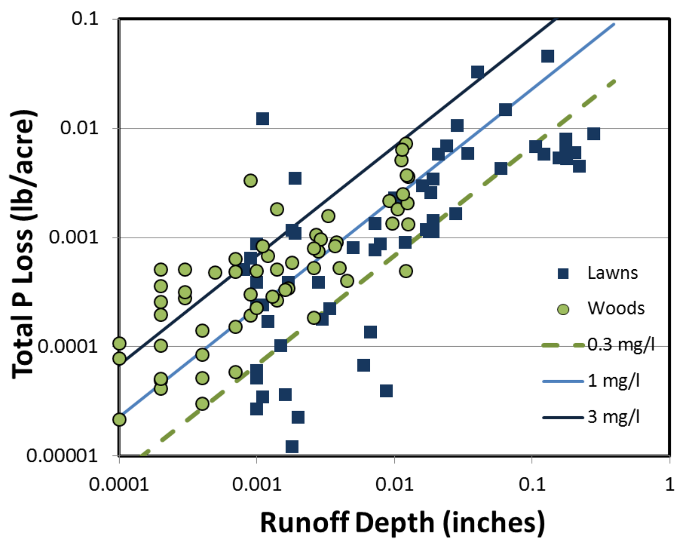

Figure 1. Results from monitoring individual runoff events on both wooded and lawn areas of northern Wisconsin in Graczyk et al. 2003. Total phosphorus transferred downslope increases with runoff volume and most of the runoff events on both lawn and woods have phosphorus concentrations between 0.3 and 3 mg/l.

Modeling runoff volume usually combines a method for estimating runoff generation and a method for describing how that runoff moves across land or through a conveyance system. Methods for runoff generation often start with the amount of precipitation and then subtract the amount of water that is lost to non-runoff processes, such as storage in depressions and infiltration into soil, and the remainder is assumed to become runoff. This calculation can assign depths or rates to these non-runoff processes (e.g., WEPP, P8, SWMM) or by an equation that includes those adjustments directly, such as in the curve number (SWAT) or runoff coefficients (WinSLAMM). Those calculations are typically based on some categorization of the land cover (e.g., parking lot or cropland) and calculated either for a single storm event or for the runoff pattern within the event.

Methods for simulating how the runoff volume moves across land or in a conveyance system depend on the purpose of the modeling. In some cases, the generated runoff volume is assumed to not change during the conveyance because the interest is in the timing and attenuation of the peak flow as it moves through elements of the conveyance. This is important, for example, in small watershed hydrology (e.g., NRCS TR-55) or in urban stormwater modeling (e.g., SWMM) where the peak flow rate is sought to determine an appropriate size for downstream structures or pipes. In other cases, the runoff volume does change during conveyance and models that combine infiltration with conveyance are needed. These models can estimate the time that the water can infiltrate while passing through the conveyance and combine that with an infiltration rate to calculate the volume reduction during conveyance. Examples of these models include the swale in WinSLAMM and P8, or the conduit in SWMM all of which approximate a swale or buffer with an infiltrating surface area and an infiltration rate. The infiltration area and the time within the conveyance can be defined by the geometry of the conveyance system and the resistance to flow (typically represented by a Manning's n value although other resistance formulas have been used). In some models, the infiltration rate is treated as constant rate (i.e., inches/hour) or may be the static infiltration rate halved as a "dynamic infiltration rate" (WDNR Technical Standard for Swales) or it may be described with an infiltration model (e.g., Green-Ampt).

4. Modeling Approach

The modeling approach developed here uses the EPA SWMM Model to calculate a runoff volume from an impervious area and then routes that volume through a series of pervious segments before it is assumed to enter the lake. Figure 2 is a schematic of the model. This approach emphasizes the connection between hydrologic change and runoff from riparian development by focusing on the areas that are likely to generate the most runoff and then trying to estimate how the infiltration characteristics between generation and the lake could reduce that runoff volume. The runoff volume estimated is then converted to a phosphorus quantity by assuming a phosphorus concentration. While the approach cannot include all of the site-specific details, it is an attempt to generalize the most important factors that control runoff volume to understand how a lot may impact phosphorus transfer and help in designing to reduce likely impact.

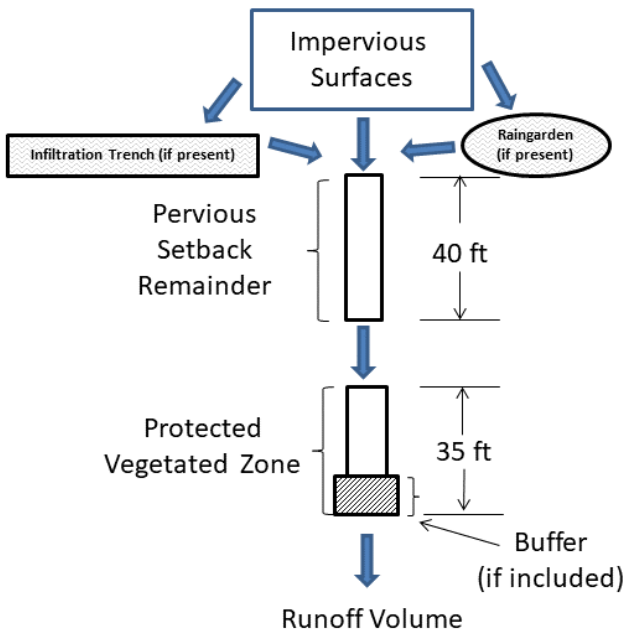

Figure 2. Schematic showing elements of the design approach for estimating the runoff from the impervious surfaces in riparian development. Dimensions shown for the element lengths are those used in the tables included but can be modified when using the model.

The EPA Stormwater Management Model (SWMM) is a continuous simulation model that uses a time series of precipitation to estimate and route runoff. This model was selected because of its ability to network impervious and pervious segments, the flexibility of its inputs, its availability as a publicly shared program and because it is actively used for other stormwater applications. The SWMM User manual provides some discussion of this modeling approach (Rossman and Huber, 2016, p. 60). The

SWMM model has also been used by others to explore the impact of lot-scale infiltration practices on stormwater runoff in urban settings (Yang and Chui, 2018).

The shoreland model developed here uses the result from the SWMM model to provide an estimate of a runoff volume for a set of input conditions. The phosphorus transfer is expressed in pounds per year calculated by multiplying the average annual runoff volume by the assumed average runoff phosphorus concentration of 0.5 mg/l. As shown in Figure 1, measured phosphorus concentrations in runoff can be greater than 0.5 mg/l and consequently, the actual phosphorus transfer may be more than those simulated. For examples shown in this report, the model simulated runoff for thirty-six years (1960-1995) and the results are reported as an average annual phosphorus transfer. Year-to-year variability is also important in phosphorus transfer from the shore. To provide an estimate of the year-to-year variability, the largest annual phosphorus transfer modeled during the 1960-1995 simulation time period is also presented.

Impervious areas are modeled as areas that generate runoff and direct it to a conveyance area. They are modeled simply as areas where all rainfall becomes runoff and no storage of water ("depression storage") is included. During the winter, the model allows snow to accumulate which will then become runoff when the temperature warms. All the runoff is routed to the first downstream pervious area.

The downstream pervious areas have infiltration characteristics that vary with soil type and condition. The infiltration rate and effective size of the pervious area is important to determining the amount of runoff that is infiltrated. Although the model can be used to simulate any runoff length, the baseline simulations in this report use a pervious area length of 35 to 75 feet to include the 75 foot setback based on Wisconsin shoreland zoning regulations and shorter setbacks to be used in describing situations with structures that did not conform to those regulations and situations where runoff generation closer to the lake results from disturbance or development. The pervious is divided into the first forty feet adjacent to the impervious termed the "pervious setback remainder" and the thirty five feet near the lake is the "protected vegetation zone." Runoff from the upstream impervious area is distributed across these pervious areas. The width of the pervious area that is considered available for infiltration was assumed to vary with the slope of the lot. This is a simple attempt to incorporate a site-specific detail into the model. Research on lawn runoff from roof downspouts has shown how widths of the inundation area downstream of a downspout could be three to five feet on loam soils with slopes of 4 to 22% (Mueller and Thompson, 2009). The width is important to determining the "effective infiltration area," where that is the area of the pervious area that infiltrates the water. Slope was included in the pervious areas by both a slope term in the Manning's calculation and by adjusting the width of this effective infiltration area within the pervious corridor. The widths of the effective infiltration areas in these simulations were 10 feet for low slopes less than 5%, 5 feet for 5-20% slope and 2.5 feet for more than 20% slope. These widths were based on the general observation by Mueller and Thompson (2009) showing inundation widths on lawns of 4 to 5 feet on slopes of 4 to 22%. This will depend on the topography of an individual lot and remains an important area for further research.

The model was also used to simulate the potential for runoff generation when the soil is disturbed in the protected vegetation zone and the pervious setback remainder. Traffic, walkways, landscaping and equipment storage lead to modifications of infiltration rates that can generate runoff and lead to phosphorus transfer. Figure 3 shows the schematic of the model used to simulated disturbed corridors near the lake with the dimensions assumed for the model results reported.

In the SWMM model, infiltration on the pervious land area can be described using one of several infiltration models. The modified Green-Ampt infiltration model was used in the simulations that follow. This describes the infiltration with a saturated hydraulic conductivity as the principal characteristic. Saturated hydraulic conductivity rates of 1.8, 0.25 and 0.05 inches/hour were used for high (sand), medium (loamy fine sand) and low (sandy clay loam) infiltration rate soils based on texture-based recommendations in the WDNR technical standards for infiltration (WDNR 1002, 2017) and swales (WDNR 1005, 2017) where the static infiltration rates are divided by 2 to provide a dynamic infiltration rate. In practice, more rapid infiltration can result in soils with higher organic matter content and more soil structure. Research by Gulliver (2016) in highway swales showed the infiltration on grassed slopes was higher than the texture would predict and attributed that to pores from roots and earthworms; however, activities that repeatedly compact soils can also lead to much lower infiltration rates than would be predicted and can be reduced by 10 to 1000-fold with compaction (Startsev and McNabb, 2000; Keller et al., 2021).

5. Results from a Baseline Model

The shoreland development model approach using the EPA SWMM model was used to develop a set of model results for combinations of impervious areas and soil/slope assumptions and infiltration practices with a setback distance from the shore. This “baseline” model uses a lot geometry based on the existing 75 foot setback in the shoreland development requirements in Wisconsin along with several shorter distances to accommodate other situations. These model simulation results are presented in Appendix A. The input model assumptions and files for these simulations are also presented in the Appendices.

One of the most important assumptions in the model is the infiltration rate of the pervious area that receives runoff from the impervious area. The baseline model used the infiltration rates adapted from the WI DNR technical standards of 1.8, 0.25 and 0.05 inches/hour and are characterized in these results as “high”, “medium” and “low.” Although these rates are typically assigned based on soil texture, because soil disturbance can substantially reduce infiltration rates, one option is to move one or two infiltration rate categories lower than the texture-based assumption when the pervious area is disturbed by activity and construction. For example, for a disturbed sandy soil, model results for the medium or low infiltration rate could be used. That was the approach used in the example presented in the first part of this report. More research and measurements on infiltration rates on developed lots would improve these assumptions.

Buffers

Buffers in this modeling approach are existing conditions or improved conditions that infiltrate water downslope from the runoff generating areas. Examples include a portion of the pervious area that provides some ponding or slows flow enough that it allows water to have more time to infiltrate or has a faster infiltration rate because of improved soil structure. Buffers were simulated by assuming a wider pervious area to allow more spreading of flow (10 foot wide effective infiltration area for all simulations), increasing the infiltration rate to describe improved soil structure and complexity of flow within the buffer (the infiltration rate was doubled from the rate in the pervious corridor), increasing the storage within the pervious area (0. 3 inches) and increasing the resistance to flow characterized by a Manning’s n value (0.3). While these changes seem reasonable based on guidance in the SWMM manual and the other references included, more research on the hydrologic behavior of buffers will help improve this modeling in the future.

The results of buffers following pervious setback areas in Appendix A show that reductions can range from 0.01 to 0.03 lb/year. For smaller impervious areas and high infiltration rate soils, the buffer might be able to reduce the modeled phosphorus to a target range (0.01 to 0.001 lb/year) but for larger impervious areas and lower infiltration rate soils, additional infiltration practices would be required to reach that target range.

Rain Gardens

Rain gardens are shallow depressions that allow ponding and infiltration of runoff. These are simulated in the model by directing the runoff from the impervious area to a raingarden and then directing any runoff that overtops the raingarden to the series of pervious land areas. The rate of runoff inflow, geometry of the raingarden and infiltration rate in the raingarden determine the effectiveness of the raingarden

Tables in Appendix A show the benefit of raingardens and how they can reduce the phosphorus transfer by half or more for the baseline case and impervious areas up to 2000 ft^2. Overall, the results show the importance of addressing runoff from the impervious areas prior to it entering the setback and the challenges that low infiltration rates in the setback pose to treating the runoff that does overtop a small raingarden.

Infiltration Trenches

Infiltration trenches are water storage areas created below the ground surface that can hold runoff until it can infiltrate into the soil below. These are simulated in the model by assuming a 24 inch deep rock filled trench with different areas and infiltration rates. In the model simulations for the baseline case in Appendix A, the trench was assumed to be filled with rocks and the storage volume was then the pore space between the rocks. The results show phosphorus reductions that are similar in magnitude and pattern to the raingarden.

6. Summary

The shoreland impact evaluation and mitigation design approach described here is a relatively simple tool to contrast the importance of impervious area and infiltration characteristics of the pervious setback on runoff and phosphorus movement for development in shoreland areas. The method simplifies what is a complex site-specific interaction of precipitation, surfaces and pathways near the lake into several general characteristics that influence water movement. The results from the baseline model show the importance of impervious area size and pervious area infiltration characteristics. Large impervious areas can generate large quantities of runoff that may move through even moderate infiltration rate pervious areas.

An important goal in the development of this model was to start developing a rational basis for estimating phosphorus transfer and designing mitigation strategies for shoreland development. A comparison of the results of the baseline model simulations with the results from shoreland monitoring in Graczyk et al. (2003) and turf monitoring of Bierman et al. (2010) and Steinke et al. (2007) suggest the results of the modeling are providing reasonable estimates of phosphorus transfer; however, the model makes assumptions, such as assuming a runoff phosphorus concentration of 0.5 mg/l and an effective infiltration area that is 2.5 feet wide at steep slopes, that are meant to provide realistic phosphorus transfer values but are not designed to describe "worse case" situations. For example, monitoring has shown how phosphorus concentrations can exceed 0.5 mg/l in runoff, and disturbed pervious areas and high runoff rates can lead to gully formation which would lead to higher phosphorus transfer rates than those simulated. The modeling, and our understanding of the impacts of shoreland development on phosphorus transfer, would benefit from additional research and monitoring.

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