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CURVE NUMBER HYDROLOGY IN WATER QUALITY MODELING: USES, ABUSES, AND FUTURE DIRECTIONS[1]

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ABSTRACT: Although the curve number method of the Natural Resources Conservation Service has been used as the foundation of the hydrology algorithms in many nonpoint source water quality models, there are significant problematic issues with the way it has been implemented and interpreted that are not generally recognized. This usage is based on misconceptions about the meaning of the runoff value that the method computes, which is a likely fundamental cause of uncertainty in subsequent erosion and pollutant loading predictions dependent on this value. As a result, there are some major limitations on the conclusions and decisions about the effects of management practices on water quality that can be supported with current nonpoint source water quality models. They also cannot supply the detailed quantitative and spatial information needed to address emerging issues. A key prerequisite for improving model predictions is to improve the hydrologic algorithms contained within them. The use of the curve number method is still appropriate for flood hydrograph engineering applications, but more physically based algorithms that simulate all streamflow generating processes are needed for nonpoint source water quality modeling. Spatially distributed hydrologic modeling has tremendous potential in achieving this goal.

(KEY TERMS: nonpoint source pollution; curve number; hydrologic modeling; water quality; agricultural hydrology; geographic information systems.)

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INTRODUCTION

The curve number method of the Natural Resources Conservation Service (formerly Soil Conservation Service) has been the foundation of the hydrology algorithms in most simulation models developed by the U.S. Department of Agriculture for hydrology, soil erosion, and nonpoint source water quality. Although it originated as an empirical, event based procedure for flood hydrology, the curve number method has been adapted and used in these models for simulating the runoff behavior of ordinary as well as large rainfalls and daily time series as well as events. Curve number runoff is subsequently used to determine soil erosion and nutrients and pesticides transported off the field and into a stream. In the continuous simulation models, where a soil moisture balance is maintained, the moisture input that is not designated as runoff is considered either to percolate on farther down into the soil or be lost to evapotranspiration, and the curve number is adjusted up or down each day to reflect the increasing or decreasing soil moisture.

The use of curve number in this manner, however, is beset with a number of problems, issues, and misinterpretations that undermine its utility in providing a realistic and accurate representation of the water flow amounts, paths, and source areas upon which erosion and water quality predictions depend. The problem stems from the fact that water quality models are doing much more than just predicting streamflow amounts at the outlet of a watershed, as is the case for a flood hydrology model. Water quality models take the hydrology a major step further, as erosion and pollutant loading predictions require knowledge of whether the water that enters a stream flows over the ground surface or through the soil and where in the watershed this stream water originates. The curve number method was never designed to make these distinctions, and no adaptation of it can ever make it be able to do so.

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At the root of the issue, there appears to be a lack of clarity as to what curve number runoff actually signifies, which has led to its common misinterpretation and use well beyond its realm of applicability. In nonpoint source water quality models, this then compromises the model's ability to simulate erosion and pollutant loadings accurately. Papers continue to be published using curve number based water quality models with essentially no stated critical consideration of the appropriateness of the driving hydrologic algorithms, indicating that these issues are little appreciated.

It is not the intent here to criticize previous studies or to declare them as misapplications or failures of the curve number method. The purpose, rather, is to raise awareness of the underappreciated problematic issues with the curve number procedure and to point to ways in which the hydrology algorithms in nonpoint source water quality models could be and are being improved. Such improvements should result in the advancement of water quality modeling because the processes that drive water quality are themselves primarily driven by hydrologic processes. It is hoped that the clarification of these issues and the discussion of encouraging improvements will provide a cautionary note for model users as well as promote continued progress in model development.

MODELING BACKGROUND

Agricultural nonpoint source water quality models are highlighted here for purposes of illustration since they are well known, they are frequently used, and they use curve number based hydrologic algorithms.

Agricultural Nonpoint Source Water Quality Models

The U.S. Department of Agriculture, particularly the Agricultural Research Service (ARS), has been active in the development of agricultural hydrology, erosion, and water quality models for over two decades now. The Natural Resources Conservation Service (NRCS) has participated in the development of some of these models but is primarily a user of the models. In the early 1990s, NRCS conducted a review of available models and selected five to recommend and support as part of a major water quality initiative. The models are: Groundwater Loading Effects of Agricultural Management Systems, or GLEAMS (Leonard *et al.,* 1987; USDA-ARS, 2004a); Erosion Productivity Impact Calculator or Environmental Policy Integrated Climate, or EPIC (Williams *et al.,* 1984; Williams and Meinardus, 2004); Nitrogen Leaching and Economic Analysis Package, or NLEAP (Shaffer *et al.,* 1991; USDA-ARS, 1999); Soil and Water Assessment Tool, or SWAT (Arnold *et al.,* 1998; USDA-ARS, 2004b); Agricultural Non-Point Source pollution model, or AGNPS (for the new model, see Cronshey and Theurer, 1998; USDA-ARS, 2004c; for the original model, see Young *et al.,* 1989). The first three are point/plot/field scale models, and the last two are watershed scale models. For AGNPS, the original model simulated only storm events, but the new version has been substantially rewritten and is now a continuous simulation model.

These models have been widely used by many investigators worldwide, and there are many papers in the hydrologic literature describing model applications. These are not the only nonpoint source water quality models available, but they represent commonly used ones, particularly for agricultural applications, and they all use the curve number runoff procedure as a fundamental part of the hydrology algorithms.

Curve Number

The curve number procedure was developed in the 1950s by the (then) Soil Conservation Service (SCS) as a simple procedure for estimating streamflow volume (exclusive of base flow) generated by large rain storms. A simple, conceptual procedure was necessary because its development took place before computers were widely available and before geographic information systems (GIS) and extensive spatial data sets on terrain, soils, and vegetation were available. It was, along with some supporting procedures, used primarily for developing design hydrographs for hydraulic structures and conservation work. It is an empirical model containing two parameters – the curve number and the initial abstraction. As typically used, however, the initial abstraction is made to be a function of the curve number, so in reality, it is a one parameter model. Since the procedure was intended to be usable in ungaged watersheds, the model parameter (curve number) was related to soil and vegetation and can be estimated with look-up tables. The primary documentation for the procedure is USDA-SCS (1972). It is also described in most engineering hydrology textbooks, and it was thoroughly reviewed by Ponce and Hawkins (1996). It is assumed that most readers are already familiar with the procedure, so a description of the details is not needed here.

Curve number was used originally in the first water quality models to be developed, and the later ones followed suit. In fact, there has been, understandably, significant sharing of hydrologic algorithms among these models. The reasons for the use of curve number include its simplicity, ease of use, widespread acceptance, and the significant infrastructure and institutional momentum for this procedure within NRCS. To date, there has been no alternative that possesses so many of these advantages, which is why it has been and continues to be commonly used, whether or not it is, in a strict scientific sense, appropriate.

A number of things about the curve number procedure, however, are apparently not well known and have led either to a misinterpretation of its results or its usage well beyond its realm of applicability. There remain issues that existing documentation and reviews have not fully brought to light. Since these issues have been somewhat murky for decades, this paper attempts to define better the scope and applicability of this hydrologic procedure, as a clarification of the past and an informed look into the future.

STREAMFLOW GENERATING PROCESSES

Before proceeding, a little groundwork needs to be laid regarding the various processes that generate streamflow and how these affect water flow paths and source areas. Differentiating among these processes is central to the simulation of erosion and pollutant loading. It should be recognized here at the outset, however, that the curve number method was never intended to differentiate among these processes. This point will be reemphasized and expanded upon in the subsequent discussion.

Precipitation falling on the land surface has several pathways it can follow (Figure 1).

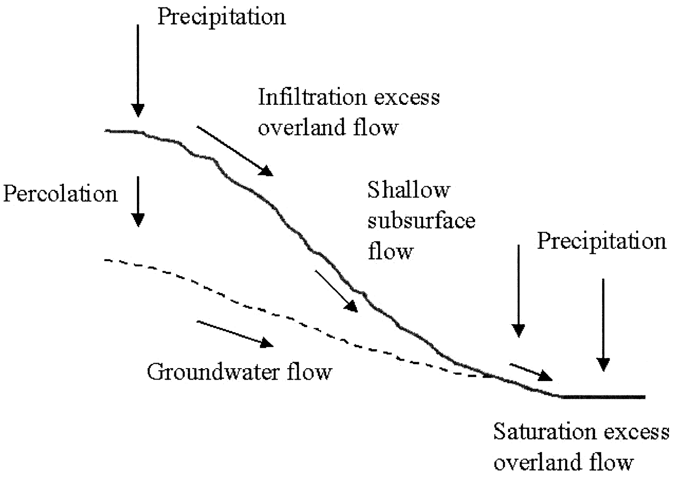

Figure 1. Water Fluxes and Streamflow Generating Processes on a Hillslope Terminating at a Stream Channel. Ground water table shown as dashed line.

Infiltration Excess Overland Flow. Sometimes called Hortonian overland flow in honor of Robert Horton, the hydrologist who identified it, this process occurs when the rainfall intensity exceeds the infiltration capacity of the soil, and the rainfall that cannot be absorbed by the soil runs down the land surface of the hillslope. This is the classic process with which most people are familiar and upon which hydrologic models have traditionally been built. (Some newer models also include all or some of the other processes in this list, but some still only include infiltration excess; many older models that only consider infiltration excess are still in operational use.) This process is what people often implicitly or explicitly assume to generate all streamflow that is not base flow, although this is not necessarily, and probably often, a misconception. This process generates surface flow only during high intensity storms (unless the soil has a very low infiltration capacity, in which case lower intensity storms can also generate surface flow).

Saturation Excess Overland Flow. This occurs where the soil is saturated, in which case any rainfall onto the soil immediately runs off. Water from the saturated soil can also exfiltrate, adding to the surface runoff; this is called return flow. Saturated areas typically form at the base of hillslopes, where soil moisture is high due to downslope movement of subsurface water. This is shown in Figure 1 as the zone where the ground water table intersects the land surface. Such zones tend to form in low spots and in areas of converging topography, where the soil moisture is initially higher than the upper hillslopes, leading to rapid saturation during a storm and a consequent rise of the ground water table. The saturated areas thus expand upslope during a rain storm, increasing the runoff contributing area, then contract afterward as the soil water and groundwater drains away (Figure 2). This process is particularly important where the infiltration capacity of the soil is relatively high, and rain storms are of low to moderate intensity. It is also enhanced if there is bedrock or a layer of low permeability beneath the soil on the hillslopes. This process was first identified in the late 1960s (see, e.g., Dunne, 1978); although this is now well known among the hydrologic research community, it seems still not to be known or understood by many practicing engineers and hydrologists. This is the dominant streamflow generating process during most storms of ordinary intensity. The key characteristic of this process is that the overland flow originates only in certain zones, or partial contributing areas, not over the entire watershed area.

Shallow Subsurface Flow. In some areas, water can flow downslope shallowly within the soil quickly

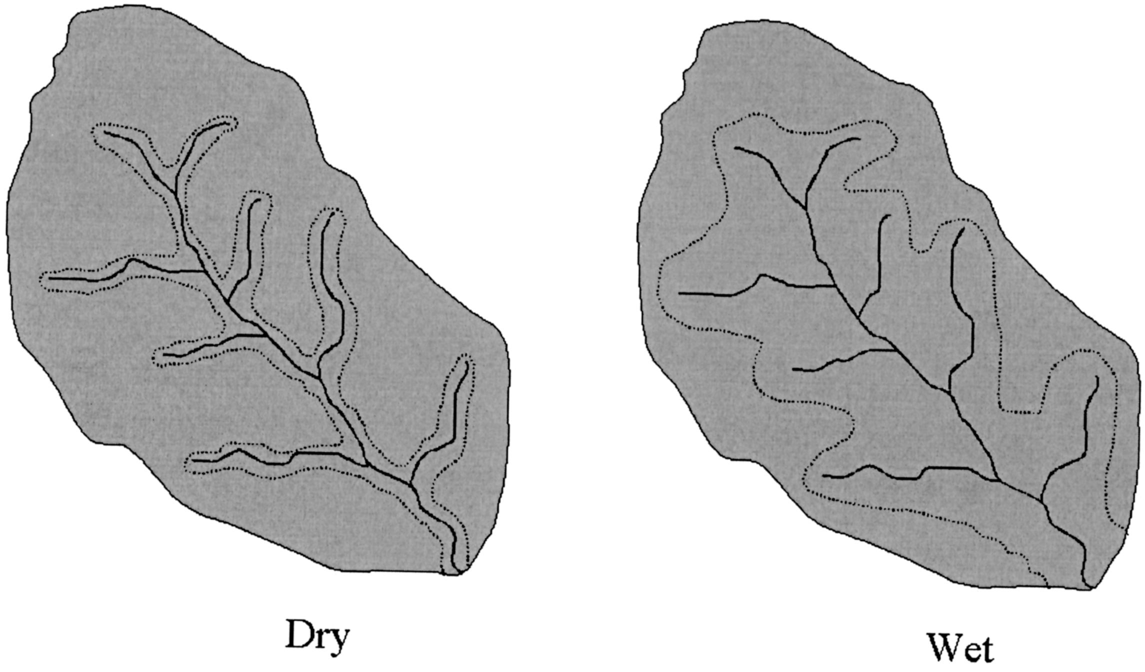

Figure 2. Schematic Representation of Saturated Zones (dashed line) in a Watershed Under Dry and Wet Soil Moisture Conditions.

enough to be considered part of the storm flow. This is often enhanced by the presence of macropores (i.e., preferred pathways for water flow created by the activity of earthworms and burrowing animals as well as by tree roots). Otherwise, this slowly redistributes soil moisture downslope.

Ground Water Flow. This is the water that exfiltrates from the aquifer to the stream. This part of streamflow is often called base flow, as it represents a fairly steady, only slowly changing component of the total flow.

Direct Precipitation Onto Stream Surface. Any precipitation falling directly on the water surface of a stream naturally becomes part of the storm flow. This is generally a small fraction of the total flow volume for small streams.

Percolation. Precipitation absorbed by the soil either remains in the soil matrix, filling its storage capacity, or, if it exceeds the field capacity of the soil, percolates on downward as recharge to the aquifer.

Not shown in Figure 1 is evapotranspiration, which can occur anywhere over the land surface, but which is generally small during a rain storm. A thorough review and discussion of these processes is given by Dunne (1978), although there are many other sources describing them as well. An understanding of these processes is essential to the following discussion of issues regarding the usage and interpretation of curve number runoff.

CURVE NUMBER ISSUES

Definition of the Term "Runoff"

One of the main sources of confusion about the curve number is the definition of exactly what the equation calculates. The confusion lies in the definition of the term "runoff" and the implied streamflow generating process. The term "runoff" is used by hydrologists and engineers to mean streamflow, but in other disciplines, it is taken specifically to mean overland flow, that is, unchannelized water flowing over the surface of the ground. The curve number procedure was designed to predict streamflow, yet in many applications, the value calculated by the equation is interpreted to be overland flow. This implies that only one process is responsible for producing streamflow, namely overland flow. The further implication (seldom explicitly stated, but implied) is that this overland flow is produced by the infiltration excess mechanism and that it occurs over the entire surface area being modeled. This, however, is a misinterpretation of what runoff from the curve number procedure is.

This confusion, then, stems from a misunderstanding of two interrelated things: the spatial scale and the streamflow generating processes involved. If one makes an equivalence between runoff and overland flow with the tacit assumption that the active mechanism is infiltration excess, then one is saying that the curve number procedure can be applied at any spatial scale – point, plot, field, or watershed. This, however, is based on a fundamental misunderstanding of the quantity that the curve number procedure calculates, and it ignores other streamflow generating processes; yet this is exactly what has happened in nonpoint source water quality models based on curve number hydrology.

Spatial Scale and Streamflow Generating Processes

The curve number procedure was developed at the watershed scale, not a point, plot, or field scale. The quantity it calculates is streamflow from a storm (total storm volume minus base flow), with no source area, flow path, or streamflow generating process specified. It is therefore incorrect to imply that the runoff computed is entirely from overland flow, and it is incorrect to imply that this flow is produced only by infiltration excess from all of the land surface considered. This has been clear from the beginning. USDA-SCS (1972) distinguishes four types of runoff (i.e., streamflow): channel runoff (from direct precipitation on stream channels), surface flow, subsurface flow, and base flow. (Their description of surface flow only mentions the infiltration excess mechanism, but this was written before the saturation excess mechanism on partial contributing areas became well known among hydrologists.) They then define "direct runoff" to be a composite of the first three runoff types (i.e., everything but base flow), recognizing that all three do not always occur (or at least are not significant) in all watersheds. The curve number procedure was designed to predict "direct runoff," which means that the quantity calculated is composed of streamflow arising from different mechanisms in unknown proportions, and it is unknown whether this flow is generated from all or only a part of the land area of the watershed. USDA-SCS (1972) goes on to say that there should be a correspondence between the magnitude of the curve number and the mix of surface versus subsurface flow – the higher the curve number, the more surface flow and, by implication, the lower the curve number, the more subsurface flow. Even with surface flow, however, it still does not specify whether this is over the whole land area or only over some saturated partial contributing areas. It is interesting to note in this regard that Victor Mockus, the developer of the curve number method, in later years said that "saturation overland flow was the most likely runoff mechanism to be simulated by the method and not necessarily Hortonian overland flow or crusting" (Ponce, 1996).

The association of curve number runoff exclusively with infiltration excess overland flow is reflected not only in how it is used in models, but it also underlies comparisons that have been made between runoff computed with the curve number procedure and that from the Green-Ampt infiltration model as well as attempts to find an equivalence between curve number and Green-Ampt model parameters (Morel-Seytoux and Verdin, 1981; Rawls and Brakensiek, 1986; Risse *et al.,* 1995; Nearing *et al.,* 1996). The Green-Ampt model is a well known point/plot scale infiltration equation that is used to compute infiltration excess overland flow. This is not the same as curve number runoff, however, and these two models should not be directly compared. They also should not be considered to be interchangeable in their application, as is sometimes believed. For example, Arnold *et al.* (1998) implied this in explaining their choice of curve number instead of an infiltration equation for use in the SWAT model, and Limaye *et al.* (2001) state that "Hortonian processes" are what are "assumed in the modeling strategy" of SWAT. All of these comparisons and statements, therefore, reveal the equivalence that is often made between curve number runoff and infiltration excess overland flow; this, however, is incorrect.

The association of curve number runoff exclusively with infiltration excess overland flow has also led to the use of the curve number procedure in point/plot/field scale water quality models, such as GLEAMS, EPIC, and NLEAP. Not only is it inappropriate, however, to apply the curve number at this spatial scale, as is contended above, but the validity of the whole concept of a point/plot/field scale model must be questioned. The only circumstances under which this scale of model is valid is when the ground surface is completely flat, thereby eliminating any lateral subsurface soil moisture flow, and when it is known *a priori* that the runoff is produced by the infiltration excess mechanism. Otherwise, one cannot consider such a small land parcel in isolation from the surrounding terrain because the moisture balance and runoff behavior of any land parcel is influenced by surface and subsurface moisture flux of the surrounding upslope and downslope land parcels. Furthermore, when the full range of streamflow generating processes is considered, particularly saturation excess overland flow from partial contributing areas, it is clear that a watershed scale approach must be adopted to explain both overland flow from a land parcel and streamflow behavior.

These interpretations and uses of curve number runoff reflect the traditional concept that infiltration excess overland flow is primarily responsible for causing erosion and pollutant loading. While this can be the case, work in the past two decades, however, has demonstrated the importance of other mechanisms of streamflow generation, even in areas that have usually been thought of as being primarily affected by the infiltration excess mechanism. For example, Huang and Laflen (1996) have shown how subsurface flow affects soil moisture and how this subsequently affects the formation of ephemeral gullies in Indiana. Similar conclusions have resulted from studies in Australia (Moore *et al.,* 1988; Barling *et al.,* 1994), The Netherlands (Kwaad, 1991), and Germany (Baade *et al.,* 1993; Baade, 1994). Work in Pennsylvania (Zollweg *et al.,* 1995; Pionke *et al.,* 1996) has shown that saturation excess overland flow from partial contributing areas is largely responsible for phosphorus loading to streams. VanderKwaak and Loague (2001) concluded that the saturation excess mechanism is also a significant streamflow generating process in an Oklahoma watershed where it was previously thought that only infiltration excess was important.

In response to increasing recognition of the streamflow generating process issue, there have been attempts to interpret curve number runoff as saturation excess overland flow from partial contributing areas. Based on knowledge of their test watersheds, Steenhuis *et al.* (1995) and Gburek *et al.* (2002) assumed that the streamflow in their watersheds comes from surface runoff due to precipitation on the expanding and contracting saturated zones and that the curve number runoff comes exclusively from these areas. While this is an important step in recognizing different streamflow generating processes and runoff source areas, an interpretation like this requires *a priori* knowledge that the saturation excess mechanism is primarily responsible for producing the streamflow. This may work in certain watersheds and for certain storms, but it is not a generally applicable procedure. In addition, it ignores rapid subsurface flow, which can also be a significant process, as recent hillslope hydrology research has established (Weiler and McDonnell, 2004). In other words, such interpretations may force the modeler to make explicit assumptions about streamflow generating processes, but it still does not remove the fact that the curve number procedure cannot and never could be used to identify runoff processes, source areas, and flow paths.

Flood Event Versus Continuous Simulation Model

Another issue is the use of the curve number procedure to compute continuous time series of daily runoff and soil moisture balance. This represents a stretch of the procedure beyond its original realm of applicability for two reasons. First, the curve number procedure is an event model, not a continuous simulation model. Although the curve number procedure has been adapted to compute daily flow time series in nonpoint source water quality models, there is no clear justification for doing so. Second, the curve number procedure was developed to predict flood streamflow volumes, not daily flows of ordinary magnitude. This is clearly stated by Mockus (1964, letter to Mr. Orrin Ferris) and USDA-SCS (1972). Again, the justification for using the curve number procedure for ordinary flow magnitudes is questionable. It is interesting to note in this regard that German researchers have realized this point and have developed alternative runoff procedures, of a similar level of complexity, to deal with a full range of flow magnitudes (Lutz, 1984). Grunwald (1997) (see also Grunwald and Frede, 1999), in seeking to apply the original AGNPS model, replaced the curve number procedure with the Lutz procedure and achieved better simulation results. Although the use of the curve number procedure in continuous simulation models can be understood as being motivated by expediency and by a desire to adhere to an already well accepted methodology, it cannot be justified based on the original design of the procedure.

Summary

In summary, the curve number procedure is a one (or two) parameter watershed scale event model that computes streamflow volume (minus base flow) for a storm. It is not specified what streamflow generating process is active or how much of the land area contributes flow. Uses of the procedure outside this realm or interpretations of the computed runoff beyond what is stated here have questionable basis. Treating the curve number runoff as only overland flow from the entire land unit being modeled, as is done in many current nonpoint source water quality models, can, in many cases, be incorrect and can lead to large errors in erosion and pollutant loading calculations.

HYDROLOGIC PROCESS REPRESENTATION NEEDS FOR NONPOINT SOURCE WATER QUALITY MODELING

A prerequisite for improving nonpoint source water quality models is to improve the representation of hydrologic processes in the models. It is likely that a significant reason for prediction inaccuracy in sediment loss and pollutant loading is the inability of curve number hydrology to represent the streamflow generating processes, water flow paths, and contributing areas upon which these calculations depend. Several aspects of this assertion and suggestions for model improvement are discussed below.

What Is Meant That a Model "Works"?

One might question this assertion by saying that these existing nonpoint source water quality models have been used successfully by many authors for years and that the models work. One needs to consider, however, what is really expected of a "successful" model and be clear what is meant that a model "works."

These terms imply that a goal is reached, and they must be interpreted with respect to the goals for the modeling exercise and the decisions to be made from the results. In the context of water quality, models are used to provide information for a wide range of decisions. Some of these are general, broad scale, spatially aggregated decisions, while others are very detailed and site-specific. If model predictions have a great deal of uncertainty, or if the model spatial resolution is coarser than the scale at which decisions need to be made, however, legitimate conclusions based on these predictions are more constrained. Some general decisions may still be made with such guidance, but others would be limited.

The claim is sometimes made that nonpoint source water quality models are not capable of or are not intended to simulate individual events accurately but that they do best and should primarily be used in estimating time-aggregated amounts or long term averages (e.g., Arnold *et al.,* 1998; Jetten *et al.,* 1999). Modelers then claim satisfaction with simulation results despite large errors for individual days or even months, as long as annual or long term average streamflow, sediment yield, and water quality constituents are "adequately" reproduced. This line of reasoning, however, is rather puzzling. First, as modelers, the authors would personally not be satisfied with the high simulation uncertainty of individual time periods reported in many papers (some recent examples include: Srinivasan *et al.,* 1998; Saleh *et al.,* 2000; Spruill *et al.,* 2000; Limaye *et al.,* 2001; Santhi *et al.,* 2001; Kirsch *et al.,* 2002; Van Liew *et al.,* 2003). Based on experience in western water resources forecasting and management, it should be possible, given a model with appropriate process descriptions, to obtain quite accurate streamflow simulations (see, for example, the results of James and Burges, 1982; Wigmosta *et al.,* 1994; Druce, 2001; Thyer *et al.,* 2004). Especially considering that most of the results reported for nonpoint source water quality model streamflow simulations are for time aggregated monthly or annual flows, or even long term average flows, it would be expected that a high degree of accuracy would be obtained, but it has not been. It is quite clear from comparing the calibration and verification results from the two groups of papers cited above that there is a significant difference in the accuracies obtained, and even expected, from the models. The western water resources group seeks quite demanding performance from their models, computing goodness-of-fit statistics such as the coefficient of determination (R^2) or the Nash-Sutcliffe coefficient of efficiency (E) for daily or even hourly time steps and often being dissatisfied with coefficient values less than 0.9. In contrast, the nonpoint source water quality group most often computes goodness-of-fit statistics only for monthly or annual flows, which is much less demanding, and they seem satisfied with coefficient values if they exceed 0.5 or 0.6 (e.g., Santhi *et al.,* 2001); rarely are coefficient values of 0.9 or greater reported. When they do compute daily goodness-of-fit coefficients, they can be very small (e.g., E values of less than 0.2 in Spruill *et al.,* 2000).

Based on these considerations, it is difficult to place a great deal of confidence in long term averages computed from individual time period results with the kinds of errors shown in these nonpoint source water quality papers; this seems very near to getting the right answer for the wrong reason, and it reduces confidence that the model can be relied upon even to give accurate long term averages for different management scenarios. It therefore appears justified to assert that current nonpoint source water quality models have large prediction uncertainties.

It is sometimes stated that, because of this prediction uncertainty, it is more reliable and justifiable to use the relative, rather than absolute, results from erosion and water quality models (e.g., Jetten *et al.,* 1999). That is, one can feel confident that the models will indicate which management scenarios will cause more erosion and pollutant loading than others, but the actual values of sediment loss or pollutant loading simulated by the models are not very reliable. Scientists might recognize this, but, unfortunately, managers may not (although even scientists can be prone to emphasize the successful part of simulations rather than focus on the difficulties). In addition, many decisions to be made require quantitative, not just relative, information; therefore, like it or not, quantitative results are likely to be used to make major policy and investment decisions, ignoring the uncertainty of the model predictions (Garen *et al.,* 1999). The conclusions one can justifiably make based on highly uncertain model results, then, are limited in scope, and great caution must be taken not to make decisions where greater accuracy than is warranted is attributed (knowingly or unknowingly) to the model results. It is also important to recognize the uncertainties involved when using a spatially lumped model to justify decisions about the effect of management practices at a smaller spatial scale (i.e., farm or field) than the model itself.

What Is Now Required of Models?

The effort to control or affect water quality has, in recent years, placed greater demands on modelers and their models. Defendable quantities are being sought for the purpose of benefit/cost assessments and better use of public funds. Models are needed to develop Total Maximum Daily Loads (TMDLs) for watersheds and to provide information for administering water quality trading programs (Greenhalgh and Sauer, 2002). Site-specific information for the design of riparian buffers and information for assessing the cost effectiveness of specific management practices and conservation programs is needed (e.g., the Conservation Effects Assessment Project of the U.S. Department of Agriculture; see USDA-NRCS, 2004). Satisfying these needs requires models quantitatively to estimate nonpoint source pollutant loadings under different management practice scenarios and to identify their source areas. This is a much greater requirement than just computing streamflow, sediment yield, and pollutant loadings at a watershed outlet. That is, it is placing an inherent demand on models to predict spatially distributed phenomena in addition to integrated watershed outputs.

Notable recent efforts along these lines involve modeling phosphorus loadings to surface waters. Zollweg *et al.* (1995) and Pionke *et al.* (1996) have shown that in central Pennsylvania, saturation excess runoff in certain runoff producing zones is largely responsible for phosphorus loading; these results are likely to be true in many other areas as well. For effective phosphorus management, then, water quality models must be able to identify these variable runoff producing zones and be able to simulate the saturation excess process. This point was recognized by Kirsch *et al.* (2002) when they acknowledged that "up to 90 percent of annual phosphorus loss comes from less than 10 percent of the land" (p. 1768) and that "knowing where these critical fields are located is an important part of implementing practical and effective BMP measures" (p. 1768). They also realized, however, that the SWAT model, which they used in their study, cannot specify individual source areas.

The ability of a model to address these more demanding tasks will depend on its ability to simulate all of the active streamflow generating processes and their spatial locations of occurrence. It also implies the use of an appropriate time scale for each process; for example, the infiltration excess mechanism operates at short (less than hourly) time scales, so a daily computational time step is inadequate for this process. Increasing the physical basis of the hydrologic algorithms is important, but unless all of the processes are represented in a model, it will not be generally applicable and therefore be of limited usefulness. For example, even the erosion model Water Erosion Prediction Project, or WEPP (Flanagan and Nearing, 1995; USDA-ARS, 2004d), which contains quite detailed physical erosion process descriptions, does not deal with the saturation excess mechanism, so it can be applied only in areas and for storms where it is known *a priori* that the infiltration excess mechanism is what generated all or most of the streamflow; this is a significant limitation on its widespread application. Comprehensive streamflow generating process descriptions are a must if a model is expected to be generally applicable in a wide range of locations and climates.

Encouraging Developments and a Look to the Future

Spatially distributed hydrologic modeling and hillslope hydrologic processes are areas of a great deal of current research. Although there is still much to be learned about how these processes work and how best to represent them in models, these areas of inquiry have much to offer in the improvement of nonpoint source water quality models, and there are some clear directions that need to be pursued.

One of these directions is to incorporate new algorithms into models to represent streamflow generating processes. The algorithms currently in common use, including the curve number method, were developed before the advent of GIS, before spatial data sets were widely available, and under severe (by today's standards) computing constraints (i.e., limited processing speed and disk storage). These constraints no longer exist, so it is no longer necessary to continue to use hydrologic algorithms (including curve number) that were developed to be functional under these constraints. Hydrologic algorithms need to be reconceptualized to take advantage of all of this new information and computing ability, which allows the physical basis of the algorithms to be increased, in accordance with current understandings of hydrologic processes. It should not be considered satisfactory to use GIS only to make convenient utilities for developing input data for the same old models or for cosmetic purposes such as making attractive user interfaces and data displays (helpful though these are). In addition, there is no real need to continue using the curve number method in some models, because they also require soil physical parameters such as saturated hydraulic conductivity, porosity, etc., which could support a more physically based runoff and soil moisture accounting algorithm, thus making curve number superfluous.

Recent examples in the literature point the way to a better hydrologic basis for nonpoint source water quality models. A very clear example is the effort of Rode and Lindenschmidt (2001). They recognized the importance of having a hydrologic basis that represented all streamflow generating processes, being especially aware of the need to include the usually-neglected saturation excess mechanism, so they replaced the hydrology routine in the (original) AGNPS model with the spatially distributed WaSiM-ETH (Wasserhaushalts-Simulations-Modell Eidgenössische Technische Hochschule Zürich) model of Schulla (1997). This is a comprehensive grid-based water balance and streamflow simulation model; a similar model developed in the United States is the Distributed Hydrology Soil Vegetation Model, or DHSVM, described by Wigmosta *et al.* (1994) and now maintained at the University of Washington (2002). Other good examples of the development and application of water quality models that recognize the importance of different streamflow generating processes and identifying pollutant loading source areas are described by Zollweg *et al.* (1996), Frankenberger *et al.* (1999), and Walter *et al.* (2000). There is a great deal of current research in hillslope hydrologic processes (e.g., Bonell, 1998; Leibundgut *et al.,* 2001; Weiler and McDonnell, 2004), and modelers need to keep abreast of these activities and find ways of incorporating these processes into models.

Another clear direction for developing new hydrologic algorithms is digital terrain analysis. There has been a great deal of development of algorithms for analyzing digital elevation models to derive landscape characteristics of hydrologic significance, such as watersheds, stream networks, saturation indexes, etc.; papers on this topic abound in the literature (e.g., Quinn *et al.,* 1995; Tarboton, 1997), and GIS software now makes such analyses routine and easy. This allows the construction of models and procedures that can account for the effects of topographic configuration (convergence and divergence) and other landscape characteristics on surface and subsurface flow, soil moisture dynamics, etc. These features and phenomena have been shown to be related not only to soil moisture and runoff behavior (e.g., Beven and Kirkby, 1979; Barling *et al.,* 1994) but also to the formation of ephemeral gullies (e.g., Moore *et al.,* 1988) and, as mentioned above, the occurrence of pollutant loading source areas. Not only can such analyses provide a basis for improved hydrologic algorithms, they can also be helpful in and of themselves in the design and siting of conservation management practices (e.g., Buttle, 2002).

The whole area of spatially distributed hydrologic modeling and fully utilizing GIS technology, then, is of unquestionable value in making fundamental improvements in the hydrologic algorithms contained within nonpoint source water quality models. There are, of course, still some scientific issues to be resolved (reflected, for example, in the recent remarks of Beven, 2002, and Jetten *et al.,* 2003), but there has been enough progress in these areas to provide some clear directions.

CONCLUSION

Because of the limitations and misinterpretations of the curve number method as it has been applied in many nonpoint source water quality models, the current generation of models does not adequately account for the full range of streamflow generating processes. As a result, these models have a large uncertainty in their predictions of sediment yield and pollutant loadings, and they do not adequately identify pollutant loading source areas. Therefore, it is justifiable only to rely on these models for certain limited, general decisions that do not require accurate simulation of absolute amounts or detailed spatial identification of source areas. It is crucial for modelers and managers to have these limitations in mind when evaluating the results of simulations from these models.

The key need is to have a hydrologic algorithm that can simulate all of the spatially variable processes that generate streamflow so that flow paths and source areas can be correctly identified. Simply finding algorithms that can predict streamflow at the watershed outlet better than curve number based models is insufficient, although several examples of models used in western water resources applications that can do so have been cited. The real need, however, is for models designed explicitly to represent the different streamflow generating processes at the space and time scales relevant to each process.

Models reported in the literature that have made progress along these lines have also been cited.

These, however, are still research models and have not yet been developed into user friendly packages. The lack of a ready-to-go alternative modeling package, however, does not negate the validity of the issues presented in this paper or the need to raise awareness of them and to point to the directions some researchers have already taken to deal with them. It is hoped that this will encourage practitioners, researchers, and model developers to continue to think about these things and by so doing help build collective motivation to move forward.

In the meantime, one should not be fooled into believing that models with a sophisticated or authoritative appearance can necessarily answer complex questions dependent on detailed spatial and temporal scales or hydrologic processes. If complex questions need to be answered, then one must be realistic and understand that a model based on simple, empirical hydrology cannot answer them. Complex questions will require complex models, which are data and resource intensive; there are no short cuts. If, on the other hand, a simple analysis is all that is really needed or all that can be afforded, then one cannot expect to use the results to address complex questions.

While the use of the curve number method for flood hydrograph engineering is still appropriate, its use in nonpoint source water quality models is questionable. These models must be improved to meet the increasing needs for quantitative evaluation of water quality benefits and evaluation of management practices. This must start with hydrology, as hydrology drives the critical processes. Progress in nonpoint source water quality (including erosion) models will only come by first paying attention to their hydrologic algorithms. By moving away from simplified empirical algorithms, such as the curve number, and moving toward improvement of the physical basis of the algorithms with the help of spatially distributed GIS-based technology, significant progress toward this goal can be realized.

LITERATURE CITED

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams, 1998. Large Area Hydrologic Modeling and Assessment – Part I: Model Development. Journal of the American Water Resources Association (JAWRA) 34(1):73-89.

Baade, J., 1994. Geländeexperiment zur Verminderung des Schwebstoffaufkommens in landwirtschaftlichen Einzugsgebieten. Heft 95, Heidelberger Geographische Arbeiten, Universität Heidelberg, Germany.

Baade, J., D. Barsch, R. Mäusbacher, and G. Schukraft, 1993. Sediment Yield and Sediment Retention in a Small Loess-Covered Catchment in SW-Germany. Zeitschrift für Geomorphologie N.F., Suppl.-Band 92, 217-230.

Barling, R.D., I.D. Moore, and R.B. Grayson, 1994. A Quasi-Dynamic Wetness Index for Characterizing the Spatial Distribution of Zones of Surface Saturation and Soil Water Content. Water Resources Research 30(4):1029-1044.

Beven, K.J., 2002. Towards an Alternative Blueprint for a Physically Based Digitally Simulated Hydrologic Response Modelling System. Hydrological Processes 16:189-206.

Beven, K.J. and M.J. Kirkby, 1979. A Physically Based, Variable Contributing Area Model of Basin Hydrology. Hydrological Sciences Bulletin 24(1):43-69.

Bonell, M., 1998. Selected Challenges in Runoff Generation Research in Forests From the Hillslope to Headwater Drainage Basin Scale. Journal of the American Water Resources Association (JAWRA) 34(4):765-785.

Buttle, J.M., 2002. Rethinking the Donut: The Case for Hydrologically Relevant Buffer Zones. Hydrological Processes 16:3093-3096.

Cronshey, R.G. and F.D. Theurer, 1998. AnnAGNPS – Non-Point Pollutant Loading Model. *In:* Subcommittee on Hydrology of the Interagency Advisory Committee on Water Data. Proceedings of the First Federal Interagency Hydrologic Modeling Conference, Las Vegas, Nevada, Vol. 1, pp. 9-16.

Druce, D.J., 2001. Insights From a History of Seasonal Inflow Forecasting With a Conceptual Hydrologic Model. Journal of Hydrology 249:102-112.

Dunne, T., 1978. Field Studies of Hillslope Flow Processes. *In:* Hillslope Hydrology, M.J. Kirkby (Editor). John Wiley and Sons, Chapter 7, pp. 227-293.

Flanagan, D.C. and M.A. Nearing (Editors), 1995. USDA-Water Erosion Prediction Project: Hillslope Profile and Watershed Model Documentation. NSERL Report No. 10, U.S. Department of Agriculture, Agricultural Research Service, National Soil Erosion Research Laboratory, West Lafayette, Indiana.

Frankenberger, J.R., E.S. Brooks, M.T. Walter, M.F. Walter, and T.S. Steenhuis, 1999. A GIS-Based Variable Source Area Hydrology Model. Hydrological Processes 13:805-822.

Garen, D., D. Woodward, and F. Geter, 1999. A User Agency's View of Hydrologic, Soil Erosion and Water Quality Modelling. Catena 37:277-289.

Gburek, W.J., C.C. Drungil, M.S. Srinivasan, B.A. Needleman, and D.E. Woodward, 2002. Variable-Source Area Controls on Phosphorus Transport: Bridging the Gap Between Research and Design. Journal of Soil and Water Conservation 57(6):534-543.

Greenhalgh, S. and A. Sauer, 2002. Environmental Benefits and Challenges of Trading Water Quality. Water Resources Impact 4(6):5-7.

Grunwald, S., 1997. GIS-gestützte Modellierung des Landschaftswasser- und Stoffhaushaltes mit dem Modell AGNPSm. Band 14, Boden und Landschaft, Justus-Liebig-Universität, Gießen, Germany.

Grunwald, S. and H.-G. Frede, 1999. Using the Modified Agricultural Non-Point Source Pollution Model in German Watersheds. Catena 37:319-328.

Huang, C. and J. M. Laflen, 1996. Seepage and Soil Erosion for a Clay Loam Soil. Soil Science Society of America Journal 60(2):408-416.

James, L.D. and S.J. Burges, 1982. Selection, Calibration, and Testing of Hydrologic Models. *In:* Hydrologic Modeling of Small Watersheds, C.T. Haan *et al.* (Editors). Monograph No. 5, American Society of Agricultural Engineers, St. Joseph, Missouri, pp. 437-472.

Jetten, V., A. de Roo, and D. Favis-Mortlock, 1999. Evaluation of Field-Scale and Catchment-Scale Soil Erosion Models. Catena 37:521-541.

Jetten, V., G. Govers, and R. Hessel, 2003. Erosion Models: Quality of Spatial Predictions. Hydrological Processes 17:887-900.

Kirsch, K., A. Kirsch, and J.G. Arnold, 2002. Predicting Sediment and Phosphorus Loads in the Rock River Basin Using SWAT. Transactions of the American Society of Agricultural Engineers 45(6):1757-1769.

Kwaad, F.J.P.M., 1991. Summer and Winter Regimes of Runoff Generation and Soil Erosion on Cultivated Loess Soils (The Netherlands). Earth Surface Processes and Landforms 16:653-662.

Leibundgut, C., S. Uhlenbrook, and J. McDonnell (Editors), 2001. Runoff Generation and Implications for River Basin Modelling. Band 13, Freiburger Schriften zur Hydrologie, Institut für Hydrologie, Universität Freiburg, Germany.

Leonard, R.A., W.G. Knisel, and D.A. Still, 1987. GLEAMS: Groundwater Loading Effects of Agricultural Management Systems. Transactions of the American Society of Agricultural Engineers 30(5):1403-1418.

Limaye, A.S., T.M. Boyington, J.F. Cruise, A.Bulusu, and E. Brown, 2001. Macroscale Hydrologic Modeling for Regional Climate Assessment Studies in the Southeastern United States. Journal of the American Water Resources Association (JAWRA) 37(3):709-722.

Lutz, W., 1984. Berechnung von Hochwasserabflüssen unter Anwendung von Gebietskenngrössen. Heft 24, Institut für Hydrologie und Wasserwirtschaft, Universität Karlsruhe, Germany.

Moore, I.D., G.J. Burch, and D.H. Mackenzie, 1988. Topographic Effects on the Distribution of Surface Soil Water and the Location of Ephemeral Gullies. Transactions of the American Society of Agricultural Engineers 31(4):1098-1107.

Morel-Seytoux, H.J. and J.P. Verdin, 1981. Extension of the Soil Conservation Service Rainfall-Runoff Methodology for Ungaged Watersheds. Report No. FHWA/RD-81/060, Federal Highway Administration, Washington, D.C.

Nearing, M.A., B.Y. Liu, L.M. Risse, and X. Zhang, 1996. Curve Numbers and Green-Ampt Effective Hydraulic Conductivities. Water Resources Bulletin 32(1):125-136.

Pionke, H.B., W.J. Gburek, A.N. Sharpley, and R.R. Schnabel, 1996. Flow and Nutrient Export Patterns for an Agricultural Hill-Land Watershed. Water Resources Research 32(6):1795-1804.

Ponce, V.M., 1996. Notes of my conversation with Vic Mockus. *Available at* http://mockus.sdsu.edu. *Accessed in* April 2003.

Ponce, V.M. and R.H. Hawkins, 1996. Runoff Curve Number: Has It Reached Maturity? Journal of Hydrologic Engineering 1(1):11-19.

Quinn, P.F., K.J. Beven, and R. Lamb, 1995. The ln(a/tanb) Index: How to Calculate It and How to Use It Within the TOPMODEL Framework. Hydrological Processes 9:161-182.

Rawls, W.J. and D.L. Brakensiek, 1986. Comparison Between Green-Ampt and Curve Number Runoff Predictions. Transactions of the American Society of Agricultural Engineers 29(6):1597-1599.

Risse, L.M., B.Y. Liu, and M.A. Nearing, 1995. Using Curve Numbers to Determine Baseline Values of Green-Ampt Effective Hydraulic Conductivities. Water Resources Bulletin 31(1):147-158.

Rode, M. and K.-E. Lindenschmidt, 2001. Distributed Sediment and Phosphorus Transport Modeling on a Medium Sized Catchment in Central Germany. Physics and Chemistry of the Earth (Part B) 26(7-8):635-640.

Saleh, A., J.G. Arnold, P.W. Gassman, L.M. Hauck, W.D. Rosenthal, J.R. Williams, and A.M.S. McFarland, 2000. Application of SWAT for the Upper North Bosque River Watershed. Transactions of the American Society of Agricultural Engineers 43(5):1077-1087.

Santhi, C., J.G. Arnold, J.R. Williams, W.A. Dugas, R. Srinivasan, and L.M. Hauck, 2001. Validation of the SWAT Model on a Large River Basin With Point and Nonpoint Sources. Journal of the American Water Resources Association (JAWRA) 37(5):1169-1188.

Schulla, J., 1997. Hydrologische Modellierung von Flussgebieten zur Abschätzung der Folgen von Klimaänderungen. Heft 69, Zürcher Geographische Schriften, Geographisches Institut, Eidgenössische Technische Hochschule (ETH) Zürich, Switzerland.

Shaffer, M.J., A.D. Halvorson, and F.J. Pierce, 1991. Nitrate Leaching and Economic Analysis Package (NLEAP): Model Description and Application. *In:* Managing Nitrogen for Groundwater Quality and Farm Profitability, R.F. Follett *et al.* (Editors). Soil Science Society of America, Madison, Wisconsin, pp. 285-322.

Spruill, C.A., S.R. Workman, and J.L. Taraba, 2000. Simulation of Daily and Monthly Stream Discharge From Small Watersheds Using the SWAT Model. Transactions of the American Society of Agricultural Engineers 43(6):1431-1439.

Srinivasan, R., T.S. Ramanarayanan, J.G. Arnold, and S.T. Bednarz, 1998. Large Area Hydrologic Modeling and Assessment – Part II: Model Application. Journal of the American Water Resources Association (JAWRA) 34(1):91-101.

Steenhuis, T.S., M. Winchell, J. Rossing, J.A. Zollweg, and M.F. Walter, 1995. SCS Runoff Equation Revisited for Variable-Source Runoff Areas. Journal of Irrigation and Drainage Engineering 121(3):234-238.

Tarboton, D.G., 1997. A New Method for the Determination of Flow Directions and Upslope Areas in Grid Digital Elevation Models. Water Resources Research 33(2):309-319.

Thyer, M., J. Beckers, D. Spittlehouse, Y. Alila, and R. Winkler, 2004. Diagnosing a Distributed Hydrologic Model for Two High-Elevation Forested Catchments Based on Detailed Stand- and Basin-Scale Data. Water Resources Research 40, W01103, doi: 10.1029/2003WR002414.

University of Washington, 2002. Distributed Hydrology Soil Vegetation Model. Land Surface Hydrology Research Group. *Available at* http://www.hydro.washington.edu/Lettenmaier/Models/DHSVM/index.htm. *Accessed in* December 2004.

USDA-ARS (U.S. Department of Agriculture-Agricultural Research Service), 1999. NLEAP. Great Plains System Research Unit, Agricultural Research Service, U.S. Department of Agriculture. *Available at* http://gpsr.ars.usda.gov/products/nleap/nleap.htm. *Accessed in* December 2004.

USDA-ARS (U.S. Department of Agriculture-Agricultural Research Service), 2004a. GLEAMS Y2K Update. Southeast Watershed Research Laboratory, Agricultural Research Service, U.S. Department of Agriculture. *Available at* http://sacs.cpes.peachnet.edu/sewrl/Gleams/gleams_y2k_update.htm. *Accessed in* December 2004.

USDA-ARS (U.S. Department of Agriculture-Agricultural Research Service), 2004b. Soil and Water Assessment Tool: SWAT. Grassland Soil and Water Research Laboratory, Agricultural Research Service, U.S. Department of Agriculture. *Available at* http://www.brc.tamus.edu/swat. *Accessed in* December 2004.

USDA-ARS (U.S. Department of Agriculture-Agricultural Research Service), 2004c. AGNPS. National Sedimentation Laboratory, Agricultural Research Service, U.S. Department of Agriculture. *Available at* http://msa.ars.usda.gov/ms/oxford/nsl/AGNPS.html. *Accessed in* December 2004.

USDA-ARS (U.S. Department of Agriculture-Agricultural Research Service), 2004d. WEPP Software: Water Erosion Prediction Project. National Soil Erosion Research Laboratory, Agricultural Research Service, U.S. Department of Agriculture. *Available at* http://topsoil.nserl.purdue.edu/nserlweb/weppmain/wepp.html. *Accessed in* December 2004.

USDA-NRCS (U.S. Department of Agriculture-Natural Resources Conservation Service), 2004. Conservation Effects Assessment Project. Natural Resources Conservation Service, U.S. Department of Agriculture. *Available at* http://www.nrcs.usda.gov/technical/nri/ceap. *Accessed in* December 2004.

USDA-SCS (U.S. Department of Agriculture-Soil Conservation Service), 1972. SCS National Engineering Handbook, Section 4, Hydrology. Chapter 10, Estimation of Direct Runoff From Storm Rainfall. U.S. Department of Agriculture, Soil Conservation Service, Washington, D.C., pp. 10.1-10.24.

Van Liew, M.W., J.G. Arnold, and J.D. Garbrecht, 2003. Hydrologic Simulation on Agricultural Watersheds: Choosing Between Two Models. Transactions of the American Society of Agricultural Engineers 46(6):1539-1551.

VanderKwaak, J.E. and K. Loague, 2001. Hydrologic-Response Simulations for the R-5 Catchment With a Comprehensive Physics-Based Model. Water Resources Research 37(4):999-1013.

Walter, M.T., M.F. Walter, E.S. Brooks, T.S. Steenhuis, J. Boll, and K. Weiler, 2000. Hydrologically Sensitive Areas: Variable Source Area Hydrology Implications for Water Quality Risk Assessment. Journal of Soil and Water Conservation 55(3):277-284.

Weiler, M. and J. McDonnell, 2004. Virtual Experiments: A New Approach for Improving Process Conceptualization in Hillslope Hydrology. Journal of Hydrology 285:3-18.

Wigmosta, M.S., L.W. Vail, and D.P. Lettenmaier, 1994. A Distributed Hydrology-Vegetation Model for Complex Terrain. Water Resources Research 30(6):1665-1679.

Williams, J. and A. Meinardus, 2004. EPIC. *Available at* http://www.brc.tamus.edu/epic. *Accessed in* December 2004.

Williams, J.R., C.A. Jones, and P.T. Dyke, 1984. A Modeling Approach to Determining the Relationship Between Erosion and Soil Productivity. Transactions of the American Society of Agricultural Engineers 27(1):129-144.

Young, R.A., C.A. Onstad, D.D. Bosch, and W.P. Anderson, 1989. AGNPS: A Nonpoint-Source Pollution Model for Evaluating Agricultural Watersheds. Journal of Soil and Water Conservation 44(2):168-173.

Zollweg, J.A., W.J. Gburek, H.B. Pionke, and A.W. Sharpley, 1995. GIS-Based Delineation of Source Areas of Phosphorus With Agricultural Watersheds of the Northeastern USA. *In:* Modelling and Management of Sustainable Basin-Scale Water Resource Systems, S. P. Simonovic *et al.* (Editors). IAHS Publication No. 231, International Association of Hydrological Sciences, Wallingford, United Kingdom, pp. 31-39.

Zollweg, J.A., W.J. Gburek, and T.S. Steenhuis, 1996. SMoRMod – A GIS-Integrated Rainfall-Runoff Model. Transactions of the American Society of Agricultural Engineers 39(4):1299-1307.