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Modeling of Nonpoint Source Water Quality in Urban and Non-urban Areas

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Foreword

As environmental controls become more costly to implement and the penalties of judgment errors become more severe, environmental quality management requires more efficient analytical tools based on greater knowledge of the environmental phenomena to be managed. As part of this Laboratory's research on the occurrence, movement, transformation, impact, and control of environmental contaminants, the Assessment Branch develops management and engineering tools to help pollution control officials address environmental problems.

Pollutants in runoff and seepage from urban, agricultural, and forested areas contribute significantly to water pollution problems in many areas of the United States. The development and application of computer-operated mathematical models to simulate the movement of pollutants and thus to anticipate environmental problems has been the subject of extensive research by government agencies, universities, and private companies for many years. This review and model-selection guidance document was developed under the direction of EPA's Office of Water and Office of Research and Development to assist water quality planners in applying modeling techniques to the development of cost-effective nonpoint source controls.

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Abstract

Nonpoint source assessment procedures and modeling techniques are reviewed and discussed for both urban and non-urban land areas. Detailed reviews of specific methodologies and models are presented, along with overview discussions focussing on urban methods and models, and on non-urban (primarily agricultural) methods and models. Simple procedures, such as constant concentration, regression, statistical, and loading function approaches are described, along with complex models such as SWMM, HSPF, STORM, CREAMS, SWRRB, and others. Brief case studies of ongoing and recently completed modeling efforts are described. Recommendations for nonpoint runoff quality modeling are presented to elucidate expected directions of future modeling efforts. This work was performed as Work Assignment No. 29 under EPA Contract No. 68-03-3513 with AQUA TERRA Consultants. Work was complete as of March 1990.

Contents

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Dr. Wayne Huber of the University of Florida performed the urban model review, and Mr. Anthony Donigian of AQUA TERRA Consultants performed the review of the non-urban models. Both authors reviewed the entire report. Mr. Avinash Patwardhan assisted Mr. Donigian with the information gathering and review of the non-urban models. Also, the draft final report was peer reviewed by Dr. Vladimir Novotny of Milwaukee, Wisconsin; and Dr. Matt C. Smith of the University of Georgia, Athens, Georgia. Their insightful comments and suggestions were sincerely appreciated.

Section 1.0

Nonpoint Source Modeling Objectives and Considerations

Studies and projects involving stormwater runoff quality from all categories of land useCurban, agricultural cropland, pasture, forestCcan relate to many environmental problems. In the broadest sense, water quality studies may be performed to protect the environment under various state and federal legislation. For example, Section 304(l) of the Clean Water Act requires States to identify waterbodies impaired by both point and nonpoint source pollution and develop appropriate control strategies; while Section 405 will eventually require analysis of stormwater outfalls in all urban areas in the U.S. In a narrower sense, a study may address a particular water quality issue in a particular receiving water, such as bacterial contamination of a beach, release of oxygen demanding material into a stream or river, unacceptable aesthetics of an open channel receiving urban and non-urban runoff, eutrophication of a lake, contamination of basements from surcharged sewers due to wet-weather flooding, etc.

By no means should it be assumed that every water quality problem requires a water quality modeling effort. Some problems may be mostly hydraulic in nature, e.g., the basement flooding problem. That is, the solution may often reside primarily in a hydrologic or hydraulic analysis in which the concentration or load of pollutants is irrelevant. In some instances, local or state regulations may prescribe a nominal Asolution@ without recourse to any water quality analysis as such. For example, stormwater runoff in Florida is considered Acontrolled@ through retention or detention with filtration of the runoff from the first inch of rainfall for areas of 100 acres or less. Other problems may be resolved through the use of measured data without the need to model. In other words, many problems do not require water quality modeling at all.

If a problem does require modeling, specific modeling objectives will need to be defined to guide the modeling exercise and approach. Models may be used for objectives such as the following:

1. Characterize runoff quantity and quality as to temporal and spatial detail, concentration/load ranges, etc.

2. Provide input to a receiving water quality analysis, e.g., drive a receiving water quality model.

3. Determine effects, magnitudes, locations, combinations, etc. of control options.

4. Perform frequency analysis on quality parameters, e.g., to determine return periods of concentrations/loads.

5. Provide input to cost-benefit analyses.

Objectives 1 and 2 characterize the magnitude of the problem, and objectives 2 through 5 are related to the analysis and solution of the problem. Computer models allow some types of analysis, such as frequency analysis, to be performed that could rarely be performed otherwise since periods of water quality measurements are seldom very long. It should always be borne in mind, however, that use of measured data is usually preferable to use of simulated data, particularly for objectives 1 and 2 in which accurate concentration values are needed. In general, models are *not* good substitutes for good field sampling programs. On the other hand, models can sometimes be used to extend and extrapolate measured data.

Careful consideration should be given to objective number 2. The first urban runoff quality model (SWMM) inadvertently overemphasized the concept of simulation of detailed intra-storm quality variations, e.g., production of a Apollutograph@ (concentration vs. time) at 5 or 10 minute intervals during a storm for input to a receiving water quality model. The early agricultural runoff quality models (e.g., ARM and ACTMO models) followed a similar detailed approach primarily to evaluate and demonstrate the models' abilities to represent observed data from small (less than 10 hectare) monitored fields.

But the fact is that the quality response of most receiving waters is insensitive to such short-term variations, as illustrated in Table 1. In most instances, the total storm load will suffice to determine the receiving water response, eliminating the necessity of becoming embroiled in calibration against detailed pollutographs especially for conventional pollutants. Instead, only the total storm loads need be matched, a much easier task. Exceptions to this general observation may be appropriate when considering *toxic* pollutants, e.g., pesticides, when short-term concentrations may be lethal to aquatic organisms. Also, simulation of short time increment changes in concentrations and loads is generally necessary for analysis of control options, such as storage or high-rate treatment, whose efficiency may depend on the transient behavior of the quality constituents.

Any consideration of water quality modeling means that some additional data will be required for model input. As described later, such requirements may be as simple as a constant concentration, or much more complex such as soil nitrification or mineralization rates. Data may be obtained from existing studies or their acquisition may require extensive field monitoring. For some conceptualizations of the urban quality cycle, e.g., buildup and washoff, it may not be routinely possible to physically measure fundamental input parameters, and such parameters will only be obtained through model calibration. Involvement in acquisition of quality data, be it through literature reviews or field surveys, profoundly escalates the level of effort required for the study. Details on data requirements for modeling will be deferred until modeling techniques are described.

Table 1. Required temporal detail for receiving water analysis

(After Driscoll, 1979, and Hydroscience, 1979)

Type of Receiving Water	Key Constituents	Response Time
Lakes, Bays	Nutrients	Weeks–Years
Estuaries	Nutrients, OD* Bacteria	Days–Weeks
Large Rivers	OD, Nitrogen	Days
Streams	OD, Nitrogen	Hours–Days
	Bacteria	Hours
Ponds	OD, Nutrients	Hours–Weeks
Beaches	Bacteria	Hours

*OD = oxygen demand, e.g., BOD, that affects dissolved oxygen.

Section 2.0

Overview of Nonpoint Source Quality Modeling

2.1 Modeling Fundamentals

Modeling caveats and an introduction to modeling are presented by several authors including James and Burges (1982), Kibler (1982), Huber (1985, 1986) and summarized in a recent manual of practice (WPCF, 1989). Space does not permit a full presentation here; a few items are highlighted below.

1. Have a clear statement of project objectives. Verify the need for quality modeling. (Perhaps the objectives can be satisfied without quality modeling).

2. Use the simplest model that will satisfy the project objectives. Often a screening model, e.g., regression or statistical, can determine whether more complex simulation models are needed.

3. To the extent possible, utilize a quality prediction method consistent with available data. This would ordinarily rule against buildup-washoff formulations, although these might still be useful for detailed simulation, especially if calibration data exist.

4. Only predict the quality parameters of interest and only over a suitable time scale. That is, storm event loads and EMCs will usually be the most detailed prediction necessary, and seasonal or annual loads will sometimes be all that is required. Do not attempt to simulate intra-storm variations in quality unless it is necessary.

5. Perform a sensitivity analysis on the selected model and familiarize yourself with the model characteristics.

6. If possible, calibrate and verify the model results. Use one set of data for calibration and another independent set for verification. If no such data exist for the application site, perhaps they exist for a similar catchment nearby.

2.2 Operational Models

Implementation of an off-the-shelf model or method will be easiest if the model can be characterized as Aoperational@ in the sense of:

1. Documentation. This should include a user's manual, explanation of theory and numerical procedures, data needs, data input format, etc. Documentation most often separates the many computerized procedures found in the literature from a model that can be accessed and easily used by others.

2. Support. This is sometimes provided by the model developer but often by a federal agency such as the HEC or EPA.

3. Experience. Every model must be used a Afirst time@ but it is best to rely on a model with a proven track record.

The models described in Sections 3.0 and 4.0 are all operational in this sense. New methods and models are constantly under development and should not be neglected simply because they lack one of these characteristics, but the user should be aware of potential difficulties if any characteristic is lacking.

2.3 Surveys and Reviews of Nonpoint Source Models

Several publications, often somewhat out of date, provide reviews of available models. Some models (e.g., SWMM, STORM, HSPF, CREAMS) have persisted for many years and are included in both older and newer reviews, while other models (e.g., USGS, Statistical, spreadsheet, AGNPS, SWRRB) are more recent. Reviews that consider surface runoff quality models include Huber and Heaney (1982), Kibler (1982), Whipple et al. (1983), Barnwell (1984, 1987), Huber (1985, 1986), Donigian and Beyerlein (1985), Bedient and Huber (1988), and Viessman et al. (1989). HEC models are described in detail by Feldman (1981). Descriptions of EPA nonpoint source water quality models are provided by Ambrose et al. (1988) and Ambrose and Barnwell (1989). Selected pesticide runoff models have been reviewed by Mulkey et al. (1986) and Lorber and Mulkey (1982). Agricultural nonpoint source models have been showcased in a number of conferences and symposia over the past few years, including a 1983 Symposium on Natural Resources Modeling (DeCoursey, 1985); a 1984 Conference on Agricultural Nonpoint source Pollution: Model Selection and Application, in Venice, Italy (Giorgini and Zingales, 1986); and a June 1988 International Symposium on Water Quality Modeling of Agricultural Nonpoint Sources (DeCoursey, In Press). Beasley and Thomas (1989) describe recent model enhancements and applications for five selected models to agricultural and forested watersheds in the southeastern U.S. These reports and proceedings provide a wealth of information on current efforts and recent developments in modeling nonpoint contributions and water quality impacts of agricultural activities.

2.4 Summary of Data Needs

In application of most models, there are two fundamental types of data requirements. First, there are the data needed simply to make the model function, that is, input parameters and timeseries data for the model. These typically include precipitation (rainfall) and other meteorologic information, drainage area, imperviousness, runoff coefficient and other quantity prediction parameters, plus quality prediction parameters such as constant concentration, constituent median and CV, regression relationships, buildup and washoff parameters, soil/chemical characteristics, partition coefficients, reaction rates, etc. In other words, each mode will have a fundamental list of required input data. Although it is difficult to generalize for the entire universe of both simple and complex nonpoint source models, Novotny and Chesters (1981) have prepared a summary table of required input data from which Table 2 was adapted.

The second type of information is required for calibration and verification of more complex models, namely, sets of measured runoff and quality samples (coincident with the input precipitation and meteorologic data) with which to test the model. Such data exist (e.g., Huber et al., 1982; Driver et al. (1985), Noel et al., 1987) but seldom for the site of interest. If the project objectives absolutely require such data (e.g., if a model must be calibrated in order to drive a receiving water quality model), then expensive local monitoring may be necessary.

This summary relates primarily to *quality* prediction and may not represent a comprehensive statement of data needs for *quantity* prediction. However, since rainfall and runoff are required for virtually every study, certain quantity-related parameters are also necessary for various methods.

Table 2. Input data needs for nonpoint source models

(after Novotny and Chesters, 1981)

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1. System Parameters
   a. Watershed Size
   b. Subdivision of the Watershed into Homogenous Subareas
   c. Imperviousness of Each Subarea
   d. Slopes
   e. Fraction of Impervious Areas Directly Connected to a Channel
   f. Maximum Surface Storage (depression plus interception storage)
   g. Soil Characteristics Including Texture, Permeability, Erodibility, and Composition
   h. Crop and Vegetation Cover
   i. Curb Density or Street Gutter Length
   k. Sewer System or Natural Drainage Characteristics

2. State Variables
   a. Ambient Temperature
   b. Reaction Rate Coefficients
   c. Adsorption/Desorption Coefficients
   d. Growth Stage of Crops
   e. Daily Accumulation Rates of Litter
   f. Traffic Density and Speed
   g. Potency Factors for Pollutants (pollutant strength on sediment)
   h. Solar Radiation (for some models)

3. Input Variables
   a. Precipitation
   b. Atmospheric Fallout
   c. Evaporation Rates

Section 3.0

Overview of Available Urban Modeling Options

3.1 Introduction

Several quality modeling options exist for simulation of quality in urban storm and combined sewer systems. These have been reviewed by Huber (1985; 1986) and range from simple to involved, although some Asimple@ methods, e.g., the EPA statistical methods, can incorporate quite sophisticated concepts. The principal methods available to the contemporary engineer are outlined below, in a rough order of complexity. Their data requirements are summarized in Table 3. The methods are:

1. Constant concentration
2. Spreadsheet
3. Statistical
4. Rating curve or regression
5. Buildup / washoff

3.2 Constant Concentration or Unit Loads

As its name implies, all runoff is assumed to have the same, constant concentration for a given pollutant. At its very simplest, an annual runoff volume can be multiplied by a concentration to produce an annual runoff load. However, this option may be coupled with a hydrologic model, wherein loads (product of concentration and flow) will vary if the model produces variable flows. This option may be quite useful because it may be used with any hydrologic or hydraulic model to produce loads, merely by multiplying by the constant concentration. For instance, the highly sophisticated SWMM Extran Block may be used for hydraulic analysis of sewer system, prediction of overflows and diversions to receiving waters, etc., yet it performs no quality simulation as such. In many instances, it may be most important to get the volume and timing of such overflows and diversions correctly, and simply estimate loads by multiplying by a concentration.

An obvious question is what (constant) concentration to use? The EPA NURP studies (EPA, 1983) have produced a large and invaluable data base from which to select numbers, but the 30 city coverage of NURP will most often not include a site representative of the area under study. Nonetheless, a large data base does exist from which to review concentrations. Another option is to use measured values from the study area. This might be done from a limited sampling program. However, the NURP study conclusively demonstrated the variation that exists in event mean concentrations (EMCs, total storm event load divided by total storm event runoff volume) at a site, within a city, and within a region or the country as a whole. Thus, while use of a constant concentration may produce *load* variations, EMC variations will not be replicated. These variations may be important in the study of control options and receiving water responses.

Unit loads are perhaps an even simpler concept. These consist of values of mass per area per time, typically lb / ac-yr or kg / ha-yr, for various pollutants, although other normalizations such as lb / curb-mile are sometimes encountered. Annual (or other time unit) loads are thus produced upon multiplication by the contributing area. Such loadings are obviously highly site-specific and depend upon both demographic and hydrologic factors. They must be based on an average or Atypical@ runoff volume and cannot vary from year to year, but they can conveniently be subject to reduction by best management practices (BMPs), if the BMP effect is known. Although early EPA references provide some information for various land used (EPA, 1973; EPA, 1976a; McElroy et al., 1976), unit loading rates are exceedingly variable and difficult to transpose from one area to another. Constant concentrations can sometimes be used for this purpose, since mg / 1 x 0.2265 = lb / ac per inch of runoff. Thus, if a concentration estimate is available, the annual loading rate, for example, may be calculated by multiplying by the inches per year of runoff. Finally, the Universal Soil Loss Equation (Wischmeier and Smith, 1978; Heaney et al., 1975) was developed to estimate tons per acre per year of sediment loss from land surfaces. If a pollutant may be considered as a fraction (Apotency factor@) of suspended solids concentration or load, this offers another option for prediction of annual loads. Lager et al. (1977), Manning et al. (1977) and Zison (1980) provide summaries of such values.

3.3 Spreadsheets

Microcomputer spreadsheet software, e.g., Lotus, Quattro, Excel, is now ubiquitous in engineering practice. Very extensive and highly sophisticated engineering analysis is routinely implemented on spreadsheets, and water quality simulation is no exception. In essence, the spreadsheet may be used to automate and extend the concept of the constant concentration idea. In the usual manifestation of this spreadsheet application, runoff volumes are calculated very simplistically, usually using a runoff coefficient times a rainfall depth. The coefficient may vary according to land use, or an SCS procedure may be used, but the hydrology is inherently simplistic in the spreadsheet predictions. The runoff volume is then multiplied by a constant concentration to predict runoff loads. The advantage of the spreadsheet is that a mixture of land uses (with varying concentrations) may easily be simulated, and an overall load and flow-weighted concentration obtained from the study area (Walker et al., 1989). The study area itself may range from a single catchment to an entire urban area. The relative contributions of different land uses may be easily identified, and handy spreadsheet graphics tools used for display of the results.

As an enhancement, control options may be simulated by application of a constant removal fraction for an assumed BMP. Although spreadsheet computations can be amazingly complex, BMP simulation is rarely more complicated than a simple removal fraction because anything further would require simulation of the dynamics of the removal device (e.g., a wet detention pond), which is usually beyond the scope of the hydrologic component of the spreadsheet model. Nonetheless, if simple BMP removal fractions can be believed, the spreadsheet can easily be used to estimate the effectiveness of control options. Loads with and without controls can be estimated and problem areas, by contributing basin and land use, can be determined. Since most engineers are familiar with spreadsheets, such models can be developed in-house in a logical manner.

The spreadsheet approach is best suited to estimation of long-term loads, such as annual or seasonal, because very simple prediction methods generally perform better over a long averaging time and poorly at the level of a single storm event. Hence, although the spreadsheet could be used at the microscale (at or within a storm event) it is most often applied for much longer time periods. It is harder to obtain the variation of predicted loads and concentrations using the spreadsheet method because this can ordinarily only be done by varying the input concentrations or rainfall values. A Monte Carlo simulation may be attempted (i.e., systematic variation of all input parameters according to an assumed frequency distribution) if the number of such parameters is not too large. These results may then be used to estimate the range and/or frequency distribution of predicted loads and concentrations.

In a generic sense, the spreadsheet idea may be used in methods programmed in other languages, e.g., Fortran. For example, comprehensive assessments of coastal zone pollution from urban areas are made by NOAA (1987) by assembling land use data with different runoff coefficients, predicting daily and seasonal runoff volumes from daily rainfall, and predicting seasonal pollutant loads using constant concentrations. Although the demographic data base and use of magnetic tapes may dictate use of mainframes, the computational concept is still that of a spreadsheet.

Again, the question arises of what concentrations to use, this time potentially for multiple land uses and subareas. And again, the NURP data base will usually be the first one to turn to, with the possibility of local monitoring to augment it.

3.4 Statistical Method

The so-called AEPA Statistical Method@ is somewhat generic and until recently was not implemented in any off-the-shelf model or even very well in any single report (Hydroscience, 1979; EPA, 1983). A new FHWA study (Driscoll et al., 1989) partially remedies this situation. The concept is straightforward, namely that of a derived frequency distribution for EMCs. This idea has been used extensively for urban runoff quantity (e.g., Howard, 1976; Loganathan and Delleur, 1984; Zukovs et al., 1986) but not as much for quality predictions.

The EPA Statistical Method utilizes the fact that EMCs are not constant but tend to exhibit a lognormal frequency distribution. When coupled with an assumed distribution of runoff volumes (also lognormal), the distribution of runoff loads may be derived. When coupled again to the distribution of streamflow, an approximate (lognormal) probability distribution of in-stream concentrations may be derived (Di Toro, 1984)Ca very useful result, although assumptions and limitations of the method have been pointed out by Novotny (1985) and Roesner and Dendrou (1985). Further analytical methods have been developed to account for storage and treatment (Di Toro and Small, 1979; Small and Di Toro, 1979). The method was used as the primary screening tool in the EPA NURP studies (EPA, 1983) and has also been adapted to combined sewer overflows (Driscoll, 1981) and highway-related runoff (Driscoll et al., 1989). This latter publication is one of the best for a concise explanation of the procedure and assumptions and includes spreadsheet software for easy implementation of the method.

A primary assumption is that EMCs are distributed lognormally at a site and across a selection of sites. The concentrations may thus be characterized by their median value and by their coefficient of variation (CV = standard deviation divided by the mean). There is little doubt that the lognormality assumption is good (Driscoll, 1986), but similar to the spreadsheet approach, the method is then usually combined with weak hydrologic assumptions, e.g., prediction of runoff using a runoff coefficient. (The accuracy of a runoff coefficient increases as urbanization and imperviousness increase.) However, since many streams of concern in an urban area consist primarily of stormwater runoff during wet weather, the ability to predict the distribution of EMCs is very useful for assessment of levels of exceedance of water quality standards. The effect of BMPs can again be estimated crudely through constant removal fractions that effect on the coefficient of variation. Overall, the method has been very successfully applied as a screening tool.

Input to the method as implemented for the FHWA (Driscoll et al., 1989) includes statistical properties of rainfall (mean and coefficient of variation of storm event depth, duration, intensity and interevent time), area, and runoff coefficient for the hydrologic component, plus EMC median and coefficient of variation for the pollutant. Generalized rainfall statistics have already been calculated for many locations in the U.S. Otherwise, the EPA SYNOP model (EPA, 1976b; Hydroscience, 1979; EPA, 1983; Woodward-Clyde, 1989) must be run on long-term hourly rainfall records. If receiving water impact is to be evaluated the mean and CV of the streamflow are required plus the upstream concentration. A Vollenweider-type lake impact analysis is also provided based on phosphorus loadings.

As with the first two methods discussed, the choice of median concentration may be difficult, and the Statistical Method requires a coefficient of variation as well. Fortunately, from NURP and highway studies, CV values for most urban runoff pollutants are fairly consistent, and a value of 0.75 is typical. If local and/or NURP data are not available or inappropriate, local monitoring may be required, as in virtually every quality prediction method. The estimation of the whole EMC frequency distribution for a pollutant is a definite advantage of the Statistical Method over some applications of constant concentration and simple spreadsheet approaches. Frequency analyses of water quantity and quality parameters may also be performed on the output of continuous simulation models such as HSPF, SWMM and STORM. The derived distribution approach of the Statistical Method avoids the considerable effort required for continuous simulation at the expense of simplifying assumptions that may or may not reflect the prototype situation adequately.

3.5 RegressionCRating Curve Approaches

With the completion of the NURP studies in 1983, there are measurements of rainfall, runoff and water quality at well over 100 sites in over 30 cities. Some regression analysis has been performed to try to relate loads and EMCs to catchment, demographic and hydrologic characteristics (e.g., McElroy et al., 1976; Miller et al., 1978; Brown, 1984), the best of which are recent results of the USGS (Tasker and Driver, 1988; Driver and Tasker, 1988), to be described briefly below. Regression approaches have also been used to estimate dry-weather pollutant deposition in combined sewers (Pisano and Queiroz, 1977), a task at which no model is very successful. What are termed Arating curves@ herein are just a special form of regression analysis, in which concentration and/or loads are related to flow rates and/or volumes. This is an obvious exercise attempted at most monitoring sites and has a historical basis in sediment discharge rating curves developed as a function of flow rate in natural river channels.

A rating curve approach is most often performed using total storm event load and runoff volume although intra-storm variations can sometimes be simulated in this manner as well (e.g., Huber and Dickinson, 1988). It is usually observed (Huber, 1980; EPA, 1983; Driscoll et al., 1989) that concentration (EMC) is poorly or not correlated with runoff flow or volume, implying that a constant concentration assumption is adequate. Since the load is the product of concentration and flow, load is usually well correlated with flow regardless of whether or not concentration correlates well. Manifestation of spurious correlation (Benson, 1962) is often ignored in urban runoff studies. If load is proportional to flow to the first power (i.e., linear), then the constant concentration assumption holds; if not, some relationship of concentration with flow is implied. Rating curve results can be used by themselves for load and EMC estimates and can be incorporated into some models (e.g., SWMM, HSPF).

Rainfall, runoff and quality data were assembled for 98 urban stations in 30 cities (NURP and other) in the U.S. for multiple regression analysis by the USGS (Driver and Tasker, 1988; Tasker and Driver 1988). Thirty-four multiple regression models (mostly log-linear) of storm runoff constituent loads and storm runoff volumes were developed, and 31 models of storm runoff EMCs were developed. Regional and seasonal effects were also considered. The two most significant explanatory variables were total storm rainfall and total contributing drainage area. Impervious area, land use, and mean annual climatic characteristics also were significant explanatory variables in some of the models. Models for estimating loads of dissolved solids, total nitrogen, and total ammonia plus organic nitrogen (TKN) generally were the most accurate, whereas models for suspended solids were the least accurate. The most accurate models were those for the more arid Western U.S., and the least accurate models were those for areas that had large mean annual rainfall.

These USGS equations represent the best generalized regression equations currently available for urban runoff quality prediction. Note that such equations do not require preliminary estimates of EMCs or local quality monitoring data except for the very useful exercise of verification of the regression predictions. Regression equations only predict the mean and do not provide the frequency distribution of predicted variable, a disadvantage compared to the statistical approach. (The USGS documentation describes procedures for calculation of statistical error bounds, however). Finally, regression approaches, including rating curves, are notoriously difficult to apply beyond the original data set from which the relationships were derived. That is, they are subject to very large potential errors when used to extrapolate to different conditions. Thus, the usual caveats about use of regression relationships continue to hold when applied to prediction of urban runoff quality.

3.6 Buildup and Washoff

In the late 1960s, a Chicago study by the American Public Works Association (1969) demonstrated the (assumed linear) buildup of Adust and dirt@ and associated pollutants on urban street surfaces. During a similar time frame, Sartor and Boyd (1972) also demonstrated buildup mechanisms on the surface as well as an exponential washoff of pollutants during rainfall events. These concepts were incorporated into the original SWMM model (Metcalf and Eddy et al., 1971) as well as into the STORM, USGS and HSPF models to a greater or lesser degree (Huber, 1985). ABuildup@ is a term that represents all of the complex spectrum of dry-weather processes that occur between storms, including deposition, wind erosion, street cleaning, etc. The idea is simply that all such processes lead to an accumulation of solids and perhaps other pollutants that are then Awashed off@ during storm events.

Although ostensibly physically based, models that include buildup and washoff mechanisms really employ conceptual algorithms because the true physics is related to principles of sediment transport and erosion that are poorly understood in this framework. Furthermore, the inherent heterogeneity of urban surfaces leads to use of average buildup and washoff parameters that may vary significantly from what may occur in an isolated street gutter, for example. Thus, except in rare instances of measurements of accumulations of surface solids, the use of buildup and washoff formulations inevitably results in a calibration exercise against measured end-of-pipe quality data. It then holds that in the absence of such data, inaccurate predictions can be expected.

Different models offer different options for conceptual buildup and washoff mechanisms, with SWMM having the greatest flexibility. In fact, with calibration, good agreement can be produced between predicted and measured concentrations and loads with such models, including intra-storm variations that cannot be duplicated with most of the methods discussed earlier. (When a rating curve is used in SWMM instead of buildup and washoff, it is also possible to simulate intra-storm variations in concentration and load.) A survey of linear buildup rates for many pollutants by Manning et al. (1977) is probably the best source of generalized buildup data, and some information is available in the literature to aid in selection of washoff coefficients (Huber 1985; Huber and Dickinson, 1988). However, such first estimates may not even get the user in the ball park (i.e., qualityCnot quantityCpredictions may be off by more than an order of magnitude); the only way to be sure is to use local monitoring data for calibration and verification. Thus, as for most of the other quality prediction options discussed herein, the buildup-washoff model may provide adequate comparisons of control measures, ranking of loads, etc. but cannot be used for prediction of absolute values of concentrations and loads, e.g., to drive a receiving water quality model, without adequate calibration and verification data. Since buildup and washoff are somewhat appealing conceptually, it is somewhat easier to simulate potential control measures such as street cleaning and surface infiltration using these mechanisms than with, say, a constant concentration or rating curve method. In the relatively unusual instance in which intra-storm variations in concentration and load must be simulated, as opposed to total storm event EMC or load, buildup and washoff also offer the most flexibility. This is sometimes important for the design of storage facilities in which first-flush mechanisms may be influential.

As mentioned above, generalized data for buildup and washoff are sparse (Manning et al., 1977) and such measurements almost never conducted as part of a routine monitoring program. For buildup, normalized loadings, e.g., mass/day-area or mass/day per curb-length, or just mass/day, are required, along with an assumed functional form for buildup vs. time, e.g., linear, exponential, Michaelis-Menton, etc. For washoff, the relationship of washoff (mass/time) vs. runoff rate must be assumed, usually in the form of a power equation. When end-of-pipe concentration and load data are all that are available, all buildup and washoff coefficients end up being calibration parameters.

3.7 Related Mechanisms

In the discussion above, washoff is assumed proportional to the runoff rate, as for sediment transport. Erosion from pervious areas may instead be proportional to the rainfall rate. HSPF does the best job of including this mechanism in its algorithms for erosion of sediment from pervious areas. SWMM includes a weaker algorithm based on the Universal Soil Loss Equation.

Many pollutants, particularly metals and organics, are adsorbed onto solid particles and are transported in particulate form. The ability of a model to include Apotency factors@ (HSPF) or Apollutant fractions@ (SWMM) enhance the ability to estimate the concentration or load of one constituent as a fraction of that of another constituent, e.g., solids (Zison, 1980).

The groundwater contribution to flow in urban areas can be important in areas with unlined and open channel drainage. Of the urban models discussed, HSPF far and away has the most complex mechanisms for simulation of subsurface water quality processes in both the saturated and unsaturated zones. Although SWMM includes subsurface flow routing, the quality of subsurface water can only be approximated using a constant concentration.

The precipitation load may be input in some models (SWMM, HSPF), usually as a constant concentration. Point source and dry-weather flow (baseflow) loads and concentrations can also be input to SWMM, STORM and HSPF to simulate background conditions. Other quality sources of potential importance include catchbasins (SWMM) and snowmelt (SWMM, STORM, HSPF).

Scour and deposition within the sewer system can be very important in combined sewer systems and some separate storm sewer systems. The state of the art in simulation of such processes is poor (Huber, 1985). SWMM offers a crude but calibratable attempt at simulation of such processes.

Table 3. Data needs for various quality prediction methods

Method	Data	Potential Source
Unit Load	Mass per time per unit tributary area.	Derive from constant concentration and runoff. Literature values.
Constant Concentration	Runoff prediction mechanism (simple to complex).	Existing model; runoff coefficient or simple method.
	Constant concentration for each constituent.	NURP; local monitoring.
Spreadsheet	Simple runoff prediction mechanism.	e.g., runoff coefficient, perhaps as function of land use.
	Constant concentration or concentration range.	NURP; local monitoring.
	Removal fractions for controls.	NURP; Schueler (1987); local and state publications.
Statistical	Rainfall statistics.	NURP; Driscoll et al. (1989); Woodward-Clyde (1989); EPA SYNOP model.
	Area, imperviousness. Pollutant median and CV.	NURP; Driscoll (1986); Driscoll et al. (1989); local monitoring.
	Receiving water characteristics and statistics.	Local or generalized data.
Regression	Storm rainfall, area, imperviousness, land use.	Local data.
Rating Curve	Measured flow rates/volumes and quality EMCs/loads.	NURP; local data.
Buildup	Loading rates and rate constants.	Literature values[*].
	Street cleaning removals.	Literature values.
Washoff	Power relationship with runoff.	Literature values.[*].

[*] Usually must be calibrated using end-of-pipe monitored quality data.

Section 4.0

Overview of Available Non-urban Modeling Options

As with the options for modeling nonpoint source pollutants from urban areas, a wide range of techniques are available for modeling these contributions from non-urban land uses, from simple annual `loading functions' to detailed process simulation models. The key issue in estimating nonpoint pollution loads from a watershed, or parcel of land, is the type and extent of human activities occurring (or *not* occurring) on the land. The same hydrologic, physical, and chemical/biological processes that determine nonpoint pollutant loads occur on all land surfaces (and in the soil profile) whether it is urban, forest, agricultural cropland, pasture, mining, etc. The relative importance and magnitude of these processes, in determining nonpoint loads, will vary among land use categories and associated human activities. Even within an urban region, the parameters required for the various modeling options described in Section 4 will differ for commercial, industrial, transportation, and various densities of residential land. Many of these same urban modeling options have been used for non-urban land areas with parameters (e.g., constant concentrations) estimated for the specific non-urban land use.

The focus of the majority of non-urban nonpoint source estimation procedures and models has been on agricultural cropland, although the procedures and models have often been adapted and applied to many other land use categories. The agricultural research community, comprised of the U.S. Department of Agriculture (including the Soil Conservation Service and Agricultural Research Service) regional laboratories and state universities, have developed a significant body of knowledge of soil processes and procedures for estimating runoff and soil erosion that have formed the `building blocks' for loading functions and nonpoint source models. This section discusses some of the loading function procedures available for agricultural and other non-urban areas and general concepts underlying the more detailed process simulation models. The individual detailed models will be discussed briefly in Section 5.2 with additional details provided in the Appendix.

4.1 Nonpoint Source Loading Functions

The term `loading function' has been used in the nonpoint pollution literature to describe simple calculational procedures usually for estimating the *average annual load*, and sometimes the storm event load, of a pollutant from an individual land use category. A number of different loading functions have been developed and proposed over the past two decades, the most widely used of which are the EPA Screening Procedures, also referred to as the EPA Water Quality Assessment Methodology. These procedures are described below, followed by a brief discussion of a few other loading functions in the literature.

4.1.1 EPA Screening Procedures

The EPA Screening Procedures (Mills et al., 1985; Mills et al., 1982) are a revision and expansion of water quality assessment procedures initially developed for nondesignated 208 areas (Zison et al., 1977). The Procedures have been expanded and revised to include consideration of the accumulation, transport, and fate of toxic chemicals, in addition to conventional pollutants included in the earlier versions. The manual includes a separate chapter describing calculation procedures for estimating nonpoint loads for urban and non-urban land areas in addition to chapters on procedures for rivers and streams, impoundments, and estuaries. The most recent update includes consideration of toxics loadings and fate/transport in groundwater systems.

The procedures for nonpoint load assessments described in the manual are essentially a compilation and integration of techniques developed earlier by Midwest Research Institute (MRI) (McElroy et al., 1976), Amy et al. (1974), Heaney et al. (1976) and Haith (1980). However, the presentation of the procedures is well-integrated, supplemented with additional parameter estimation guidance, and includes sample calculations. The procedures for non-urban areas are derived from the MRI loading functions for average annual estimates based on the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978), while the storm event procedures use the Modified USLE (Williams, 1975) and the SCS Runoff Curve Number procedure (Mockus, 1972) for storm runoff volume. Pollutant concentrations in runoff and soil, and enrichment ratios are required for estimating pollutant loads; precipitation contributions of nutrients can be included. Specific information is included for estimation of salinity loads in irrigation return flows. Separate equations are provided for estimating loads for sorbed pollutants, dissolved pollutants, and partitioned pollutants (i.e., both sorbed and dissolved phases); this latter category is primarily for pesticides for which the procedures were developed by Haith (1980) for storm event loads. Guidance is provided for estimating *all* required parameters.

The primary strengths and advantages of the EPA Screening Procedures are as follows:

a. Excellent user documentation and guidance, including occasional workshops sponsored by the EPA Center for Exposure Assessment Modeling, in Athens, GA.

b. No computer requirements since the procedures can be performed on hand calculators; associated programs have been developed for river quality analyses (Mills et al., 1979).

c. Loading calculations and procedures can be linked to water quality procedures in other chapters to assess water quality impacts of nonpoint source loads.

d. Relatively simple procedures with minimal data requirements that can be satisfied from the user manual when site-specific data are lacking.

These screening procedures are well suited for general screening-level assessments; however, they suffer from the same disadvantages as all such gross estimation techniques. As with the urban options discussed above, the accuracy of the loads depends on the accuracy of the user-assumed pollutant concentration; the impacts of management options is usually represented by a simple, constant `removal fraction'; snowmelt and associated loadings are not represented; and calculations can be tedious and time consuming for complex multi-land use basins. In spite of these disadvantages and limitations, the EPA Screening Procedures are appropriate for many types of nonpoint load assessments. They have enjoyed wide popularity, partly due to the availability of training workshops sponsored by EPA, and have been applied in a number of regions, including the Sandusky River in northern Ohio and the Patuxent, Ware, Chester, and Occoquan basins in the Chesapeake Bay region (Davis et al., 1981; Dean et al., 1981a; Dean et al., 1981b). Although the procedures are quite amenable to a computerized or spreadsheet implementation, to our knowledge no effort has been made to implement such a format.

4.1.2 Other Loading Functions

As noted earlier, other loading functions have been developed and proposed by various groups and authors, though none have the support nor have they demonstrated the longevity of the EPA Screening Procedures. The WRENS handbook (Water Resources Evaluation of Nonpoint Silvicultural Sources, U.S. Forest Service (1980)) is similar to the EPA procedures but its focus is directed to the effects of forestry activities on water quality. The handbook provides quantitative techniques for estimating potential changes in streamflow, surface erosion, soil mass movement, total potential sediment discharge, and water temperature for comparative analyses of alternative silvicultural management practices. Runoff and erosion estimation techniques are similar to those used in the EPA Screening Procedures with parameters modified for forestry conditions.

Haith and Tubbs (1981) developed watershed loading functions as a screening tool to evaluate agricultural nonpoint source pollution in large watersheds. These functions also use the SCS Curve Number procedure for runofff estimation and the USLE for erosion; then, based on user-defined pollutant concentrations in runoff and attached to sediment, the procedures allow calculation of loadings to receiving waters. These functions have been added to the most recent update of the EPA Screening Procedures manual (i.e., 1985). A validation of the loading functions for a 850 km^2 watershed is described by Haith and Shoemaker (1987).

More recently, Li et al. (1989) have proposed loading functions for estimating the average annual pesticide loads in surface runoff. They developed regression equations derived from 100-year simulations of daily pesticide runoff using the Haith (1980) pesticide model. The regression equation coefficients are based on pesticide half life and soil partition coefficients, and are tabulated in the article for a wide range of values. Two different regressions are described: one based simply on mean annual soil erosion, and the other based on mean annual soil erosion and surface runoff volume during the month of pesticide application.

4.1.3 Discussion

The loading functions discussed above, and other similar techniques in the literature, differ from the simulation models primarily in time scale definition and their simplified, mostly empirical techniques for estimating nonpoint loads. They are used primarily to estimate average annual or event loads, and potential changes in these loads with land use and management practice. These procedures and associated calculations can usually be performed with a hand calculator, and with proliferation of personal computers and advances in computer technology we can expect to see more and more of these techniques available on PCs. However, users should not interpret the aura of implementation on a PC as an improvement in the capabilities, accuracy, or validity of these techniques. There are significant limitations in these procedures, because of their simplified nature, especially for evaluation of the impacts of management practices. As described above, they often require user-specified concentrations of pollutants in runoff and/or attached to sediment; some assume the total pollutant load can be estimated as a function of sediment alone.

Unfortunately, a comprehensive data base, comparable to the NURP data base for urban areas, does not exist for estimating the needed input concentrations for the wide range of non-urban land use categories. Also, there appears to be much greater variability in runoff concentrations from non-urban land than from urban land areas; consequently, extrapolation of concentrations from other sites may be less appropriate for non-urban land categories. Agricultural cropland is especially difficult to represent by single-valued `representative' concentrations due to differences in crops, fertilizer applications, tillage practices, agronomic practices, soils characteristics, etc.

In spite of these limitations, loading functions can be useful for general screening assessments to identify relative nonpoint contributions under different conditions as long as their assumptions and limitations are recognized. They are more popular than the detailed simulation models and have thus been applied more frequently, primarily because of their ease of use. Also, the loading functions are a very useful precursor to more detailed modeling studies for general problem assessment and identification and to determine if such detailed studies are warranted.

4.2 Simulation Models

The primary differences between nonpoint runoff simulation models and the loading functions described above relate to the temporal and spatial detail of the analysis, along with (usually) a more refined representation of the processes that determine nonpoint pollutant loadings. Whereas the loading functions can be used with only a hand calculator (or spreadsheet), the added detail of most simulation models requires a computer code, computer facilities, and significantly more input data, such as daily rainfall and possibly other meteorologic timeseries. These models are most often computerized procedures that perform hydrologic (runoff), sediment erosion, and pollutant (chemical/ biological) calculations on short time intervals, usually ranging from one hour to one day, for many years. The resulting values for each time interval, e.g., runoff, sediment, pollutant load or concentration, can be analyzed statistically and/or aggregated to daily, monthly, or annual values for estimates of nonpoint loadings under the conditions simulated.

As with the urban models, a wide range of nonpoint models appropriate for non-urban areas are available and have been used for many different types of land categories. The available models also cover a large range of complexity depending on the extent to which hydrologic, sediment erosion, and chemical/ biological processes are modeled in a mechanistic manner or based on empirical procedures. Similar to urban modeling, many of the same simple procedures and assumptions used in the loading functions are also incorporated into a number of simulation models, e.g., USLE, SCS Curve Number, constant pollutant concentration. Section 5.2 provides brief summaries of a number of the more widely used and `operational' non-urban models, along with a brief discussion of relative strengths and weaknesses; additional details for each of the models is provided in the Appendix.

In the remainder of this section, we discuss the two major modeling efforts that have dominated the non-urban (primarily agricultural) nonpoint modeling arena over the past two decades as a basis for describing the types of modeling techniques used for non-urban land uses. In addition, we will briefly discuss the key differences between urban and non-urban models and identify a number of ongoing model development efforts.

4.2.1 HSPF and CREAMS Model Development

The 1970's and early 1980's was a period of increasing pollution, and corresponding development of mathematical models to both characterize the pollutant loadings and water quality impacts, and evaluate alternative means of control. During this period the EPA, through the Athens-ERL, sponsored a number of model development and testing efforts (i.e., PTR, ARM, NPS, WEST) culminating in the HSPF model—Hydrologic Simulation Program-Fortran (Johanson et al, 1980). Barnwell and Johanson (1981) discuss the various model development and testing efforts leading to the initial release of HSPF in 1980; HSPF is currently in Release No. 9 (Johanson et al., 1984) as a result of numerous enhancements and code corrections. The focus of the model development was the ability to represent contributions of sediment, pesticides, and nutrients from agricultural areas, and evaluate resulting water quality conditions at the watershed scale considering both nonpoint contributions and instream water quality processes. Only the nonpoint capabilities of HSPF (i.e., PERLND and IMPLND modules) are discussed in this report.

Coincident with the HSPF (and predecessor models) development, the U.S. Department of Agriculture through the Agricultural Research Service (ARS) assembled a group of ARS scientists to refine, improve, and integrate existing models into a package for representing runoff, sediment, nutrient, and pesticide runoff from agricultural fields. The effort was initiated in 1977 and the resulting CREAMS model (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel, 1980) was first published in 1980. Since its initial release, CREAMS has undergone testing and application and a companion version, called GLEAMS (Leonard et al., 1986) has been developed with special emphasis on vadose zone processes to represent movement of chemicals to groundwater.

CREAMS and HSPF PERLND are the most detailed, operational models of agricultural runoff available at the current time. In many ways, they are more alike than they are different. Both models simulate runoff and erosion from field size areas, using different methods, and both simulate land surface and soil profile chemical/biological processes (using similar methods) that determine the fate and transport of pesticides and nutrients. Figure 1 shows the structure of the various subroutines that comprise the HSPF PERLND module; note that the Agrichemical Modules of PERLND perform the soil chemical/biological process simulation. Figure 2 conceptually shows the structure and processes simulated for pesticides and nutrients in the ARM model which was the basis for the HSPF Agrichemical Modules. Figure 3 includes analogous diagrams for CREAMS, showing the structure of the model and the processes involved in estimating nutrient losses in runoff and through leaching. Although the hydrology and sediment algorithms are different for the two models, the soil processes that determine the availability of chemicals for runoff and leaching are quite similar; both consider sorption/desorption, plant uptake, soil transformations (e.g., mineralization, nitrification), attenuation/decay, etc. that control the fate and migration of chemicals in the soil.

The two models differ primarily in their scope and level of detail, largely as a result of their historical origins. HSPF PERLND was derived from the Stanford Watershed Model (SWM) which was subsequently used as the basis for the HSP, ARM, and NPS models forming the predecessor components for HSPF. This model development effort originated in the hydrologic research community with emphasis on not only runoff modeling but also on watershed scale modeling, including both runoff and hydraulic routing needed for large watersheds and river basins. When EPA selected SWM as the basis for modeling nonpoint pollutant runoff, their ultimate goal was to be able to evaluate the downstream water quality impacts of pesticide and nutrient runoff from agricultural lands. Consequently, HSPF considers *all* streamflow components—surface runoff, interflow, baseflow—***and*** their pollutant contributions (as shown in Figure 2), and then allows direct linkage of these contributions to an instream water quality model. Also, since HSP and NPS included algorithms for urban runoff loadings, and since most large watersheds would include a variety of land use types, HSPF includes many of the simplified options (described above in Section 4.1) for modeling runoff from *any* land category, including both pervious and impervious urban categories.

On the other hand, CREAMS is a product of the agricultural research community with specific emphasis on representing soil profile and field-scale processes at the level of detail appropriate for design of field-based agricultural management systems. Thus, CREAMS allows more detailed representation of field terraces, drainage systems, field topography, etc. and associated sediment erosion processes. A detailed hydrology option is available, requiring breakpoint rainfall (i.e., short time interval rainfall, hourly or less), or the popular SCS Curve Number procedure can be used with daily rainfall. Because of its field-scale focus, CREAMS is limited to representing only *surface runoff* contributions; subsurface and leaching losses of chemicals are simply removed from the system. The original CREAMS documentation published in 1980 indicated that an effort to expand the model to a basin-scale was underway. The SWAM model (DeCoursey, 1982; Alonso and DeCoursey, 1985) uses CREAMS as a source area component and adds the capabilities to consider watershed and basin scale analyses; however, the model development effort is still underway at this time and SWAM is not currently considered `operational' in terms of documentation and use by non-developers (DeCoursey, personal communication, 1990). CREAMS has been used as the source area model by a number of investigators for specific studies (e.g. SWRRB (Williams et al., 1985), ADAPT (Ward et al., 1988), ARDBSN (Devaurs et al., 1988)) but no fully integrated, operational package with CREAMS for use at the basin / watershed scale is available comparable to HSPF.

4.2.2 Other Non-Urban Nonpoint Models

Many other non-urban nonpoint models exist in the modeling community and have been used to varying CREAMS, but each has been used by the developers, a few, by outside users. A comprehensive review of *all* available and relevant nonpoint models was well beyond the scope of this review effort. Below we discuss a few additional models, selected by the authors, that have been applied more often than typical `research' models, but they may not fully satisfy the definition of an `operational' model described in Section 2.2. The ANSWERS, AGNPS, PRZM, SWRRB / PRS, and UTM-TOX models are discussed briefly below; a paragraph description is included in Section 5.2 and additional details are provided in the Appendix.

The ANSWERS model (Areal Nonpoint Source Watershed Environment Response Simulation) developed by Beasley and Huggins (1981) at Purdue University differs from most other nonpoint models in that it is an `event', distributed-parameter model, as opposed to a continuous, lumped parameter modeling approach. ANSWERS is designed primarily to simulate single storm events, and requires that the watershed be subdivided into grid elements with parameter information provided for each element; most continuous nonpoint models only require specification of average or mean parameter values for a watershed or subwatershed area. The ANSWERS approach imposes greater computational burden and spatial data requirements, thus limiting most analyses to single `design' storms. However, the additional spatial detail allows greater evaluation of source areas within a specific watershed area if required by the problem assessment. ANSWERS is primarily a runoff and sediment model; the nutrient simulation is based on simple correlations between concentration and sediment yield / runoff volume; soil nutrient processes are not simulated.

The AGNPS model (Agricultural Nonpoint Source Pollution Model) developed by the USDA Agricultural Research Service (Young et al., 1986) is one of the most recent nonpoint models and thus has limited demonstrated experience. It is designed to simulate runoff, sediment, and nutrients from watershed-scale areas for either single event or continuous periods. It uses a distributed approach, similar to ANSWERS, whereby the watershed area is divided into cells, model computations are done at the cell level, and runoff, sediment, and nutrients are routed from cell to cell from the watershed boundaries to the outlet. AGNPS uses the SCS curve number approach combined with a unit hydrograph routing procedure, the Modified USLE, and simple correlations of extraction coefficients of nutrients in runoff and sediment. AGNPS can accommodate point source inputs from feedlots, wastewater treatment plants, and user-defined stream bank and gully erosion. Because of its distributed approach, its spatial data requirements are similar to ANSWERS.

The PRZM model (Pesticide Root Zone Model) (Carsel et al., 1984) was developed by the EPA Athens laboratory for modeling the fate of pesticides within the crop root zone, and subsequent leaching to groundwater. However, it includes a runoff and erosion component based on the SCS curve number and Modified USLE, respectively. PRZM represents dissolved, adsorbed, and vapor phase chemical concentrations in the soil by modeling the processes of surface runoff, erosion, evapotranspiration, plant uptake, soil temperature, pesticide decay, volatilization, foliar washoff, advection, dispersion, and decay. The most recent version of PRZM is included in an integrated root / vadose / groundwater model called RUSTIC recently released by the EPA Athens Laboratory (Dean et al., 1989). PRZM is currently limited to simulation of organic chemicals like pesticides, but its runoff and erosion components are similar to many other nonpoint models.

The SWRRB model (Simulator for Water Resources in Rural Basins) was developed by USDA (Williams et al., 1985; Arnold et al., 1989) for basin scale water quality modeling. Its runoff (SCS curve number) and erosion (Modified USLE) components are similar to the other nonpoint models, but SWRRB also includes channel processes and subsurface flow components to allow representation of large basin areas. It performs calculations on a daily timestep, and simulates hydrology, crop growth, sediment erosion, sediment transport, and nitrogen / phosphorus / pesticide movement in runoff. Its nutrient and pesticide capabilities are derived from CREAMS; these are the most recent additions to the model and they are still undergoing testing and validation by the developers.

The UTM-TOX model (Unified Transport Model for Toxic Materials) (Patterson et al., 1983), developed by the Oak Ridge National Laboratory for the U.S. EPA Office of Pesticides and Toxic Substances, is a multimedia model that combines hydrologic, atmospheric, and sediment transport in one computer code. It is similar to HSPF in many ways, in terms of its comprehensive scope; its representation of soil, land surface, and channel processes; and its use of the Stanford Watershed Model as its hydrologic module. UTM-TOX provides a more detailed simulation of soil-plant processes, includes atmospheric transport and deposition, and is designed primarily for organic chemicals; no specific capabilities are included for nutrients or agricultural conditions. UTM-TOX, to our knowledge, has had limited application, possibly because of its relatively complex nature and the lack of user support.

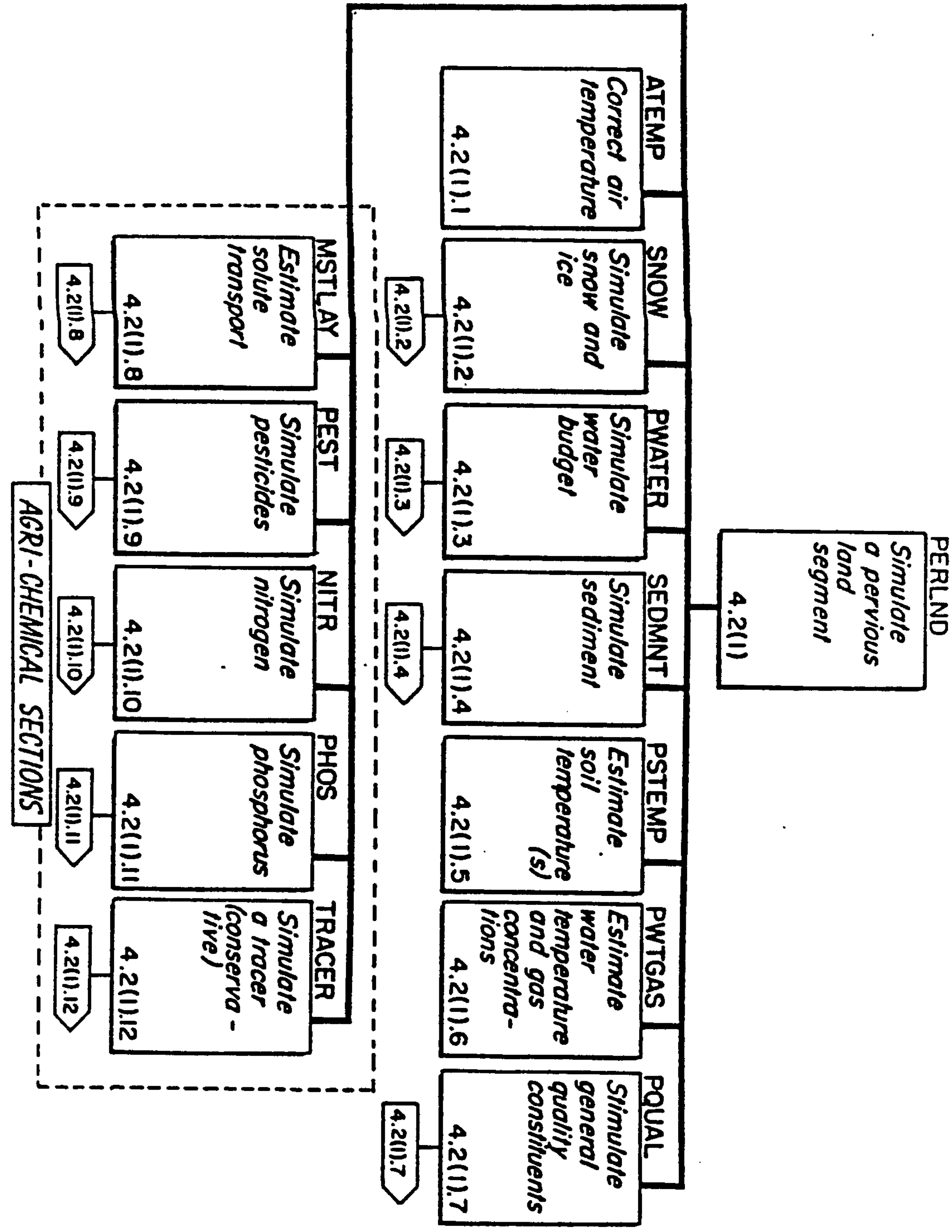
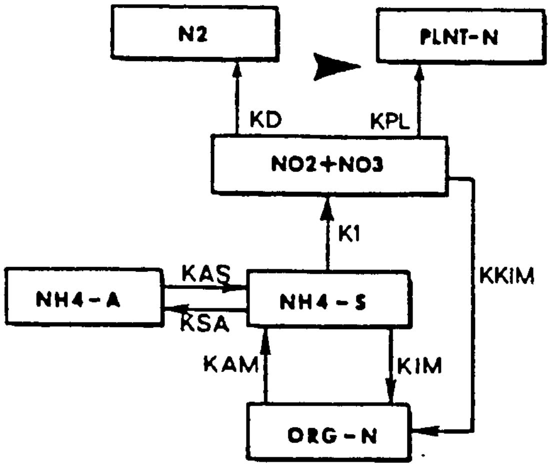
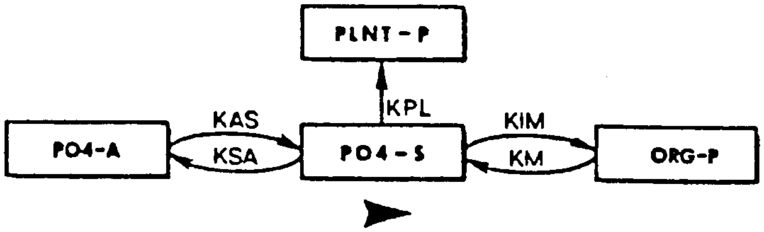


Figure 1. Subroutine structure for HSPF PERLND.

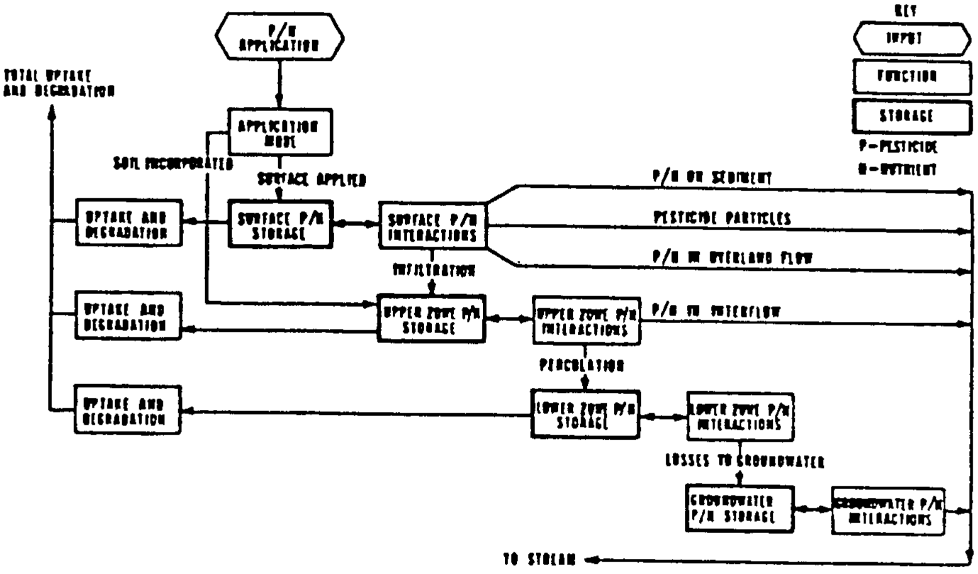


A. Nitrogen transformations in ARM model



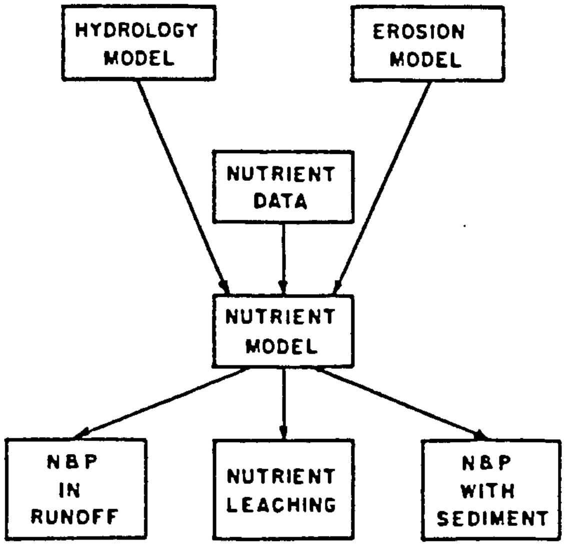
B. Phosphorus transformations in ARM model

Nutrient transformations in the ARM model



Pesticide (P) and nutrient (N) movement in the ARM model

Figure 2. ARM Model pesticide and nutrient and nutrient simulation included in HSPF PERLND.



Flow diagram of input and output for the nutrient model

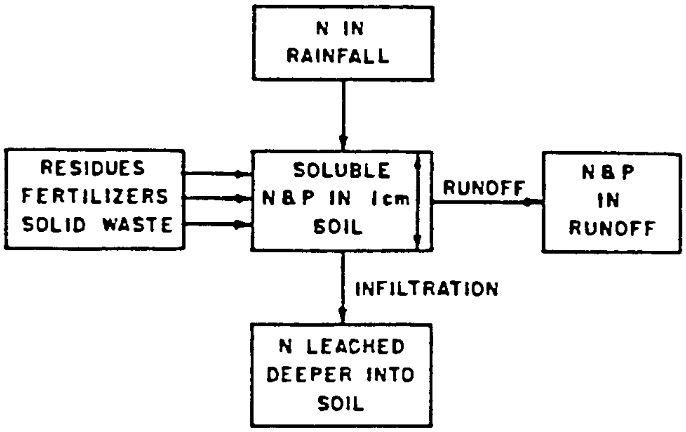


Diagram for estimating nutrient losses in runoff

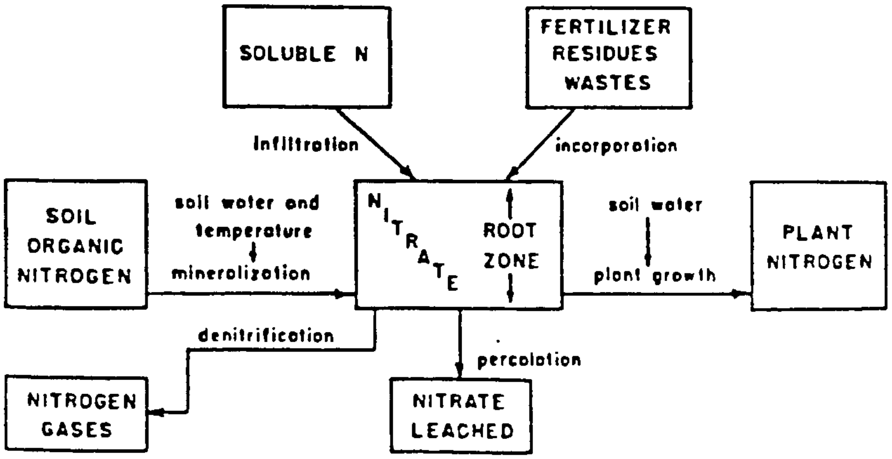


Diagram for estimating nitrate leaching

Figure 3 Nutrient simulation in CREAMS

Section 5.0

Nonpoint Source Runoff Quality Simulation Models and Methods

5.1 Urban Runoff Quality Models

5.1.1 Introduction

Four models (USGS, HSPF, STORM, SWMM) will be described briefly at this point; extensive details about the four models may be found in the Appendix. These four models essentially make up the best choice of full-scale simulation models for urban areas. Other models have been adapted from SWMM (e.g., FHWA, RUNQUAL) and STORM (e.g., SEMSTORM) and given modified names, but the principles are fairly similar. Still other models, such as the Illinois State Water Survey ILLUDAS model (Terstriep and Stall, 1974) have sometimes been adapted for water quality simulation for a specific project (Noel and Terstriep, 1982), but such modifications and quality procedures remain undocumented, and the quality model can be considered not operational. At least two European models are available that simulate water quality. These are described briefly at the end of this section. Finally, there are many models well known in the hydrologic literature, such as those developed by the HEC and SCS, that might be useful in the hydrologic aspect of water quality studies but that do not simulate water quality directly. This review is limited to models that directly simulate water quality. A general comparison of model attributes is given in Table 4. This table includes the EPA Statistical Method since with the publication of the recent FHWA study, it can be considered a formalized procedure (Driscoll et al., 1989). The constant concentration, spreadsheet, and regression approaches described earlier are more generic in nature and not included in Table 4, but their attributes were provided in the earlier text.

5.1.2 DR3M-QUAL

A version of the USGS Distributed Routing Rainfall Runoff Model that includes quality simulation (DR3M-QUAL) is available from that agency for general use (Alley and Smith, 1982a, 1982b). Runoff generation and subsequent routing use the kinematic wave method, and parameter estimation assistance is included in the model. Quality is simulated using buildup and washoff functions, with settling of solids in storage units dependent on a particle size distribution. The model has been used in some of the NURP studies that were conducted by the USGS (see the Appendix and Alley, 1986). No microcomputer version is available.

5.1.3 HSPF

The Hydrological Simulation ProgramCFortran (HSPF) is the culmination of hydrologic routines that originated with the Stanford Watershed Model in 1966 and eventually incorporated many nonpoint source modeling efforts of the EPA Athens laboratory (Johanson et al., 1984). This model has been widely used for non-urban nonpoint source modeling and is described additionally in that section of this report as well as in detail in the Appendix. The user's manual includes information on all hydrologic and water quality routines, including the IMPLND (impervious land) segment for use in urban area. Additional guidelines for application are provided by Donigian et al. (1984). The model has special provisions for management of time series that result from continuous simulation. A microcomputer version is available.

5.1.4 STORM

The first significant use of continuous simulation in urban hydrology came with the Storage, Treatment, Overflow, Runoff Model (STORM), developed by the Corps of Engineers Hydrologic Engineering Center (HEC, 1977; Roesner et al., 1974) for application to the San Francisco master plan for CSO pollution abatement. The HEC also provides application guidelines (Abbott, 1977). The current version includes dry-weather flow input for combined sewer simulation. The support of the HEC led to the wide use of STORM for planning purposes, especially for evaluation of the trade-off between treatment and storage as control options for CSOs (e.g., Heaney et al., 1977). Statistics of long-term runoff and quality time series permit optimization of control measures.

STORM utilizes simple runoff coefficient, SCS and unit hydrograph methods for generation of hourly runoff depths from hourly rainfall inputs. No flow routing is performed, but runoff may be routed through a constant-rate treatment device, with excess flow diverted to a storage device. Flows exceeding the treatment rate cause CSOs when storage is filled. The build-up and wash-off formulations are used for simulation of six pre-specified pollutants. However, the model can be manipulated to provide loads for arbitrary conservative pollutants (e.g., Najarian et al., 1986). The model is hampered somewhat by lack of an operational microcomputer version. However, various individual consultants have adapted the nonproprietary code to their own project needs.

5.1.5 SWMM

The original version of the Storm Water Management Model (SWMM) was developed for EPA as single-event model specifically for the analysis of CSOs (Metcalf and Eddy et al., 1971), but its scope has vastly broadened since the original release. Version 4 (Huber and Dickinson, 1988; Roesner et al., 1988) of the model performs both continuous and single-event simulation throughout the whole model, can simulate backwater, surcharging, pressure flow and looped connections (by solving the complete dynamic wave equations) in its Extran Block, and has a variety of options for quality simulation, including traditional build-up and wash-off formulations as well as rating curves and regression techniques. Subsurface flow routing (constant quality) may be performed in the Runoff Block in addition to surface quantity and quality routing, and treatment devices may be simulated in the Storage/Treatment Block using removal functions and sedimentation theory. A hydraulic design routine is included for sizing of pipes, and a variety of regulator devices may be simulated, including orifices (fixed and variable), weirs, pumps, and storage. A bibliography of SWMM usage is available (Huber et al., 1986) that contains many references to case studies.

SWMM is segmented into the Runoff, Transport, Extran, Storage/Treatment and Statistics blocks for rainfall-runoff, routing, and statistical computations. Water quality may be simulated in all blocks except Extran, and metric units are optional. Since the model is non-proprietary, portions have been adapted for various specific purposes and locales by individual consultants and other federal agencies, e.g., FHWA. A microcomputer version is available.

5.1.6 Two European Models

The four U.S. models discussed above do not take advantage of graphics and other Auser-friendly@ capabilities of microcomputers. Two well-known and commercially-available European models, MOUSE and Wallingford, are excellent examples of application of the full power of the microcomputer when used in conjunction with recent programming languages and graphics hardware and software. Both models feature menu-driven pre-processors for data input, graphical display and interactive editing of catchment boundaries and sewer networks, and post-processing of predicted hydrographs and pollutographs, including graphical displays and statistical analysis. Although the quality algorithms are relatively simple, the hydrologic and hydraulic components of both models are relatively sophisticated. The cost of each model is approximately $15,000, including training and documentation but not the source code.

The Danish Hydraulic Institute, in cooperation with various other laboratories and private software firms has produced the MOUSE (Modeling of Urban Sewers) model. Included in the package are modules for generation of runoff from rainfall, sewer routing (the S11S model, comparable to the SWMM Extran Block), and a simple quality routine that uses the constant concentration approach (Jacobsen et al., 1984; Johansen et al., 1984). Further information on MOUSE is available from Danish Hydraulic Institute, Agern Alle 5, DK-2970 Hørsholm, Denmark.

The Wallingford model is maintained by Hydraulics Research Ltd. in the United Kingdom. It also consists of a cluster of modules, including runoff generation from rainfall (WASSP), simple and fully-dynamic sewer routing (WALLRUS and SPIDA, respectively), and a quality routine (MOSQITO)featuring processes similar to those in SWMM (Henderson and Moys, 1987). Further information on the group of Wallingford models is available from Hydraulics Research Ltd., Wallingford, Oxfordshire OX10 8BA, United Kingdom.

5.2 Non-urban Runoff Quality Models and Methods

In this section we provide brief summaries of the primary non-urban runoff quality models reviewed; as noted earlier additional details on each model are provided in the Appendix. Below summaries are presented for HSPF, CREAMS/GLEAMS, ANSWERS, AGNPS, PRZM, SWRRB, and UTM-TOX, and Table 5 shows a comparison of selected model attributes and capabilities.

5.2.1 HSPF

The Hydrological Simulation ProgramCFORTRAN

(HSPF) (Johanson et al., 1981; 1984) is a comprehensive package for simulation of watershed hydrology and water quality for both conventional and toxic organic pollutants. HSPF incorporates the watershed scale ARM and NPS models into a basin-scale analysis framework that includes fate and transport in one-dimensional stream channels. It is the only comprehensive model of watershed hydrology and water quality that allows the integrated simulation of land and soil contaminant runoff processes with instream hydraulic, water temperature, sediment transport, nutrient, and sediment-chemical interactions. The runoff quality capabilities include both simple relationships (i.e. empirical buildup/washoff, constant concentrations) and detailed soil process options (i.e., leaching, sorption, soil attenuation and soil nutrient transformations).

The result of this simulation is a time history of the runoff flow rate, sediment load, nutrient, pesticide, and/or user-specified pollutant concentrations, along with a time history of water quantity and quality at any point in a watershed. HSPF simulates three sediment types (sand, silt, and clay) in addition to a single organic chemical and transformation products of that chemical. The instream nutrient processes include DO, BOD, nitrogen and phosphorus reactions, pH, phytoplankton, zooplankton, and benthic algae.

The organic chemical transfer and reaction processes included are hydrolysis, oxidation, photolysis, biodegradation, a volatilization, and sorption. Sorption is modeled as a first-order kinetic process in which the user must specify a desorption rate and an equilibrium partition coefficient for each of the three solid types. Resuspension and settling of silts and clays (cohesive solids) are defined in terms of shear stress at the sediment-water interface. For sands, the capacity of the system to transport sand at a particular flow is calculated and resuspension or settling is defined by the difference between the sand in suspension and the capacity. Calibration of the model requires data for each of the three solids types. Benthic exchange is modeled as sorption/desorption and desorption/scour with surficial benthic sediments. Underlying sediment and pore water are not modeled.

5.2.2 CREAMS/GLEAMS

Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) was developed by the U.S. Department of Agriculture—Agricultural Research Service (Knisel, 1980; Leonard and Ferreira, 1984) for the analysis of agricultural best management practices for pollution control. CREAMS is a field scale model that uses separate hydrology, erosion, and chemistry submodels connected together by pass files.

Runoff volume, peak flow, infiltration, evapotranspiration, soil water content, and percolation are computed on a daily basis. If detailed precipitation data are available then infiltration is calculated at histogram breakpoints. Daily erosion and sediment yield, including particle size distribution, are estimated at the edge of the field. Plant nutrients and pesticides are simulated and storm load and average concentrations of sediment-associated and dissolved chemicals are determined in the runoff, sediment, and percolation through the root zone (Leonard and Knisel, 1984).

User defined management activities can be simulated by CREAMS. These activities include aerial spraying (foliar or soil directed) or soil incorporation of pesticides, animal waste management, and agricultural best management practices (minimum tillage, terracing, etc.).

Calibration is not specifically required for CREAMS simulation, but is usually desirable. The model provides accurate representation of the various soil processes. Most of the CREAMS parameter values are physically measurable. The model has the capability of simulating 20 pesticides at one time.

Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) was developed by the United States Department of Agriculture—Agriculture Research Service (Leonard et al., 1987) to utilize the management oriented physically based CREAMS model (Knisel, 1980) and incorporate a component for vertical flux of pesticides. GLEAMS is the vadose zone component of the CREAMS model.

GLEAMS consists of three major components namely hydrology, erosion/sediment yield, and pesticides. Precipitation is partitioned between surface runoff and infiltration and water balance computations are done on a daily basis. Surface runoff is estimated using the Soil Conservation Service Curve Number Method as modified by Williams and Nicks (1982). The soil is divided into various layers, with a minimum of 3 and a maximum of 12 layers of variable thickness are used for water and pesticide routing (Knisel et al., 1989)

5.2.3 ANSWERS

Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) was developed at the Agricultural Engineering Department of Purdue University (Beasley and Huggins, 1981). It is an event based, distributed parameter model capable of predicting the hydrologic and erosion response of agricultural watersheds. Application of ANSWERS requires that the watershed to be subdivided into a grid of square elements. Each element must be small enough so that all important parameter values within its boundaries are uniform. For a practical application element sizes range from one to four hectares. Within each element the model simulates the processes of interception, infiltration, surface storage, surface flow, subsurface drainage, and sediment drainage, and sediment detachment, transport, and deposition. The output from one element then becomes a source of input to an adjacent element.

As the model is based on a modular program structure it allows easier modification of existing program code and/or addition of user supplied algorithms. Model parameter values are allowed to vary between elements, thus, any degree of spatial variability within the watershed is easily represented.

Nutrients (nitrogen and phosphorus) are simulated using correlation relationships between chemical concentrations, sediment yield and runoff volume. A research version (Amin-Sichani, 1982) of the model uses Aclay enrichment@ information and a very descriptive phosphorus fate model to predict total, particulate, and soluble phosphorus yields.

5.2.4 AGNPS

Agricultural Nonpoint Source Pollution Model (AGNPS) was developed by the U.S. Department of AgricultureCAgriculture Research Service (Young et al., 1986) to obtain uniform and accurate estimates of runoff quality with primary emphasis on nutrients and sediments and to compare the effects of various pollution control practices that could be incorporated into the management of watersheds.

The AGNPS model simulates sediments and nutrients from agricultural watersheds for a single storm event or for continuous simulation. Watersheds examined by AGNPS must be divided into square working areas called cells. Grouping of cells results in the formation of subwatersheds, which can be individually examined. The output from the model can be used to compare the watershed examined against other watersheds to point sources of water quality problems, and to investigate possible solutions to these problems.

AGNPS is also capable of handling point source inputs from feedlots, waste water treatment plant discharges, and stream bank and gully erosion (user specified). In the model, pollutants are routed from the top of the watershed to the outlet in a series of steps so that flow and water quality at any point in the watershed may be examined. The Modified Universal Soil Loss Equation is used for predicting soil erosion, and a unit hydrograph approach used for the flow in the watershed. Erosion is predicted in five different particle sizes namely sand, silt, clay, small aggregates, and large aggregates.

The pollutant transport portion is subdivided into one part handling soluble pollutants and another part handling sediment attached pollutants. The methods used to predict nitrogen and phosphorus yields from the watershed and individual cells were developed by Frere et al. (1980) and are also used in CREAMS (Knisel, 1980). The nitrogen and phosphorus calculations are performed using relationships between chemical concentration, sediment yield and runoff volume.

Data needed for the model can be classified into two categories: watershed data and cell data. Watershed data includes information applying to the entire watershed which would include watershed size, number of cells in the watershed, and if running for a single storm event then the storm intensity. The cell data includes information on the parameters based on the land practices in the cell.

Additional model components that are under development are unsaturated/saturated zone routines, economic analysis, and linkage to Geographic Information System.

5.2.5 PRZM

Pesticide Root Zone Model (PRZM) was developed at the U.S. EPA Environmental Research Laboratory in Athens, Georgia by Carsel et al. (1984). It is a one-dimensional, dynamic, compartmental model that can be used to simulate chemical movement in unsaturated zone within and immediately below the plant root zone. The model is divided into two major components namely, the hydrology (and hydraulics) and chemical transport. The hydrology component which calculates runoff and erosion is based upon the Soil Conservation Service curve number procedure and the Universal Soil Loss Equation respectively. Evapotranspiration is estimated directly from pan evaporation or by an empirical formula if pan evaporation data is not available. Soil-water capacity terms including field capacity, wilting point, and saturation water content are used for simulating water movement within the unsaturated zone. Irrigation application is also within model capabilities.

Pesticide application on soil or on the plant foliage are considered in the chemical transport simulation. Dissolved, adsorbed, and vapor-phase concentrations in the soil are estimated by simultaneously considering the processes of pesticide uptake by plants, surface runoff, erosion, decay, volatilization, foliar washoff, advection, dispersion, and retardation.

The user has two options to solve the transport equations using the original backward difference implicit scheme or the method of characteristics (Dean et al., 1989). As the model is dynamic it allows considerations of pulse loads.

PRZM is an integral part of a unsaturated/saturated zone model RUSTIC (Dean et al., 1989). RUSTIC (Risk of Unsaturated/Saturated Transport and Transformation of Chemical Concentrations) links three subordinate models in order to predict pesticide fate and transport through the crop root zone, and saturated zone to drinking water wells through PRZM, VADOFT, SAFTMOD.

VADOFT is a one-dimensional finite element model which solves Richard's equation for water flow in the unsaturated zone. VADOFT can also simulate the fate and transport of two parent and two daughter products. SAFTMOD is a two-dimensional finite element model which simulates flow and transport in the saturated zone in either an X-Y or X-Z configuration. The three codes PRZM, VADOFT, and SAFTMOD are linked together through an execution supervisor which allows users to build models for site specific situation. In order to perform exposure assessments, the code is equipped with a Monte Carlo pre and post processor (Dean et al., 1989).

5.2.6 SWRRB

Simulator for Water Resources in Rural Basins (SWRRB) was developed by Williams et al. (1985), and Arnold et al. (1989) for evaluating basin scale water quality. SWRRB operates on a daily time step and simulates weather, hydrology, crop growth, sedimentation, and nitrogen, phosphorous, and pesticide movement. The model was developed by modifying the CREAMS (Knisel, 1980) daily rainfall hydrology model for application to large, complex, rural basins.

Surface runoff is calculated using the Soil Conservation Service Curve Number technique. Sediment yield is computed for each basin by using the Modified Universal Soil Loss Equation (Williams and Berndt, 1977). The channel and floodplain sediment routing model is composed of two components operating simultaneously (deposition and degradation). Degradation is based on Bagnold's stream power concept and deposition is based on the fall velocity of the sediment particles (Arnold et al., 1989).

Return flow is calculated as a function of soil water content and return flow travel time. The percolation component uses a storage routing model combined with a crack flow model to predict the flow through the root zone. The crop growth model (Arnold et al., 1989) computes total biomass each day during the growing season as a function of solar radiation and leaf area index.

The pollutant transport portion is subdivided into one part handling soluble pollutants and another part handling sediment attached pollutants. The methods used to predict nitrogen and phosphorus yields from the rural basins are adopted from CREAMS (Knisel, 1980). The nitrogen and phosphorus calculations are performed using relationships between chemical concentration, sediment yield and runoff volume. The nutrient capabilities are still undergoing testing and validation at this time.

The pesticide component is directly taken from Holst and Kutney (1989) and is a modification of the CREAMS (Smith and Williams, 1980) pesticide model. The amount of pesticide reaching the ground or plants is based on a pesticide application efficiency factor. Empirical equations are used for calculating pesticide washoff which are based on threshold rainfall amount. Pesticide decay from the plants and the soil are predicted using exponential functions based on the decay constant for pesticide in the soil, and half life of pesticide on foliar residue.

The Pesticide Runoff Simulator (PRS) was developed for the U.S. EPA Office of Pesticide and Toxic Substances by Computer Sciences Corporation (1980) to simulate pesticide runoff and adsorption into the soil on small agricultural watersheds. PRS is based on SWRRB. Thus, the PRS hydrology and sediment simulation is based on the USDA CREAMS model, and the SCS curve number technique is used to predict surface runoff. Sediment yield is simulated using a modified version of the Universal Soil Loss Equation and a sediment routing model.

The pesticide component of PRS is a modified version of the CREAMS pesticide model. Pesticide application (foliar and soil applied) can be removed by atmospheric loss, wash off by rainfall, and leaching into the soil. Pesticide yield is divided into a soluble fraction and an adsorbed phase based on an enrichment ratio.

The model includes a built in weather generator based on temperature, solar radiation, and precipitation statistics. Calibration is not specifically required, but is usually desirable.

5.2.7 UTM-TOX

Unified Transport Model for Toxic Materials (UTM-TOX) was developed by Oak Ridge National Laboratory for the U.S. EPA Office of Pesticides and Toxic Substances, Washington, D.C. (Patterson et al., 1983). UTM-TOX is a multimedia model that combines hydrologic, atmospheric, and sediment transport in one computer code. The model calculates rates of flux of a chemical from release to the atmosphere, through deposition on a watershed, infiltration and runoff from the soil, to flow in a stream channel and associated sediment transport. From these calculations mass balances can be established, chemical budgets made, and concentrations in the environment estimated. The atmospheric transport model (ATM) portion of UTM-TOX is a Gaussian plume model that calculates dispersion of pollutants emitted from point (stack), area, or line sources. ATM operates on a monthly time step, which is longer than the hydrologic portion of the model and results in the use of an average chemical deposition falling on the watershed.

The Terrestrial Ecology and Hydrology Model (TEHM) describes soil-plant water fluxes, interception, infiltration, and storm and groundwater flow. The hydrologic portion of the model is from the Wisconsin Hydrologic Transport Model (WHTM), which is a modified version of the Stanford Watershed Model (SWM). WHTM includes all of the hydrologic processes of the SWM and also simulates soluble chemical movement, litter and vegetation interception of the chemical, erosion of sorbed chemical, chemical degradation in soil and litter, and sorption in top layers of the soil. Stream transport includes transfer between three sediment components (suspended, bed, and resident bed).

5.3 Discussion

The models discussed briefly here (and more extensively in the Appendix) do not represent all of the modeling options available for runoff quality simulation, but they are certainly the most notable, widely used and most operational. Selection from among these models is often made on the basis of personal preference and familiarity, in addition to needed model capabilities. For example, for urban modeling various in-house versions of STORM are still used by consultants even though the Aofficial@ HEC version has not been updated since 1977, because these versions have been adapted to the needs of the firm and because STORM has proven to provide useful continuous simulation results. The USGS DR3M-QUAL model has perhaps been used the least by persons outside that agency, but has worked satisfactorily in several applications documented in the Appendix. Support for both STORM and DR3M-QUAL would be minimal. CREAMS has been used most extensively for field-scale agricultural runoff modeling because of its agricultural origins and ties to the agricultural research community.

HSPF and SWMM are probably the most versatile and most widely applicable of the models, with the nod to SWMM if the urban hydrology and hydraulics must be simulated in detail. On the other hand, the water quality routines in HSPF for sediment erosion, pollutant interaction and groundwater quality are superior in HSPF, and the capability to efficiently handle *all* types of land uses and pollutant sources, (including urban and agriculture, point and non-point), is a definite advantage when needed for large complex basins. Both models appear somewhat overwhelming in terms of size to the novice user, but only the components of interest of either model need be used in a given study, and the catchment schematization can often be coarse for purposes of simulation of water quality at the outlet. Thus, although the installation of these models on a microcomputer may occupy several megabytes of a hard disk, they may be applied in simple ways (i.e., applied to a simplified schematization of the catchment) with a significant reduction in data requirements. Furthermore, the several quality modeling options within SWMM permit simple conceptual water quality simulation using constant concentration and rating curves as well as the more formidable buildup-washoff methods. Similarly for HSPF, the ability to use the simple SWMM-type formulations for urban and non-agricultural areas, and detailed soil/runoff process simulation for agricultural areas provides the user with great flexibility in representing the watershed system.

Continuing model development and testing within the agricultural research community will likely lead to further enhancements and development of many of the agricultural models, like CREAMS, SWRRB, and AGNPS. In fact, USDA has supported, and continues to support, a wide range of model development work in individual research facilities, many of which are (or at least appear to be) very similar in terms of using similar algorithms or model formulations (e.g. EPIC (Williams et al., 1984), Opus (V. Ferreira, 1989, personal communication), SWAM (DeCoursey, 1982). The SWRRB development effort appears to be focussing in on a middle ground (in terms of complexity) between HSPF and the detailed field-scale models which are limited to small areas; its use of daily rainfall, as opposed to smaller time interval measurements (usually hourly is needed for HSPF) is seen as a definite advantage by many users. However, most of these efforts still focus primarily on agricultural areas, with limited abilities to be used in large, complex multi-land use basins.

Regression, spreadsheet, statistical methods, and loading functions are most useful as screening tools. Indeed if the Statistical Method or EPA's Screening Procedures, indicate that there should be no water quality problem (as defined by exceedance of a specified concentration level with a specified frequency), then more detailed water quality simulation may not be required at all. If sensitivity analyses and `worst-case' evaluations further support the conclusions, detailed water quality modeling will probably not be needed.

Table 4. Comparison of urban model attributes

Attribute	Model: DR3M-QUAL	HSPF	Statistical[a]	STORM	SWMM
Sponsoring agency	USGS	EPA	EPA	HEC	EPA
Simulation type[b]	C,SE	C,SE	N/A	C	C,SE
No. pollutants	4	10	Any	6	10
Rainfall/runoff analysis	Y	Y	N[c]	Y	Y
Sewer system flow routing	Y	Y	N/A	N	Y
Full, dynamic flow routing equations	N	N	N/A	N	Y[d]
Surcharge	Y[e]	N	N/A	N	Y[d]
Regulators, overflow structures, e.g., weirs, orificies, etc.	N	N	N/A	Y	Y
Special solids routines	Y	Y	N	N	Y
Storage analysis	Y	Y	Y[f]	Y	Y
Treatment analysis	Y	Y	Y[f]	Y	Y
Suitable for screening (S), design (D)	S,D	S,D	S	S	S,D
Available on micro-computer	N	Y	Y[g]	N	Y
Data and personnel requirements[h]	Medium	High	Medium	Low	High
Overall model complexity[i]	Medium	High	Medium	Medium	High

[a] EPA procedure.
[b] C = continuous simulation, SE = single event simulation.
[c] Runoff coefficient used to obtain runoff volumes.
[d] Full dynamic equations and surcharge calculations only in Extran Block of SWMM.
[e] Surcharge simulated by storing excess inflow at upstream end of pipe. Pressure flow not simulated.
[f] Storage and treatment analyzed analytically.
[g] FHWA study, Driscoll et al. (1989)
[h] General requirements for model installation, familiarization, data require ments, etc. To be interpretted only very generally.
[i] Reflection of general size and overall model capabilities. Note that complex models may still be used to simulate very simple systems with attendant minimal data requirements.

Table 5. Comparison of non-urban model attributes

Attribute	AGNPS	ANSWERS	CREAMS	HSPF	PRZM	SWRRB	UTM-TOX
Sponsoring Agency	USDA	Purdue	USDA	EPA	EPA	USDA	ORNL & EPA
Simulation type	C,SE	SE	C,SE	C,SE	C	C	C,SE
Rainfall/Runoff analysis	Y	Y	Y	Y	Y	Y	Y
Erosion Modeling	Y	Y	Y	Y	Y	Y	Y
Pesticides	Y	N	Y	Y	Y	Y	N
Nutrients	Y	Y	Y	Y	N	Y	N
User-Defined Constituents	N	N	N	Y	N	N	Y
Soil Processes							
Pesticides	N	N	Y	Y	Y	Y	N
Nutrients	N	N	Y	Y	N	Y	N
Multiple Land Type Capability	Y	Y	N	Y	N	Y	Y
Instream Water Quality Simulation	N	N	N	Y	N	N	Y
Available on Micro-computer	Y	Y	Y	Y	Y	Y	N
Data and Personnel Requirements	M	M/H	H	H	M	M	H
Overall Model Complexity	M	M	H	H	M	M/H	H

Y = yes, N = no, M = Moderate, H = High
C = Continuous, SE = Storm Event

Section 6.0

Brief Case Studies

How are quality processes being simulated in studies of urban and rural runoff quality problems? Below, the authors draw upon their personal knowledge of a few ongoing and recently completed studies (listed alphabetically).

6.1 Urban Model Applications

6.1.1 Boston

CH2M-Hill (Gainesville, FL) used continuous SWMM modeling for the development of TSS and BOD loads from CSOs to Boston Harbor (Morrissey and Harleman, 1989). After first estimates from Sartor and Boyd (1972) and Pitt (1979), buildup and washoff functions were calibrated to estimates of annual totals based on monitoring. A Atypical@ five years of hourly precipitation data selected from 40 years of available record were input to SWMM to develop CSO loads, and the effectiveness of street cleaning and catchbasin cleaning BMPs was studied using the model (V. Adderly, CH2M-Hill, Inc., Gainesville, FL, Personal Communication, 1989).

6.1.2 Delevan Lake, Wisconsin

A joint project of the USGS (Madison) and the University of Wisconsin investigated suspended solids and phosphorus loads to 1800-ac Delevan Lake in southeastern Wisconsin (Walker et al., 1989). A spreadsheet approach was implemented using Multiplan, with unit load estimates for the surrounding basin (agricultural, urban, industrial). The Universal Soil Loss Equation was used for sediment loads from agricultural areas. Some calibration was possible using measurements on four tributaries. The cost-effectiveness of agricultural control options was evaluated based on cost estimates for various agricultural BMPs.

6.1.3 Hackensack River Basin

Pollution problems in the lower and estuarine portion of the Hackensack River in New Jersey are being studied by Najarian and Associates (Eatontown, NJ) using SWMM coupled with monitoring data from four CSO and five storm sewered areas (Huang and DiLorenzo, 1990; Najarian et al., 1990). The pollutants of primary interest are BOD and ammonia for input to a dynamic receiving water quality model of the river and estuary, with emphasis upon the relative contributions of CSOs, separate storm sewered areas and point sources. Although rating curve results were very good predictors for the monitored catchments from which they were derived, it was found that they could not be extrapolated (transferred) to the ungaged catchments. Hence, Michaelis-Menton buildup and exponential washoff parameters were calibrated for the basins and transferable generalized coefficients developed as a function of land use. Intra-storm variations were simulated in order to use SWMM to drive a short time increment dynamic model of the river and estuary.

6.1.4 Jacksonville

Camp, Dresser and McKee (Jacksonville) will use SWMM for quantity predictions and both a spreadsheet and SWMM or STORM with constant concentrations for load estimates to the St. Johns River (Camp, Dresser and McKee, Inc., 1989). The constant concentrations are based on NURP data and limited Florida data. If SWMM or STORM is used to drive a receiving water quality model for the river, local data will be used for better calibration. At the moment, CDM feels that both quantity and quality control options can be compared on the basis of present data, with a minimum of expensive local sampling.

6.1.5 Orlando

To help alleviate nonpoint source pollution to lakes downstream from the Boggy Creek Watershed south of Orlando, Camp, Dresser and McKee (Orlando) developed a spreadsheet model to assess nutrient loadings resulting from existing and future land uses (Camp, Dresser and McKee, 1987). Runoff coefficients were calibrated to match measured creek runoff volumes, and EMCs as a function of land use were estimated from sampling in Orlando and Tampa. An overall calibration factor was used to obtain agreement between the total estimated TN and TP loads produced by the product of flows and EMCs for the various land uses and measured annual nutrient loads in Boggy Creek. Thus, relative contributions from various land uses remained the same while the overall loads were adjusted. BMP removal efficiencies were applied in conjunction with changing land uses to obtain control strategies for future watershed development.

6.1.6 Providence

SWMM is being used by Greeley and Hanson (Philadelphia) to simulate CSO loads from Providence using three monitored storms for calibration and verification (R. Janga, Greeley and Hansen, Inc., Philadelphia, PA, Personal Communication, 1989). Quality is being simulated using constant concentration in the Runoff Block and the quality routing routines in the Transport Block. SWMM may be used to drive a receiving water model before the project is completed. Extran is also being used to simulate some of the overflow hydraulics.

6.1.7 San Francisco Bay

Woodward-Clyde (Oakland) is using SWMM to simulate loads from the Santa Clara Valley into South San Francisco Bay (P. Mangarella, Woodward-Clyde Consultants, Oakland, CA, Personal Communication, 1989). Measured runoff and flow data are being used to calibrate the Runoff Block quantity routines, and constant concentrations are being used (no buildup or washoff) based on one year of monitoring of a selection of land use types. The model may not be used to drive a receiving water model but it will be used to compare alternatives to reduce loads of toxics to the Bay.

6.1.8 Tallahassee

The Northwest Florida Water Management District (Havana, FL) is using SWMM to develop the stormwater master plan for Tallahassee and Leon County (R. Ortega, Northwest Florida Water Management District, Havana, FL, Personal Communication, 1989). Extensive use of the model has already been made for quantity predictions. The present plan is to develop rating curve relationships on the basis of considerable quality monitoring data gathered during the study for input into SWMM. BMPs will also be studied with the model, especially storage. Final control decisions will be made on the basis of 28-year SWMM simulations using 15-min rainfall data.

6.2 Non-urban Model Applications

6.2.1 Chesapeake Bay Program

The EPA Chesapeake Bay Program has been using the HSPF model as the framework for modeling total watershed contributions of flow, sediment, and nutrients (and associated constituents such as water temperature, DO, BOD, etc.) to the tidal region of the Chesapeake Bay (Donigian et al., 1986; 1990). The watershed modeling represents pollutant contributions from an area of more than 68,000 sq. mi., and provides input to drive a fully dynamic three-dimensional, hydrodynamic/water quality model of the Bay. The watershed drainage area is divided into land segments and stream channel segments; the land areas modeled include forest, agricultural cropland (conventional and conservation tillage systems), pasture, urban (pervious and impervious areas), and uncontrolled animal waste contributions. The stream channel simulation includes flow routing and oxygen and nutrient biochemical modeling (through phytoplankton) in order to account for instream processes affecting nutrient delivery to the Bay.

Currently, buildup/washoff type algorithms are being used for urban impervious areas, potency factors for all pervious areas, and constant (or seasonally variable) concentrations for all subsurface contributions and animal waste components. Enhancements are underway to utilize the detailed process (i.e. Agri-chemical modules) simulation for cropland areas to better represent the impacts of agricultural BMPs. The watershed modeling is being used to evaluate nutrient management alternatives for attaining a 40% reduction in nutrient loads delivered to the Bay, as defined in a joint agreement among the governors of the member states.

6.2.2 Alachlor Special Review

The EPA Office of Pesticide Programs performed a `Special Review' of the herbicide alachlor, which is widely used on corn and soybeans, to determine estimated concentrations in surface waters resulting from agricultural applications. HSPF was applied to selected watersheds in three separate agricultural regions—Iowa River Basin, IA; Honey Creek, OH; and Little River, GA—under different usage assumptions to evaluate a likely range of both mean annual and maximum daily alachlor concentrations (Mulkey and Donigian, 1984). The modeling results provided input to the human health risk assessment in which EPA decided to allow continued use of alachlor in the U.S.

6.2.3 CREAMS Application in Pennsylvania

The CREAMS model was applied by the University of Maryland Department of Agriculture and Engineering to selected subbasins of the Susquehanna and Potomac river basins in Pennsylvania to evaluate the effects of agricultural BMPs on nutrient loadings to surface water and to groundwater (Shirmohammadi and Shoemaker, 1988). The study was sponsored by the Interstate Commission on the Potomac River to evaluate the relative nutrient loading impacts of a wide range of potential BMPs, including no till, contouring, terracing, strip cropping, diversions, grass waterways, nutrient management, and various joint combination scenarios. Although the model was applied without calibration or observed runoff/leaching data for comparison, the results showed the *relative* effectiveness of the alternatives analyzed. The study was performed in support of efforts to evaluate alternative means of achieving the 40% reduction goal of the Chesapeake Bay Agreement.

6.2.4 Use of SWRRB in NOAA's National Coastal Pollutant Discharge Inventory

The National Oceanic and Atmospheric Administration (NOAA) is using the SWRRB model to evaluate pollutant loadings to coastal estuaries and embayments as part of its National Coastal Pollutant Discharge Inventory (NOAA, 1987a; 1987b). SWRRB is being used for loadings from all non-urban areas, while a separate procedure is proposed for all urban areas. SWRRB has been run for all major estuaries on the East Coast, Gulf Coast, and West Coast for a wide range of pollutants.

6.2.5 Use of AGNPS in Virginia

The Virginia Department of Soil and Water Conservation is applying the AGNPS model to evaluate sediment erosion and nutrient loadings from land uses within the Owl Creek and Nomini Creek watersheds. Both watersheds have been instrumented to monitor runoff quality from forest, agricultural cropland, and animal feedlot areas. AGNPS is being applied to the watersheds to analyze potential reductions in nutrient loadings for alternative management scenarios (M. Flagg, Virginia Dept. of Soil and Water Conservation, Richmond, VA, Personal Communication, 1990). The results of these applications, and planned use of the calibrated HSPF model resulting from the Chesapeake Bay Program application noted above, will be used to evaluate the means of achieving Virginia's 40% nutrient reductions required by the Chesapeake Bay Agreement.

6.2.6 Use of HSPF in Metropolitan Washington

The Metropolitan Washington Council of Governments has used HSPF in a number of modeling studies to evaluate water quality impacts of nonpoint sources, potential changes resulting from proposed urban stormwater management practices, and water quality changes resulting from alternative wastewater treatment levels (Sullivan and Schueler, 1982; Schueler, 1983; Metropolitan Washington Council of Governments, 1985). Studies on Piscataway and Seneca Creeks demonstrated reasonable agreement with observed instream water quality variables, and then the calibrated model was used to analyze water quality impacts of alternative scenarios including increased street sweeping, stormwater detention, and stormwater treatment. Since the watershed areas are primarily urban, the buildup/washoff algorithms were used to calculate loadings from all land areas. In a separate study, the HSPF instream module was used with pre-defined nonpoint and point source loadings to evaluate the impacts of proposed alternative wastewater treatment levels on the segment of the Potomac River near Washington, D.C.

6.2.7 Patuxent River Nonpoint Source Management Study

The Maryland Department of the Environment is conducting a study of the Patuxent River to quantify nonpoint source contributions and evaluate alternative means of improving downstream water quality in the Patuxent River Estuary (Summers, 1986). The study includes a 7-year monitoring program that involves observations of runoff quantity and quality at both field size (single land use) locations and instream, multi-land use sites. HSPF is being applied to calculate nonpoint loadings from the forest, agricultural, and urban land areas of the watershed and the instream water quality throughout the river system. The Patuxent is a microcosm of the larger Chesapeake Bay, a complex watershed with multiple land uses, point and nonpoint sources, and reservoirs draining to a tidal estuary. Like the larger Chesapeake Bay study, both simple and complex nonpoint runoff algorithms will be used to represent all land uses and effects of potential management practices.

6.2.8 European Case Studies in Application of the CREAMS Model

Svetlosanov and Knisel (1982) provide a compendium of case studies describing applications of CREAMS in Europe. The work was sponsored by the International Institute of Applied Systems Analysis in Laxenburg, Austria, with the dual objectives of demonstrating the use of CREAMS for quantitative evaluation of the impacts of agricultural management in different countries, and performing model testing and validation studies. The report describes applications in Finland, West Germany, Poland, Sweden, the United Kingdom, and the Soviet Union; comparisons of model results with observations were made in a few of the studies, while in others CREAMS was used without comparison to observed data to investigate alternative practices. Analysis of the case studies identified some of the potential benefits from the model applications, and elucidated some of the generic model weaknesses (e.g., smowmelt) and specific refinements needed for European conditions.

Section 7.0

Summary and Recommendations for Nonpoint Source Runoff Quality Modeling

Simulation of runoff quality will increase in importance as regulation and control of nonpoint sources increases in the next several years. The implementation of Section 405 of the Clean Water Act is especially important if stormwater outfalls will be required to have NPDES permits. The EPA is currently establishing guidelines for data collection, quality monitoring and forms of analysis such that urban areas can meet their obligations under these regulations. Waste load allocations and appropriate control strategies required under Section 303 (d) and 319 will demand more detailed analyses of nonpoint contributions for comprehensive water quality management.

Some form of modeling will almost assuredly become part of routine analyses performed at some portion of the thousands upon thousands of CSO and stormwater discharge locations around the country. Several modeling options exist, but none of them are truly Adeterministic@ in the sense of fully characterizing the physical, chemical and biological mechanisms that underlie conceptual buildup, erosion, transport and degradation processes that occur in an urban drainage system. Even if fully deterministic models were available, it is doubtful that they could be routinely applied without calibration data. But this is essentially true of almost all methods. Because a method is simple, e.g., constant concentration, does not make it more correct. Rather, the assumption is made that there will be some error in prediction regardless of the method, and there may be no point in compiling many hypothetical input parameters for a more complex model lacking a guarantee of a better prediction. For example, a study in Denver showed that regression equations could predict about as well as DR3M-QUAL given the available quality information (Ellis and Lindner-Lunsford, 1986). But physically-based (conceptual) models do have certain advantages, discussed later.

Physically-based urban models depend upon conceptual buildup and washoff processes incorporated into the quality algorithms. Such models have withstood the test of time and have been applied in major urban runoff quality studies. However, the relative lack of fundamental data on buildup and washoff parameters has lead to simpler methods more often being applied, starting with the assumption of a constant concentration and becoming more complex. For example, the derived distribution approach of the EPA Statistical Method provides very useful screening information with minimal dataCbut more than are required by just assuming a constant concentration. With the mass of NURP and other data, regression approaches are now more viable but still subject to the usual restrictions of regression analysis. Spreadsheets are ubiquitous on microcomputers and serve as a convenient mechanism to implement several of the simple approaches, especially those that rely upon sets of coefficients and EMCs as a function of land use or other demographic information. For example, the EPA Screening Procedures could easily be implemented in a spreadsheet format, and would be an appropriate tool for nonpoint source wasteload allocation assessments, at least for screening purposes.

Minimal data requirements and ease of application are the principal advantages of simpler simulation methods (constant concentration, statistical, regression, loading functions). However, in spite of their more complex data requirements, conceptual models (DR3M-QUAL, HSPF, STORM, SWMM, CREAMS, SWRRB) have advantages in terms of simulation of routing effects and control options as well as superior statistical properties of continuous time series. For example, the EPA Statistical Method assumes that stream flow is not correlated with the urban runoff flow. This may or may not be true in a given situation, but it is not necessary to require such an assumption when running a model such as HSPF or SWMM. The urban and non-urban conceptual models discussed in detail all have a means of simulating storage and treatment effects, and/or impacts of a significant number of management options. Other than a constant removal, this is difficult to do with the simpler methods. The conceptual models generally have very much superior hydrologic and hydraulic simulation capabilities (not true for STORM except that it can also use real rainfall hyetographs as input). This alone usually leads to better prediction of loads (product of flow times concentration). It should also be borne in mind that even complex models such as SWMM can be run with minimal quality (and quantity) data requirements, such as using only a constant concentration. Finally, some of the case studies imply that transferability of coefficients and parameters is easier with buildup and washoff than with rating curve and constant concentration methods.

If a more complex conceptual model is to be applied, which one should it be from among the ones described herein? SWMM is certainly the most widely used and probably the most versatile for urban areas, but all have their advocates. HSPF may be more appropriate in large multiple land use watersheds, in areas with more open space where groundwater contributions increase in importance, where rainfall-induced erosion occurs, or where quality interactions are important along the runoff pathway. The simplicity of STORM remains attractive, and various consultants have utilized their own version as a planning tool. The USGS DR3M-QUAL model has been successfully applied in several USGS studies but has not seen much use outside the agency. It contains useful techniques for quality calibration.

SWMM and HSPF retain limited support from the EPA Center for Exposure Assessment Modeling (CEAM) at Athens, Georgia, and a similar level of support is available for CREAMS from the USDA Southeast Watershed Research Laboratory in Tifton, Georgia. Unfortunately, this support is limited mainly to distribution and implementation on a computer system. STORM and DR3M-QUAL will remain useful, but it is unlikely that either of these two models will enjoy enhancements or support from their sponsoring agencies in the near future. Extramural support for all major operational models is highly desirable for maintenance and improvements, especially in light of the general models in nonpoint source studies in the U.S. **No model can exist for long without continuing sustenance in the form of user support, maintenance, and refinements in response to changing technology.** All agencies who have sponsored, or are currently sponsoring, model development efforts need to recognize the critical importance of these activities if their efforts are to produce `operational' models with associated widespread usage.

Agricultural model development will continue largely under the continuing sponsorship of the U.S.D.A. Currently, CREAMS is the most used model for strictly agricultural land, but a number of model development efforts are ongoing at various agricultural research stations across the country. The continuing development and testing of the SWRRB model will likely lead to its increased use in a number of non-urban studies; its use of a daily time step is attractive to users because of the less intensive data needs than for HSPF. However, for large complex watersheds, involving both urban and non-urban areas, HSPF will remain the model of choice for many users. Ongoing agricultural research will likely lead to improved understanding of processes, with improved algorithms that should be incorporated into current models. For example, the U.S.D.A. effort to develop a more process-oriented replacement for the USLE (i.e. the WEPP^{C}Watershed Erosion Prediction Project) will likely lead to improved soil erosion algorithms that may be appropriate for incorporation into current models.

What is a reasonable approach to simulation of runoff quality? The main idea, for both urban and non-urban areas, is to use the simplest approach that will address the project objectives at the time. This usually means to start simple with a screening tool such as constant concentration (usually implemented in a spreadsheet), regression, statistical, or loading function approach. If these methods indicate that more detailed study is necessary or if they are unable to address all the aspects of the problem, e.g., the effectiveness of control options or management alternatives, then one of the more complex models must be run. No method currently available (or likely to be available) can predict absolute (accurate) values of concentrations and loads without local calibration data, including complex buildup and washoff models for urban areas, and soil process models for agricultural croplands. Thus, if a study objective is to provide input loads to a receiving water quality model, local site-specific data will probably be required. On the other hand, several methods and models might be able to compare the relative contributions from different source areas, or to determine the relative effectiveness of control and/or management options (if the controls can be characterized by simple removal fractions). When used for purposes such as these, the methods, including buildup and washoff models, can usually be applied on the basis of NURP data (for urban models) and/or the best currently available source of quality data, such as data from agricultural research stations for the non-urban models.

When properly applied and their assumptions respected, models can be tremendously useful tools in analysis of urban and non-urban runoff quality problems. Methods and models are evolving that utilize the large and currently expanding data base of quality information. As increasing attention is paid to runoff problems in the future, the methods and models can only be expected to improve.

Section 8.0

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Section 9.0

Appendix

Detailed Model Descriptions

Urban

SWMM
STORM
DR3M-QUAL

Non-Urban

EPA Screening Procedures
AGNPS
ANSWERS
CREAMS/GLEAMS
HSPF
PRZM
SWRRB
UTM-TOX

Nonpoint Source Model Review

1. Name of Method

Storm Water Management Model (SWMM)

2. Type of Method

Surface Water Model: Simple Approach
xx Surface Water Model: Refined Approach
xx Soil (Groundwater) Model: Simple Approach
Soil (Groundwater) Model: Refined Approach

3. Purpose/Scope

Purpose: Predict rainfall/runoff/quality processes in urban and other areas. Predict hydrographs and pollutographs (concentration vs. time) in

xx runoff waters
xx surface waters
xx ground waters

Source/Release Types:

xx Continuous   xx Intermittent
xx Single   xx Multiple   xx Diffuse

Level of Application:

xx Screening   xx Intermediate   xx Detailed

Types of Chemicals:

xx Conventional   xx Organic   xx Metals

Unique Features:

xx Addresses degradation products
xx Integral database/database manager
xx Integral uncertainty analysis capabilities
Interactive input/execution manager

4. Level of Effort

System setup: xx mandays   xx manweeks   manmonths
Assessments: mandays   xx manweeks   xx manmonths

(Estimates reflect order-of-magnitude values and depend heavily on the experience and ability of the assessor.)

5. Description of the Method/Techniques

The *Storm Water Management Model (SWMM)* consists of several modules or Ablocks@ designed to simulate most quantity and quality processes in the urban hydrologic cycle. Storm sewers, combined sewers, and natural drainage systems can be simulated. For generation of hydrographs, the Runoff Block simulates the rainfall-runoff process using a nonlinear reservoir approach, with an option for snowmelt simulation. Groundwater and unsaturated zone flow and outflow are simulated using a simple lumped storage scheme. A water balance is maintained between storms, and the entire model may be used for both continuous and single event simulation. Flow routing is accomplished in order of increasing complexity in the Runoff Block (nonlinear reservoir), Transport Block (kinematic wave) and/or Extran Block (complete dynamic equations). The Extran Block is the most comprehensive simulation program available in the public domain for a drainage system domain and is capable of simulating backwater, surcharging, looped sewer connections and a variety of hydraulic structures and appurtenances. The Storage/Treatment Block may be used for storage-indication flow routing. Output from all blocks includes both flow and stage hydrographs.

Quality processes in the Runoff Block include generation of surface runoff constituent loads through a variety of options: 1) build-up of constituents during dry weather and wash-off during wet weather, 2) Arating curve@ approach in which load is proportional to flow rate to a power, 3) constant concentration (including precipitation loads), and/or 4) Universal Soil Loss Equation. Removal of Abuilt-up@ loads can occur by street cleaning during dry weather, and special options are available for snow. One constituent can be taken as a fraction (Apotency factor@) of another to simulate adsorption onto solids, for example. The concentration of groundwater outflow may only be treated as a constant. Routing and first-order decay may be simulated in the Runoff and Transport Blocks. (Extran includes no quality simulation.) The Transport Block may also be used to simulate scour and deposition within the sewer system based Shield's criterion for initiation of motion, and generation of dry-weather flow and quality. The Storage/Treatment Block simulates removal in storage/treatment devices by 1) first-order decay coupled with complete mixing or plug flow, 2) removal functions (e.g., solids deposition as a function of detention time), or 3) sedimentation dynamics. Residuals (e.g., sludge) are accounted for. Any constituent may be simulated, but sediment processes, e.g., scour and deposition, are generally weak with the exception of the Storage/Treatment Block.

The blocks can be run independently or in any sequence. Additional blocks are available for statistical analysis of the output time series (Statistics Block), input and manipulation of precipitation, evaporation, and temperature time series (Rain and Temp Blocks), line printer graphics (Graph Block), and output time series manipulation (Combine Block).

6. Data Needs/Availability

SWMM can be run in a very simple configuration, e.g., a single subcatchment and no drainage network, or in a very detailed configuration, e.g., many subcatchments and channels and pipes. The volume of data varies accordingly, but at a minimum will require information on area, imperviousness, slope, roughness, depression storage and infiltration characteristics at the desired level of detail. Channel/pipe data include shapes, dimensions, slopes or invert elevations, roughnesses, etc. Quantity data are usually available from the urban municipality in the form of contour maps and drainage plans.

If quality is generated in the Runoff Block using a build-up/wash-off formulation, then build-up coefficients are needed for alternative build-up formulations (i.e., linear, power, exponential or Michaelis-Menton) as well as for wash-off equations. Due to lack of data availability for these conceptual mechanisms, users often resort to rating curves that may be more readily derived from measurements, or to constant concentrations.

Precipitation input can be in the form of hyetographs for individual storm events, or long-term hourly or 15-minute precipitation (or arbitrary time interval) records from the National Climatic Data Center. Measured hydrographs and pollutographs (or storm event loads or event mean concentrations) are required for calibration and verification. Quantity results are often reasonably good with little or no calibration, whereas quality results need local, site-specific measurements to ensure accurate predictions. Since quality measurements are expensive and sparse, reliance is often placed on generalized data from other sites, e.g., EPA Nationwide Urban Runoff Program (NURP) data, from which reasonable comparative assessments may usually be made. However, if SWMM (or any urban nonpoint source model) is used to drive a receiving water quality model, local, site-specific quality measurements are normally required.

7. Output of the Assessment

SWMM produces a time history of flow, stage and constituent concentration at any point in the watershed. Seasonal and annual summaries are also produced, along with continuity checks and other summary output. The Statistics Block may be used for storm event separation and frequency analysis of any of the time series. Somewhat crude (by today's standards) line printer graphics are available for hydrograph and pollutograph plots, including comparison with measured data.

8. Limitations

The simulation methods used in various blocks are extensively described in the SWMM documentation and need to conceptually represent the prototype watershed for a satisfactory simulation. Experience has shown SWMM quantity simulations to compare favorably with measurements and with other conventional hydrologic methods, e.g., unit hydrographs. Quality simulation is especially weak in representation of the true physical, chemical and biological processes that occur in nature and is often a calibration or curve-fitting exercise. This accounts for the tendency for users to bypass build-up/wash-off formulations in favor of constant concentrations or rating curves that may be more easily calibrated. Perhaps the weakest component of the model is simulation of solids transport, although it should be borne in mind that this is difficult to do in any model. The microcomputer version of the program is not especially Auser friendly@ and lacks good graphics routines. However, on-screen messages are provided during program execution to inform the user of the current program status.

9. Hardware/Software Requirements

SWMM is written in ANSI standard Fortran 77. Executable code prepared using the Ryan-McFarland Fortran compiler is distributed for IBM XT/AT-compatibles. A hard disk is required and a math co-processor is usually required (see Contact section, below). No special peripherals other than a printer are required. Over 200 sample input files are also distributed, along with the Fortran source code. The program is also maintained for DEC/VAX systems; however, the user must perform his/her own compilation from the Fortran source code. Input files must be prepared using an editor capable of producing an ASCII file as output. No automatic or menu-driven input routine is available. The program can be obtained in either floppy disk format for MS-DOS applications or on a 9-track magnetic tape (from EPA only) with installation instructions for the DEC/VAX VMS environment. SWMM has been installed on many computers world-wide with no or minor modifications.

10. Experience

The original version of SWMM was developed in 1969-71 by a consortium of Metcalf and Eddy, Inc., Water Resources Engineers, Inc. (now a part of Camp, Dresser and McKee, Inc.), and the University of Florida (Metcalf and Eddy et al., 1971). The program was maintained intermittently for several years at the University of Florida under the sponsorship first of the EPA Storm and Combined Sewer Branch (Cincinnati) and later by the EPA Center for Exposure Assessment Modeling (Athens, GA). Limited (unsponsored) maintenance and development work continues at the University of Florida. Continuing updates to the Extran Block have been placed in the public domain by Camp, Dresser and McKee, Inc. and incorporated into the model. The most current version of the model is Version 4 (Huber and Dickinson, 1988; Roesner et al., 1988) following earlier Version 2 (Heaney et al., 1975; Huber et al., 1975) and Version 3 (Huber et al., 1981; Roesner et al., 1981). A SWMM bibliography (Huber et al., 1985) contains over 200 SWMM-related references, including many references to case studies. The model is often referenced in texts (e.g., Viessman et al., 1989) and has been used in applications ranging from routine drainage design to highly complex hydraulic routing and analysis to large nonpoint and point source pollution abatement studies, e.g., Boston, Detroit, Washington DC.

Maintaining SWMM as a non-proprietary model and in the public domain has produced massive user feedback to the model developers and led to many improvements (Huber, 1989). This has been greatly facilitated by approximately semi-annual meetings of the Storm and Water Quality Model Users Group and publication of proceedings by EPA. The model has achieved the status of a Astandard of comparison@ for modelers wishing to develop new and improved techniques.

SWMM has been applied to urban hydrologic quantity and quality problems in many locations world-wide, including probably over 100 locations in the U.S. and Canada. Applications in major U.S. cities include Albuquerque, Atlanta, Boston, Chicago, Cincinnati, Denver, Detroit, Hartford, Jacksonville, New Haven, New Orleans, Newark, New York, Philadelphia, Providence, Rochester, San Jose, San Francisco, Seattle, Syracuse, Tallahassee, Tampa, Washington DC.

Because SWMM is in the public domain, portions of the model have been adapted for related modeling purposes. A model similar to SWMM in many ways was developed for the Federal Highway Administration (Dever et al., 1981, 1983). It contains components of the Runoff and Extran Blocks along with specialized hydraulic simulation capabilities for highway drainage. Because SWMM contains much more versatile water quality routines, the FHWA model will not be discussed further here; however, some of its characteristics are compared to those of other models by Huber (1985).

11. Validation/Review

The program has been calibrated and verified on many independent data sets, and the model algorithms have been validated through extensive outside analysis and review during the 20 years of model history. Several comparisons of SWMM and other models have been conducted (e.g., Heeps and Mein, 1974; Brandstetter, 1977; Huber and Heaney, 1982; Huber, 1985; Water Pollution Control Federation, 1989). In 1982 the U.S. Office of Technology Assessment said that its Areliability and widespread availability have made SWMM the most widely used model of its type in the United States and Canada, and have been important in increasing the use of models by engineers and planners. The SWMM User's Group [now the Storm and Water Quality Model Users Group, sponsored by the EPA CEAM] has been instrumental in achieving the widespread dissemination and acceptance enjoyed by this important modeling tool.@ (Office of Technology Assessment, 1982).

A final caveat about water quality predictions is still in order: neither SWMM or any other urban nonpoint model can predict accurate concentrations and loads in urban runoff without local, site-specific data. Such data would likely be required in order to drive a receiving water quality model, for example. However, relative values and comparison of alternatives can usually still be studied from approximate quality predictions.

12. Contact

SWMM is available from the EPA Center for Exposure Assessment Modeling (CEAM) at no charge. It can be downloaded from the CEAM electronic bulletin board, from Internet node earth1.epa.gov via anonymous ftp, or obtained on floppy disks (on two high-density disks). The CEAM also maintains the Fortran source code for a DEC/VAX VMS version. The same program is also available for $50 from the Department of Civil Engineering, Oregon State University. The Oregon and CEAM versions for PCs require a math co-processor. For further information at the CEAM, contact

Model Distribution Coordinator
Athens Environmental Research Laboratory
U.S. Environmental Protection Agency
960 College Station Road
Athens, Georgia 30605
(706) 546-3549

Documentation (Huber et al., 1988; Roesner et al., 1988) can be obtained from the NTIS or from Oregon State University:

Dr. Wayne C. Huber
Dept. of Civil Engineering
Oregon State University Apperson Hall 202
Corvallis, OR 97331-2302
(503) 737-4934

13. References

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Nonpoint Source Model Review

1. Name of Method

Storage, Treatment, Overflow, Runoff Model (STORM)

2. Type of Method

xx Surface Water Model: Simple Approach
Surface Water Model: Refined Approach
Soil (Groundwater) Model: Simple Approach
Soil (Groundwater) Model: Refined Approach

3. Purpose/Scope

Purpose: Predict rainfall/runoff/quality processes in urban areas. Predict hydrographs and pollutographs (concentration vs. time) in

xx runoff waters
surface waters
ground waters

Source/Release Types:

xx Continuous
Single

Intermittent
Multiple

xx Diffuse

Level of Application:

xx Screening
Intermediate
Detailed

Types of Chemicals:

xx Conventional
Organic
Metals

Unique Features:

Addresses degradation products
Integral database/database manager
xx Integral uncertainty analysis capabilities
Interactive input/execution manager

4. Level of Effort

System setup: xx mandays xx manweeks manmonths
Assessments: mandays xx manweeks xx manmonths

(Estimates reflect order-of-magnitude values and depend heavily on the experience and ability of the assessor.)

5. Description of Method/Techniques

The Storage, Treatment, Overflow, Runoff Model (STORM) contains simplified hydrologic and water quality routines for continuous simulation in urban areas. Hourly runoff depths are computed by means of an area-weighted runoff coefficient for the pervious and impervious portions, with recovery of depression storage between events. Alternatively, the SCS method can be used to generate hourly runoff volumes. There is no flow routing as such. Runoff passes through a treatment device up to its capacity and is otherwise diverted to a storage unit. If treatment is at capacity and the storage is full, an Aoverflow@ occurs to the receiving water. This scheme results from the origins of the model for simulation of combined sewer overflows. At the end of the storm, remaining storage is routed through treatment. The program is driven by hourly precipitation records obtained from the National Climatic Data Center, and snowmelt can be simulated using the degree-day method. Dry-weather flows can also be simulated; these provide a baseflow and are mixed with stormwater runoff during a storm event.

Linear build-up and first-order exponential wash-off is used to simulate concentrations of up to six pre-specified pollutants (suspended solids, settleable solids, BOD, total coliforms, ortho-phosphate, and nitrogen). Because build-up and wash-off parameters are adjustable, other conservative pollutants could be simulated under the guise of the above names. Erosion may be simulated using the Universal Soil Loss Equation. Runoff is mixed with dry-weather flow, if any, and transported without quality routing or decay to the treatment device. Flows passing through treatment are not included as loads to receiving waters (i.e., treatment releases are handled as if there is 100% removal). However, a summary is maintained of concentrations and loads that bypass the storage/treatment option and overflow to the receiving water. No treatment occurs in the storage device.

6. Data Needs/Availability

Data needs are somewhat less for STORM than for comparable continuous simulation models because of its simple hydrologic and water quality routines. Runoff coefficients may be estimated from standard handbooks and textbooks, and SCS parameters are widely available if the soil types are known. Build-up and wash-off parameters are less flexible than in models such as SWMM, HSPF or DR3M-QUAL and no more easy to estimate. Calibration is advisable but somewhat awkward because the model is primarily set up to run in only a continuous mode. However, since STORM is usually run only in a screening or planning mode, comparative evaluations can usually be made without calibration.

7. Output of the Assessment

Output includes storm event summaries of runoff volume, concentrations and loads plus summaries of storage and treatment utilization and total overflow loads and concentrations. Hourly hydrographs and pollutographs (concentration vs. time) may be computed but rarely are because there is no way to do this for only brief periods during a long, continuous simulation. Useful statistical summaries on an annual and total simulation period basis that enable an estimation of Apercent control,@ i.e., percentage of runoff passing through storage and also the number of overflows, both as a function of the treatment rate and storage capacity. The storage-treatment combination can then be optimized. The utilization of storage is also summarized, which helps in defining the duration of critical events, e.g., time required between events for complete drainage of the storage.

8. Limitations

STORM's hydrologic routines (runoff coefficient, SCS, no routing) are the simplest of any simulation model considered. Although they lead to minimal data requirements, they also lead to less flexibility in matching observed hydrographs. Similarly, STORM uses the quality routines embodied in the original SWMM program (Metcalf and Eddy et al., 1971) with very few modifications. These have been shown to be relatively inflexible in matching observed pollutographs and have been updated in SWMM and other models. Only hourly precipitation inputs are possible, making it difficult to work with more recent continuous records of 15-minute precipitation data or arbitrary input hyetographs, e.g., measured rainfall and runoff data. Lack of an agency-supported microcomputer version currently hampers the model's use.

9. Hardware/Software Requirements

STORM is written in Fortran IV and must be compiled by the user on a mainframe. It is available only on a 9-track magnetic tape and has been installed on IBM and CDC systems, among others. Although individual users have prepared versions for IBM PC/AT-compatibles, the model developer does not sell or support such a version.

10. Experience

STORM represents the first significant use of continuous simulation, especially quality applications, in the urban setting. (The Stanford Watershed Model, incorporated into HSPF, was the first continuous model.) The model was developed by the Army Corps of Engineers, Hydrologic Engineering Center (HEC) originally for application to the San Francisco master drainage plan (Roesner et al., 1974; HEC, 1977) for abatement of combined sewer overflows (CSOs) into San Francisco Bay (McPherson, 1974). Sixty-two years of hourly rainfall data were analyzed with STORM to provide optimal combinations of storage and treatment for the master plan. The HEC also provides additional guidelines for model application (Abbott, 1977).

The support of the HEC, renowned for the suite of hydrologic models, led to extensive use of STORM in the late 70s and early 80s, but the lack of HEC updates in recent years has caused a decline in model use. Nonetheless, many applications may be found, including Heaney et al. (1977) for a nationwide assessment, Shubinski et al. (1977) for the Detroit area, and Najarian et al. (1986) in New Jersey. A simplified receiving water quality model was developed for streams for use with the STORM model (Medina, 1979), although Medina's model could also be driven by other continuous simulation models.

A very similar model to STORM was developed by Lager et al. (1976) for application in San Francisco and Rochester, known as ASimplified SWMM.@ This model is not currently available, and STORM is essentially a substitute.

11. Validation/Review

STORM has been used in many applications although seldom compared against measured rainfall-runoff data; one such comparison is by Abbott (1978) in which model predictions compared favorably with hourly runoff values. The model's many applications by diverse users serve as a form of validation.

12. Contact

In 1989, the distribution of the most popular of the HEC programs, e.g., HEC-1 and HEC-2 and some others, was transferred to selected private vendors. Direct HEC support for these programs is limited to Corps of Engineers or other federal agencies. However, STORM is still available directly only from the HEC for $200 on a 9-track magnetic tape. No microcomputer version is available. Only the Fortran IV source code is distributed; the user must perform the compilation. Contact

The Hydrologic Engineering Center
Corps of Engineers
609 Second Street
Davis, California 95616

13. References

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Nonpoint Source Model Review

1. Name of Method

*Distributed Routing Rainfall Runoff Model*C*Quality DR3M-QUAL*

2. Type of Method

	Surface Water Model:	Simple Approach
xx	Surface Water Model:	Refined Approach
	Soil (Groundwater) Model:	Simple Approach
	Soil (Groundwater) Model:	Refined Approach

3. Purpose/Scope

Purpose: Predict rainfall/runoff/quality processes in urban and other areas. Predict hydrographs and pollutographs (concentration vs. time) in

xx runoff waters
xx surface waters
ground waters

Source/Release Types:

xx Continuous
Single
xx Intermittent
Multiple
xx Diffuse

Level of Application:

Screening
xx Intermediate
xx Detailed

Types of Chemicals:

xx Conventional
xx Organic
xx Metals

Unique Features:

xx Addresses degradation products
Integral database/database manager
Integral uncertainty analysis capabilities
Interactive input/execution manager

4. Level of Effort

System setup:	xx mandays	xx manweeks	manmonths
Assessments:	mandays	xx manweeks	xx manmonths

(Estimates reflect order-of-magnitude values and depend heavily on the experience and ability of the assessor.)

5. Description of the Method/Techniques

The Distributed Routing Rainfall Runoff ModelCQuality (DR3M-QUAL) incorporates water quality routines into an updated version of an earlier U.S. Geological Survey (USGS) urban hydrologic model (Dawdy et al., 1972). Runoff is generated from rainfall using the kinematic wave method over multiple subcatchments and routed through drainage pathways by the same technique. Storage-indication routing is available for storage basins. The model can be run over any time period and is sometimes used to simulate a group of storms while bypassing simulation of the intervening dry periods (although a moisture balance is maintained). A built-in optimization routine aids in estimation of quantity parameters.

Quality is simulated for arbitrary parameters using exponential build-up functions plus wash-off functions determined from experience with model calibration. Considerable guidance is provided for parameter estimation. Removal of built-up solids can occur during dry weather by street cleaning. Erosion is simulated using empirical equations relating sediment yield to runoff volume and peak. Some guidance is provided for the erosion parameters using relationships based on the Universal Soil Loss Equation. Concentrations of other constituents can be taken as a fraction (Apotency factors@) of sediment concentration. Precipitation can contribute a constant concentration.

Quality routing through the drainage network is done by a Lagrangian scheme to simulate plug flow and no decay. Plug flow routing is also performed in storage basins, with settling based on sedimentation theory and dependent on a particle size distribution.

6. Data Needs/Availability

Data needs depend on the degree of schematization. Quantity parameters for a subcatchment include area, imperviousness, length, slope, roughness and infiltration parameters. Channels are characterized by trapezoidal or circular dimensions and kinematic wave parameters. Storage basins require stage-area-discharge relationships. Quality parameters include build-up and wash-off coefficients. Rainfall input can be for single or multiple storms.

Quantity data are similar in form to those required by other urban hydrologic models and may be derived from contour maps and drainage plans available from municipalities. Build-up and wash-off parameters are very difficult to estimate a priori and require local, site-specific quality measurements for calibration if accurate quality predictions are needed, e.g., to drive a receiving water quality model.

7. Output of the Assessment

DR3M-QUAL produces a time history of runoff hydrographs and quality pollutographs (concentration or load vs. time) at any location in the drainage system. Summaries for storm events are provided as well as line printer graphics for hydrographs and pollutographs.

8. Limitations

The kinematic wave is perhaps as good a conceptual model as exists for overland flow but approximations are always inherent in its application, as for any conceptual model. The quantity model can be expected to perform reasonably well with minimal calibration. No interaction among quality parameters exists (other than the ability to treat one pollutant as a fraction of sediment concentration). Except for the sedimentation algorithm within storage units, simulation of sediment transport processes is weak, as with virtually all other models of this type. Generally, quality predictions must be calibrated if accurate concentrations and loads are required, e.g., to drive a receiving water quality model. On the other hand, relative comparisons can be made using generalized U.S. data for calibration purposes.

9. Hardware/Software Requirements

The program is written in Fortran 77 for IBM or Prime mainframes. Source code is provided on a 9-track magnetic tape for compilation and installation on the user's computer.

10. Experience

The basis for the hydrologic components of DR3M-QUAL is the earlier modeling work of Dawdy et al. (1972) that was updated first for the quantity portion of the model (Dawdy et al., 1978; Alley and Smith, 1982a) and then for additional quality routines (Alley and Smith, 1982b). Much of the emphasis on the form and calibration of build-up and wash-off parameters is based on research done by Alley et al. (1980), Alley (1981), and Alley and Smith (1981). The program has received extensive internal review within the USGS and has been applied to their urban modeling studies in South Florida (Doyle and Miller, 1980), Rochester (Kappel et al., 1985; Zarriello, 1988), Anchorage (Brabets, 1986), Denver (Lindner-Lunsford and Ellis, 1987), and Fresno (Guay and Smith, 1988). A summary of experience with the model is given by Alley (1986).

11. Validation/Review

The program has undergone the extensive internal peer review process of the USGS and has been tested and compared with field data on at least 37 catchments by various individuals (Alley, 1986). It has primarily been used by persons within the USGS although it is freely available to anyone.

12. Contact

The Fortran 77 source code and documentation are available on a 9-track magnetic tape (to be supplied by the user) from the USGS National Center:

Ms. Kate Flynn
U.S. Geological Survey
410 National Center
Reston, Virginia 22092
(703) 648-5313

Minimal support is available from the program authors (Alley and Smith).

13. References

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Nonpoint Source Model Review

1. Name of the Method

EPA Screening Procedures

2. Type of Method

xxx Surface Water Model: Simple Approach
Surface Water Model: Refined Approach
Air Model: Simple Approach
Air Model: Refined Approach
Soil (Groundwater) Model: Simple Approach
Soil (Groundwater) Model: Refined Approach
Multi-media Model: Simple Approach
Multi-media Model: Refined Approach

3. Purpose/Scope

Purpose: Predict concentrations of contaminants in

xxx runoff waters
xxx surface waters
ground waters

Source/Release Types:

Continuous Intermittent
Single xxx Multiple xxx Diffuse

Level of Application:

xxx Screening Intermediate Detailed

Type of Chemicals:

xxx Conventional xxx Organic xxx Metals

Unique Features:

Addresses degradation products
Integral Database/Database manager
Integral Uncertainty Analysis Capabilities
Interactive Input/Execution Manager

4. Level of Effort

System setup:	xx mandays	manweeks	manmonths	manyear
Assessments:	xx mandays	xx manweeks	manmonths	manyear

(Estimates reflect order-of-magnitude values and depend heavily on the experience and ability of the assessor.)

5. Description of the Method/Techniques

EPA Screening Procedures (Mills et al., 1982, 1985) are a revision and expansion of water quality assessment procedures initially developed for nondesignated 208 areas (Zison et al., 1977). The procedures have been expanded and revised to include consideration of the accumulation, transport, and fate of toxic chemicals, in addition to conventional pollutants included in the earliest version. The manual includes a separate chapter describing calculation procedures for estimating NPS loads for urban and nonurban land areas in addition to chapters on procedures for rivers and streams, impoundments, and estuaries. A useful overview chapter on the aquatic fate processes of toxic organisms is also included.

The procedures for NPS load assessments described in the manual are essentially a compilation and integration of estimation techniques developed earlier by Midwest Research Institute (McElroy et al., 1976), Amy et al. (1974), Heany et al. (1976) (i.e., SWMM-Level I), and Haith (1980). However, the presentation of the procedures is well integrated, supplemented with additional parameter estimation information, and includes sample calculations. The procedures for nonurban areas are derived from MRI loading functions for average annual estimates based on Universal Soil Loss Equation (Wischmeier and Smith, 1978), while the storm event procedures use the modified USLE (Williams, 1975) and the SCS Runoff Curve Number procedure (Mockus, 1972) for storm runoff. Pollutant concentrations in soils and enrichment ratios are required for estimating pollutant loads; precipitation contributions of nutrients can be included. Specific information is included for estimation of salinity loads in irrigation return flows, and storm event pesticide losses are estimated separately based on procedures developed by Haith (1980).

Annual and storm event loads from urban areas follow the procedures included in the SWMM-Level I (Heaney et al., 1976) and Amy et al. (1974) respectively. The basic procedures are relatively standard for urban areas, calculating pollutant loads as a function of solids accumulation and washoff.

The EPA Screening Procedures have excellent user documentation and guidance, including occasional workshops sponsored by the EPA Water Quality Modeling Center, Athens, Georgia.

6. Data Needs/Availability

The data requirement is minimal and is also available from the manual when site specific data is lacking. Soil and land use data is required for estimating runoff and sediment yield. This data is readily available from USDA-SCS soil survey reports. Tables for estimating water quality input parameters for nitrogen, phosphorous, heavy metals, and pesticides are included in the manual.

7. Output of the Assessment

Output available from the model include predicted stream concentrations of BOD, DO, total N, total P, temperature, and conservative and organic pollutants by reach; total lake concentrations, organic pollutants eutrophic status, and hypolimnion DO deficit; and estuary concentrations of BOD, DO, total N, total P, and conservative pollutants by reach. As calculations are done on a hand calculator they can be arranged according to user's convenience.

8. Limitations

It is a very simplified procedure requiring the user to estimate pollutant concentrations. It use is very limited while evaluating impacts of various management practices. As calculations are done on a hand calculator, they can be tedious and time consuming for complex multi-media use basins. Snowmelt runoff and loadings are ignored.

9. Hardware/Software Requirements

No computer requirement, calculations can be done by hand calculators.

10. Experience

These procedures have enjoyed wide popularity, partly due to the availability of training workshops sponsored by EPA, and have been applied in a number of regions, including the Sandusky River in northern Ohio and the Patuxent, Ware, Chester, and Occuquan basins in the Chesapeake Bay region (Davis et al., 1981; Dean et al., 1981a; and Dean et al., 1981b).

11. Validation/Review

12. Contact

For copies of the manual contact

Center for Exposure Assessment Modeling
U.S. Environmental Protection Agency
Environmental Research Laboratory
Athens, GA. 30605
(706) 546-3549

13. References

Amy, G., R. Pitt, R. Singh, W.L. Bradford and M.B. LaGraff. 1974. Water Quality Management Planning for Urban Runoff. U.S. EPA, Washington, D.C., EPA 440/9-75-004. (NTIS PB 241 689/AS).

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Zison, S.W., K. Haven and W.B. Mills. 1977. Water Quality Assessment: A Screening Methodology for Nondesignated 208 Areas. EPA-600/6-77-023, U.S. EPA, Athens, GA.

Nonpoint Source Model Review

1. Name of the Method

Agricultural NonPoint Source Pollution Model©(AGNPS)

2. Type of Method

Surface Water Model: Simple Approach
xxx Surface Water Model: Refined Approach
Air Model: Simple Approach
Air Model: Refined Approach
Soil (Groundwater) Model: Simple Approach
Soil (Groundwater) Model: Refined Approach
Multi-media Model: Simple Approach
Multi-media Model: Refined Approach

3. Purpose/Scope

Purpose: Predict concentrations of contaminants in

xxx runoff waters
xxx surface waters
ground waters

Source/Release Types:

Continuous Intermittent
Single xxx Multiple xxx Diffuse

Level of Application:

xxx Screening xxx Intermediate xxx Detailed

Type of Chemicals:

xxx Conventional Organic Metals

Unique Features:

Addresses degradation products
Integral Database/Database manager
Integral Uncertainty Analysis Capabilities
xxx Interactive Input/Execution Manager

4. Level of Effort

System setup:	xx mandays	xx manweeks	manmonths	manyear
Assessments:	mandays	xx manweeks	xx manmonths	manyear

(Estimates reflect order-of-magnitude values and depend heavily on the experience and ability of the assessor.)

5. Description of the Method/Techniques

Agricultural Nonpoint Source Pollution Model (AGNPS) was developed by the U.S. Department of Agriculture—Agriculture Research Service (Young et al., 1986) to obtain uniform and accurate estimates of runoff quality with primary emphasis on nutrients and sediments and to compare the effects of various pollution control practices that could be incorporated into the management of watersheds.

The AGNPS model simulates sediments and nutrients from agricultural watersheds for a single storm event or for continuous simulation. Watersheds examined by AGNPS must be divided into square working areas called cells. Grouping of cells results in the formation of subwatersheds, which can be individually examined. The output from the model can be used to compare the watershed examined against other watersheds to point sources of water quality problems, and to investigate possible solutions to these problems.

AGNPS is also capable of handling point source inputs from feedlots, waste water treatment plant discharges, and stream bank and gully erosion (user specified). In the model, pollutants are routed from the top of the watershed to the outlet in a series of steps so that flow and water quality at any point in the watershed may be examined. The Modified Universal Soil Loss Equation is used for predicting soil erosion, and a unit hydrograph approach used for the flow in the watershed. Erosion is predicted in five different particle sizes namely sand, silt, clay, small aggregates, and large aggregates.

The pollutant transport portion is subdivided into one part handling soluble pollutants and another part handling sediment attached pollutants. The methods used to predict nitrogen and phosphorus yields from the watershed and individual cells were developed by Frere et al. (1980) and are also used in CREAMS (Knisel, 1980). The nitrogen and phosphorus calculations are performed using relationships between chemical concentration, sediment yield and runoff volume.

Data needed for the model can be classified into two categories: watershed data and cell data. Watershed data includes information applying to the entire watershed which would include watershed size, number of cells in the watershed, and if running for a single storm event then the storm intensity. The cell data includes information on the parameters based on the land practices in the cell.

Additional model components that are under development are unsaturated/saturated zone routines, economic analysis, and linkage to Geographic Information System.

6. Data Needs/Availability

The input data needed are extensive however, can be obtained through visual field observations, maps (topographic and soils) and from various publications, table and graphs (Young et al. 1986). Meteorologic data consisting of daily rainfall is needed for hydrology simulation. The model also has an option to evaluate watershed response to a single storm event. Data on soil and land use can be obtained from local USDA-SCS field offices.

7. Output of the Assessment

The model provides estimates of: (1) hydrology, with estimates of both runoff volume and peak runoff rate; (2) sediment, with estimates of upland erosion, channel erosion, and sediment yield; and nutrients (both sediment attached and dissolved), with estimates of pollution loadings to receiving cells. A graphics option in the program allows the user to plot different variables within the watershed.

8. Limitations

The model does not handle pesticides. The pollutant transport component needs further field testing. Nutrient transformation and instream processes are not within model capabilities.

9. Hardware/Software Requirements

The program is written in standard FORTRAN 77 and has been installed on IBM PC/AT and compatibles. A hard disk is required for operation of the program and a math co-processor is highly recommended. Executable code prepared with Ryan-McFarland compiler and is available only for MS/DOS environment. Source code is only available for MS/DOS environment.

10. Experience

The model is being used extensively within United States to evaluate nonpoint source pollution by various government agencies and consultants. The model has been used by Shi (1987) to perform economic assessment of soil erosion and water quality in Idaho. Setia and Magleby (1987) and Setia et al. (1988) used AGNPS for evaluating the economic effect of nonpoint pollution control alternatives. The model has also been used by Koelliker and Humbert (1989) for water quality planning. APNPS was used by Frevert and Crowder (1987) to analyze agricultural nonpoint pollution control options in the St. Albans Bay watershed.

11. Validation/Review

The model has been validated using field data from agricultural watersheds in Minnesota, Iowa, and Nebraska (Young et al., 1986). Lee (1987) validated the model in an Illinois watershed using the single storm option of the model. The author found that the simulated and observed data for runoff volume and sediment yield were well represented when compared with observed data.

12. Contact

The copies of the AGNPS program and the manual are available from

Dr. Robert Young
USDA-ARS
North Central Research Laboratory
Morris, MN 56267
Phone: (612) 589-3411

13. References

Frere, M.H., J.D. Ross and L.J. Lane. 1980. AThe Nutrient Submodel.@ In: Knisel, W.G. (ed.). 1980. CREAMS: A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. U.S. Department of Agriculture. Conservation Research Report No. 26. pp. 65-86.

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Nonpoint Source Model Review

1. Name of the Method

Areal Nonpoint Source Watershed Environment Response SimulationC(ANSWERS)

2. Type of Method

Surface Water Model: Simple Approach
xxx Surface Water Model: Refined Approach
Air Model: Simple Approach
Air Model: Refined Approach
Soil (Groundwater) Model: Simple Approach
xxx Soil (Groundwater) Model: Refined Approach
Multi-media Model: Simple Approach
Multi-media Model: Refined Approach

3. Purpose/Scope

Purpose: Predict concentrations of contaminants in

xxx runoff waters
surface waters
ground waters

Source/Release Types:

Continuous
Single
Intermittent
Multiple
xxx Diffuse

Level of Application:

xxx Screening
xxx Intermediate
Detailed

Type of Chemicals:

xxx Conventional
Organic
Metals

Unique Features:

Addresses degradation products
xxx Integral Database/Database manager
Integral Uncertainty Analysis Capabilities
Interactive Input/Execution Manager

4. Level of Effort

System setup: xx mandays xx manweeks manmonths manyear
Assessments: mandays xx manweeks xx manmonths manyear

(Estimates reflect order-of-magnitude values and depend heavily on the experience and ability of the assessor.)

5. Description of the Method/Techniques

Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) was developed at the Agricultural Engineering Department of Purdue University (Beasley and Huggins, 1981). It is an event based, distributed parameter model capable of predicting the hydrologic and erosion response of agricultural watersheds.

Application of ANSWERS requires that the watershed to be subdivided into a grid of square elements. Each element must be small enough so that all important parameter values within its boundaries are uniform. For a practical application element sizes range from one to four hectares. Within each element the model simulates the processes of interception, infiltration, surface storage, surface flow, subsurface drainage, and sediment drainage, and sediment detachment, transport, and deposition. The output from one element then becomes a source of input to an adjacent element.

As the model is based on a modular program structure it allows easier modification of existing program code and/or addition of user supplied algorithms. Model parameter values are allowed to vary between elements, thus, any degree of spatial variability within the watershed is easily represented.

Nutrients (nitrogen and phosphorus) are simulated using correlation relationships between chemical concentrations, sediment yield and runoff volume. A research version (Amin-Sichani, 1982) of the model uses Aclay enrichment@ information and a very descriptive phosphorus fate model to predict total, particulate, and soluble phosphorus yields.

6. Data Needs/Availability

Data need comprise of detailed description of the watershed topography, drainage network, soils, and land use. Most of the data can be obtained from USDA-SCS soil surveys, land use and cropping surveys.

7. Output of the Assessment

The model can evaluate alternative erosion control management practices for both agricultural land and construction sites (Dillaha et al., 1982). Output can be obtained on an element basis or for the entire watershed in terms of flow and sediment. The ANSWERS program comes with a plotting program.

8. Limitations

For a simulation run of ANSWERS on a large watershed a mainframe computer is required. However, for smaller watersheds a IBM-PC compatible version of ANSWERS is available. The model is a storm event model and the input data file is quite complex to prepare. Snowmelt processes or pesticides cannot be simulated by the model. The water quality constituents modeled are limited to nitrogen and phosphorous. These constituents are represented by relationships between chemical concentrations with sediment yield and runoff volume. No transformation of nitrogen and phosphorus is accounted for in the model.

9. Hardware/Software Requirements

The program is written in standard FORTRAN 77 and has been installed on IBM PC/AT and compatibles. A hard disk is required for operation of the program and a math co-processor is highly recommended. Executable code prepared with Ryan-McFarland compiler.

10. Experience

The model has been successfully applied in Indiana on an agricultural watershed and a construction site to evaluate best management practices by Beasley (1986).

11. Validation/Review

Individual components of the model have been validated by the developers.

12. Contact

To obtain copies of the model please write or call Dr. David Beasley at the following address:

Dr. David Beasley, Professor and Head
Dept. of Agricultural Engineering
University of Georgia
Coastal Plain Experiment Station
P.O. Box 748
Tifton, GA 31793
(912) 386-3377

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Nonpoint Source Model Review

1. Name of the Method

Chemicals, Runoff, and Erosion from Agricultural Management SystemsC(CREAMS)
Groundwater Loading Effects of Agricultural Management SystemsC(GLEAMS)

2. Type of Method

Surface Water Model: Simple Approach
xxx Surface Water Model: Refined Approach
Air Model: Simple Approach
Air Model: Refined Approach
Soil (Groundwater) Model: Simple Approach
xxx Soil (Groundwater) Model: Refined Approach
Multi-media Model: Simple Approach
Multi-media Model: Refined Approach

3. Purpose/Scope

Purpose: Predict concentrations of contaminants in

xxx runoff waters
surface waters
xxx ground waters (vadose and root zone)

Source/Release Types:

Continuous   Intermittent
Single   xxx Multiple   xxx Diffuse

Level of Application:

xxx Screening   xxx Intermediate   xxx Detailed

Type of Chemicals:

xxx Conventional   xxx Organic   Metals

Unique Features:

xxx Addresses degradation products
Integral Database/Database manager
Integral Uncertainty Analysis Capabilities
Interactive Input/Execution Manager

4. Level of Effort

System setup: xx mandays   xx manweeks   manmonths   manyear

Assessments: mandays xx manweeks xx manmonths manyear

(Estimates reflect order-of-magnitude values and depend heavily on the experience and ability of the assessor.)

5. Description of the Method/Techniques

Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) was developed by the U.S. Department of AgricultureCAgricultural Research Service (Knisel, 1980; Leonard and Ferreira, 1984) for the analysis of agricultural best management practices for pollution control. CREAMS is a field scale model that uses separate hydrology, erosion, and chemistry submodels connected together by pass files.

Runoff volume, peak flow, infiltration, evapotranspiration, soil water content, and percolation are computed on a daily basis. If detailed precipitation data are available then infiltration is calculated at histogram breakpoints. Daily erosion and sediment yield, including particle size distribution, are estimated at the edge of the field. Plant nutrients and pesticides are simulated and storm load and average concentrations of sediment-associated and dissolved chemicals are determined in the runoff, sediment, and percolation through the root zone (Leonard and Knisel, 1984).

User defined management activities can be simulated by CREAMS. These activities include aerial spraying (foliar or soil directed) or soil incorporation of pesticides, animal waste management, and agricultural best management practices (minimum tillage, terracing, etc.).

Calibration is not specifically required for CREAMS simulation, but is usually desirable. The model provides accurate representation of the various soil processes. Most of the CREAMS parameter values are physically measurable. The model has the capability of simulating 20 pesticides at one time.

Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) was developed by the United States Department of AgricultureCAgriculture Research Service (Leonard et al., 1987) to utilize the management oriented physically based CREAMS model (Knisel, 1980) and incorporate a component for vertical flux of pesticides in the root zone. A nitrogen component for the root zone is in development.

GLEAMS consists of three major components namely hydrology, erosion/sediment yield, and pesticides. Precipitation is partitioned between surface runoff and infiltration and water balance computations are done on a daily basis. Surface runoff is estimated using the Soil Conservation Service Curve Number Method as modified by Williams and Nicks (1982). The soil is divided into various layers, with a minimum of 3 and a maximum of 12 layers of variable thickness are used for water and pesticide routing (Knisel et al., 1989).

6. Data Needs/Availability

The data needed for CREAMS are quite detailed. As CREAMS is a continuous simulation model the data needs are extensive. Meteorologic data consisting of daily or breakpoint precipitation is required for hydrology simulation. Monthly solar radiation and air temperature data is also needed for estimating components of the hydrological cycle. Data regarding soil type and properties along with information on crops to be grown is needed. A broad range of values for various model parameters can be obtained from the user's manual.

7. Output of the Assessment

Various output options are available for hydrology and nutrient simulations, including storm, monthly, or annual summary. Output for each segment of the overland flow and channel elements is available from areas in the watershed where intense erosion or deposition can be identified.

8. Limitations

The maximum size of the simulated area is limited to a field plots. A watershed scale version (Opus) of CREAMS/GLEAMS is currently under development (Ferreira, personal communication). The model is limited in data management and handling. The model cannot simulate instream processes. Although CREAMS has been applied in a wide range of climatic regimes, there is concern regarding its simulation capability for snow accumulation, melt, and resulting runoff, and hydrologic impacts of frozen ground conditions (see Jamieson and Clausen, 1988; Kauppi, 1982; Knisel et al., 1983).

9. Hardware/Software Requirements

The program is written in standard FORTRAN 77 and has been installed on IBM PC/AT-compatibles. A hard disk is required for operation of the program and a math co-processor is highly recommended. The program can be obtained on floppy disk for MS/DOS operating systems.

10. Experience

CREAMS has been extensively applied in a wide variety of hydrologic settings with good success. CREAMS has been used for in a wide variety of hydrologic and water quality studies (Smith and Williams, 1980; Morgan and Morgan, 1982; Lane and

Ferreira, 1980; Kauppi, 1982; Knisel et al., 1983; and Jamieson and Clausen, 1988). Crowder et al. (1985) have used CREAMS in conjunction with an economic model to evaluate effects of conservation practices.

11. Validation/Review

The model has been validated by the developers along with independent experts. Erosion/sedimentation component of the CREAMS model has been verified by Foster and Ferreira (1981). Smith and Williams (1980) have validated the hydrology submodel at 46 sites in the southern and midwestern portions of United States. GLEAMS model has been validated with field data for Fenamiphos and its metabolites by Leonard et al., 1990. The authors report satisfactory comparison between observed and simulated results.

12. Contact

To obtain copies of the model please write or call Dr. Walt Knisel or Frank Davis at the following address:

USDA-Agricultural Research Service
Southeast Watershed Research Lab
P.O. Box 946
Tifton, Georgia 31793
(912) 386-3462

13. References

Beasley, D.B. and D.L. Thomas. 1989. Application of Water Quality Models for Agricultural and Forested Watersheds. Southern Cooperative Series Bulletin No. 338. Agricultural Experiment Station, University of Georgia, Athens, GA.

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Nonpoint Source Model Review

1. Name of the Method

Hydrological Simulation ProgramCFortran (HSPF)
Stream Transport and Agricultural Runoff of Pesticides for Exposure Assessment (STREAM)

2. Type of Method

Surface Water Model: Simple Approach
xxx Surface Water Model: Refined Approach
Air Model: Simple Approach
Air Model: Refined Approach
Soil (Groundwater) Model: Simple Approach
xxx Soil (Groundwater) Model: Refined Approach
Multi-media Model: Simple Approach
Multi-media Model: Refined Approach

3. Purpose/Scope

Purpose: Predict concentrations of contaminants in

xxx runoff waters
xxx surface waters
xxx ground waters

Source/Release Types:

xxx Continuous
xxx Single
xxx Intermittent
xxx Multiple
xxx Diffuse

Level of Application:

xxx Screening
xxx Intermediate
xxx Detailed

Type of Chemicals:

xxx Conventional
xxx Organic
Metals

Unique Features:

xxx Addresses degradation products
xxx Integral Database/Database manager
Integral Uncertainty Analysis Capabilities
xxx Interactive Input/Execution Manager

4. Level of Effort

System setup:	xx mandays	xx manweeks	manmonths	manyear
Assessments:	mandays	xx manweeks	xx manmonths	manyear

(Estimates reflect order-of-magnitude values and depend heavily on the experience and ability of the assessor.)

5. Description of the Method/Techniques

Hydrological Simulation ProgramCFORTRAN (HSPF) is a comprehensive package for simulation of watershed hydrology and water quality for both conventional and toxic organic pollutants. HSPF incorporates the watershed scale ARM and NPS models into a basic-scale analysis framework that includes fate and transport in one-dimensional stream channels. It is the only comprehensive model of watershed hydrology and water quality that allows the integrated simulation of land and soil contaminant runoff processes with instream hydraulic and sediment-chemical interactions.

The result of this simulation is a time history of the runoff flow rate, sediment load, and nutrient and pesticide concentrations, along with a time history of water quantity and quality at any point in a watershed. HSPF simulates three sediment types (sand, silt, and clay) in addition to a single organic chemical and transformation products of that chemical. The transfer and reaction processes included are hydrolysis, oxidation, photolysis, biodegradation, a volatilization, and sorption. Sorption is modeled as a first-order kinetic process in which the user must specify a desorption rate and an equilibrium partition coefficient for each of the three solid types. Resuspension and settling of silts and clays (cohesive solids) are defined in terms of shear stress at the sediment-water interface. For sands, the capacity of the system to transport sand at a particular flow is calculated and resuspension or settling is defined by the difference between the sand in suspension and the capacity. Calibration of the model requires data for each of the three solids types. Benthic exchange is modeled as sorption/desorption and desorption/scour with surficial benthic sediments. Underlying sediment and pore water are not modeled.

6. Data Needs/Availability

Data needs for HSPF are extensive. HSPF is a continuous simulation program and requires continuous data to drive the simulations. As a minimum, continuous rainfall records are required to drive the runoff model and additional records of evapotranspiration, temperature, and solar intensity are desirable. A large number of model parameters can also be specified although default values are provided where reasonable values are available. HSPF is a general-purpose program and special attention has been paid to cases where input parameters are omitted. Option flags allow bypassing of whole sections of the program where data are not available.

7. Output of the Assessment

HSPF produces a time history of the runoff flow rate, sediment load, and nutrient and pesticide concentrations, along with a time history of water quantity and quality at any point in a watershed. Simulation results can be processed through a frequency and duration analysis routine that produces output compatible with conventional toxicological measures (e.g., 96-hour LC50).

8. Limitations

HSPF assumes that the AStanford Watershed Model@ hydrologic model is appropriate for the area being modeled. Further, the instream model assumes the receiving water body model is well-mixed with width and depth and is thus limited to well-mixed rivers and reservoirs. Application of this methodology generally requires a team effort because of its comprehensive nature.

9. Hardware/Software Requirements

The program is written in standard FORTRAN 77 and has been installed on systems as small as IBM compatibles (80386/486). A hard disk is required for operation of the program and a math co-processor is required. No special peripherals other than a printer are required. The program is maintained for both the IBM PC-compatible and the DEC/VAX with VMS operating system. Executable code prepared with the Lahey FORTRAN compiler and Phar Lap DOS extender is available for the MS/DOS environment. Source code only is available for the VAX environment.

The program can be obtained in either floppy disk format for MS/DOS operation systems, or through the CEAM BBS or the CEAM Internet node earth1.epa.gov with interactive installation program. This program has been installed on a wide range of computers world-wide with no or minor modifications.

10. Experience

HSPF and the earlier models from which it was developed have been extensively applied in a wide variety of hydrologic and water quality studies (Barnwell and Johanson, 1981; Barnwell and Kittle, 1984) including pesticide runoff testing (Lorber and Mulkey, 1981), aquatic fate and transport model testing (Mulkey et al., 1986; Schnoor et al., 1987) analyses of agricultural best management practices (Donigian et al., 1983a; 1983b; Imhoff et al., 1983) and as part of pesticide exposure assessments in surface waters (Mulkey and Donigian, 1984).

An application of HSPF to five agricultural watersheds in a screening methodology for pesticide review is given in Donigian (1986). The Stream Transport and Agricultural Runoff for Exposure Assessment (STREAM) Methodology applies the HSPF program to various test watersheds for five major crops in four agricultural regions in the U.S., defines a “representative watershed” based on regional conditions and an extrapolation of the calibration for the test watershed, and performs a sensitivity analysis on key pesticide parameters to generate cumulative frequency distributions of pesticide loads and concentrations in each region. The resulting methodology requires the user to evaluate only the crops and regions of interest, the pesticide application rate, and three pesticide parameters—the partition coefficient, the soil/sediment decay rate, and the solution decay rate.

11. Validation/Review

The program has been validated with both field data and model experiments and has been reviewed by independent experts. Numerous citations for model applications are included in the References below. Recently, model refinements for instream algorithms related to pH and sediment-nutrient interactions have been sponsored by the USGS and the EPA Chesapeake Bay Program, respectively.

12. Contact

The model is available from the Center for Exposure Assessment Modeling at no charge. Mainframe versions of the programs compatible with the DEC VAX systems are available on standard on-half inch, 9-track magnetic tape. When ordering tapes, please specify the type of computer system that the model will be installed on (VAX, PRIME, HP, Cyber, IBM, etc.), whether the tape should be non-labeled, if non-labeled specify the storage formate (EBCDIC or ASCII), or if the tape should be formatted as a VAX files-11, labeled (ASCII) tape for DEC systems. Model distributions tapes contain documentation covering installation instructions on DEC systems, FORTRAN source code files, and test input data sets and output files that may be used to test and confirm the installation of the model on your system. Users are responsible for installing programs.

Requests for PC versions of the models should be accompanied by 6 formatted double-sided, high-density (DS/HD), error free diskettes. Please do not send 5.25" diskettes. Model distribution diskettes contain documentation covering installation instructions on PC systems, DOS batch files for compiling, linking, and executing the model, executable task image(s) ready for execution of the model(s), all associated runtime files, and test input data sets and corresponding output files that may be used to test and confirm the installation of the model on your PC or compatible system.

To obtain copies of the models, please send appropriate number of formatted diskettes to the attention of Model Distribution Coordinator at the following address:

Center for Exposure Assessment Modeling
U.S. Environmental Protection Agency
Athens Environmental Research Laboratory
Athens, Georgia 30605
(706) 546-3549
USA

Program and/or user documentation, or instructions on how to order documentation, will accompany each response.

13. References

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Nonpoint Source Model Review

1. Name of the Method

*Pesticide Root Zone Model*C*PRZM*

2. Type of Method

xxx	Surface Water Model:	Simple Approach
	Surface Water Model:	Refined Approach
	Air Model:	Simple Approach
	Air Model:	Refined Approach
	Soil (Groundwater) Model:	Simple Approach
xxx	Soil (Groundwater) Model:	Refined Approach
	Multi-media Model:	Simple Approach
	Multi-media Model:	Refined Approach

3. Purpose/Scope

Purpose: Predict concentrations of contaminants in

xxx runoff waters
surface waters
xxx ground waters (vadose and root zone)

Source/Release Types:

Continuous — xxx Intermittent
Single — xxx Multiple — xxx Diffuse

Level of Application:

xxx Screening — xxx Intermediate — xxx Detailed

Type of Chemicals:

Conventional — xxx Organic — Metals (pesticides)

Unique Features:

xxx Addresses degradation products
Integral Database/Database manager

Integral Uncertainty Analysis Capabilities
Interactive Input/Execution Manager

4. Level of Effort

System setup:	xx mandays	xx manweeks	manmonths	manyear
Assessments:	mandays	xx manweeks	xx manmonths	manyear

(Estimates reflect order-of-magnitude values and depend heavily on the experience and ability of the assessor.)

5. Description of the Method/Techniques

Pesticide Root Zone Model (PRZM) was developed at the U.S. EPA Environmental Research Laboratory in Athens, Georgia by Carsel et al. (1984). It is a one-dimensional, dynamic, compartmental model that can be used to simulate chemical movement in unsaturated zone within and immediately below the plant root zone. The model is divided into two major components namely, the hydrology (and hydraulics) and chemical transport. The hydrology component which calculates runoff and erosion is based upon the Soil Conservation Service curve number procedure and the Universal Soil Loss Equation respectively. Evapotranspiration is estimated directly from pan evaporation or by an empirical formula if pan evaporation data is not available. Soil-water capacity terms including field capacity, wilting point, and saturation water content are used for simulating water movement within the unsaturated zone. Irrigation application is also within model capabilities.

Pesticide application on soil or on the plant foliage are considered in the chemical transport simulation. Dissolved, adsorbed, and vapor-phase concentrations in the soil are estimated by simultaneously considering the processes of pesticide uptake by plants, surface runoff, erosion, decay, volatilization, foliar washoff, advection, dispersion, and retardation. The user has two options to solve the transport equations using the original backward difference implicit scheme or the method of characteristics (Dean et al., 1989). As the model is dynamic it allows considerations of pulse loads.

PRZM is an integral part of a unsaturated/saturated zone model RUSTIC (Dean et al., 1989). RUSTIC (Risk of Unsaturated/Saturated Transport and Transformation of Chemical Concentrations) links three subordinate models in order to predict pesticide fate and transport through the crop root zone, and saturated zone to drinking water wells through PRZM, VADOFT, SAFTMOD.

VADOFT is a one-dimensional finite element model which solves Richard's equation for water flow in the unsaturated zone. VADOFT can also simulate the fate and transport of two parent and two daughter products. SAFTMOD is a two-dimensional finite element model which simulates flow and transport in the saturated zone in either an X-Y or X-Z configuration. The three codes PRZM, VADOFT, and SAFTMOD are linked together through an execution supervisor which allows users to build models for site specific situation. In order to perform exposure assessments, the code is equipped with a Monte Carlo pre and post processor (Dean et al., 1989).

6. Data Needs/Availability

The meteorological data needed by the model consist of daily rainfall, potential evaporation, and air temperature. If pesticide volatilization is to be simulated then additional meteorological data consisting daily wind speed and solar radiation are needed. Soils and land use data are required which can be obtained from local USDA-SCS field offices. The data regarding pesticide input parameters can be obtained from the user's manual or from published research.

7. Output of the Assessment

Predictions are made on a daily basis. Output can also be summarized for a daily, monthly, or annual period. Daily time series values of various fluxes and soil storages can be written to sequential files for further evaluation. In addition, a Special Action' option allows the user to output soil profile pesticide concentrations at user specified times (Dean et al., 1989).

8. Limitations

One of the model limitation is that it one-dimensional in the vertical direction and hence does not handle lateral flow. PRZM only simulates downward movement of water and does not account for diffusive movement due to soil water gradients. This process has been identified to be important when simulating the effects of volatilization by Jury et al. (1984). The model only simulates organic chemicals, for example pesticides.

9. Hardware/Software Requirements

The program is written in standard FORTRAN 77 and has been installed on IBM PC/AT-compatibles. A hard disk is required for operation of the program and a math co-processor is required. The program can be obtained on floppy disk for MS/DOS operating systems.

10. Experience

PRZM has been used to study Aldicarb application to citrus in Florida (Jones et al., 1983), and potatoes in New York (Carsel et al., 1985) and Wisconsin (Jones, 1983). It has also been used for Metalaxyl application to tobacco in Florida and Maryland (Carsel et al., 1986) and to Atrazine and chloride application to corn in Georgia (Carsel et al., 1985).

11. Validation/Review

The PRZM model has undergone testing with field data in New York and Wisconsin (potatoes), Florida (citrus), and Georgia (corn) (Carsel, et al., 1985, Jones 1983, Jones et al., 1983). The results of these tests demonstrate that PRZM is a useful tool for evaluating groundwater threats for pesticide use.

12. Contact

To obtain copies of the user's manual and the computer program contact

Center for Exposure Assessment Modeling
U.S. Environmental Protection Agency
Environmental Research Laboratory
Athens, GA. 30605
(706) 546-3549

13. References

Carsel, R.F., C.N. Smith, L.A. Mulkey, J.D. Dean and P. Jowise. 1984. User's Manual for the Pesticide Root Zone Model (PRZM): Release 1. EPA-600/3-84-109. U.S. Environmental Protection Agency. Environmental Research Laboratory, Athens, GA.

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Nonpoint Source Model Review

1. Name of the Method

Simulator for Water Resources in Rural Basins^{C}*(SWRRB)*
Pesticide Runoff Simulator^{C}*(PRS)*

2. Type of Method

Surface Water Model: Simple Approach
xxx Surface Water Model: Refined Approach
Air Model: Simple Approach
Air Model: Refined Approach
Soil (Groundwater) Model: Simple Approach
xxx Soil (Groundwater) Model: Refined Approach
Multi-media Model: Simple Approach
Multi-media Model: Refined Approach

3. Purpose/Scope

Purpose: Predict concentrations of contaminants in

xxx runoff waters
surface waters
xxx ground waters

Source/Release Types:

Continuous Intermittent
Single Multiple xxx Diffuse

Level of Application:

xxx Screening xxx Intermediate xxx Detailed

Type of Chemicals:

xxx Conventional xxx Organic Metals

Unique Features:

Addresses degradation products
Integral Database/Database manager
xxx Integral Uncertainty Analysis Capabilities
Interactive Input/Execution Manager

4. Level of Effort

System setup: xx mandays xx manweeks manmonths manyear

Assessments: mandays xx manweeks xx manmonths manyear

(Estimates reflect order-of-magnitude values and depend heavily on the experience and ability of the assessor.)

5. Description of the Method/Techniques

Pesticide Runoff Simulator (PRS) was developed for the U.S. EPA Office of Pesticide and Toxic Substances by Computer Sciences Corporation (1980) to simulate pesticide runoff and adsorption into the soil on small agricultural watersheds. PRS is based on SWRRB (Simulator for Water Resources in Rural Basins) originally developed by Williams et al. (1985) at the USDA.

The PRS hydrology and sediment simulation is based on the USDA CREAMS model. The SCS curve number technique is used to predict surface runoff. Sediment yield is simulated using a modified version of the Universal Soil Loss Equation and a sediment routing model.

The pesticide component of PRS is a modified version of the CREAMS pesticide model. Pesticide application (foliar and soil applied) can be removed by atmospheric loss, wash off by rainfall, and leaching into the soil. Pesticide yield is divided into a soluble fraction and an adsorbed phase based on an enrichment ratio.

The model includes a built in weather generator based on temperature, solar radiation, and precipitation statistics. Calibration is not specifically required, but is usually desirable.

Simulator for Water Resources in Rural Basins (SWRRB) was developed by Williams et al. (1985), and Arnold et al., (1989) for evaluating basin scale water quality. SWRRB operates on a daily time step and simulates weather, hydrology, crop growth, sedimentation, and nitrogen, phosphorous, and pesticide movement. The model was developed by modifying the CREAMS (Knisel, 1980) daily rainfall hydrology model for application to large, complex, rural basins.

Surface runoff is calculated using the Soil Conservation Service Curve Number technique. Sediment yield is computed for each basin by using the Modified Universal Soil Loss Equation (Williams and Berndt, 1977). The channel and floodplain sediment routing model is composed of two components operating simultaneously (deposition and degradation). Degradation is based on Bagnold's stream power concept and deposition is based on the fall velocity of the sediment particles (Arnold et al., 1989).

Return flow is calculated as a function of soil water content and return flow travel time. The percolation component uses a storage routing model combined with a crack flow model to predict the flow through the root zone. The crop growth model (Arnold et al., 1989) computes total biomass each day during the growing season as a function of solar radiation and leaf area index.

The pollutant transport portion is subdivided into one part handling soluble pollutants and another part handling sediment attached pollutants. The methods used to predict nitrogen and phosphorus yields from the rural basins are adopted from CREAMS (Knisel, 1980). The nitrogen and phosphorus calculations are performed using relationships between chemical concentration, sediment yield and runoff volume.

The pesticide component is directly taken from Holst and Kutney (1989) and is a modification of the CREAMS (Smith and Williams, 1980) pesticide model. The amount of pesticide reaching the ground or plants is based on a pesticide application efficiency factor. Empirical equations are used for calculating pesticide washoff which are based on threshold rainfall amount. Pesticide decay from the plants and the soil are predicted using exponential functions based on the decay constant for pesticide in the soil, and half life of pesticide on foliar residue.

6. Data Needs/Availability

Meteorologic data comprising of daily precipitation and solar radiation are required for hydrology simulations. Another set of input data consists of soils, land use, fertilizer, and pesticide application. The soils and land use data can be obtained from USDA-SCS soil survey maps. Some guidance is available in the manual for estimating parameters required for nutrient and pesticide simulation.

7. Output of the Assessment

The model predicts daily runoff volume and peak rate, sediment yield, evapotranspiration, percolation, return flow, and pesticide concentration in runoff and sediment.

8. Limitations

There is very minimal model documentation. In the hydrology component the snow accumulation processes are ignored, and for the case of pesticides no comprehensive instream simulation is available. Nutrient transformations along with pesticide daughter products are not accounted for in the model.

9. Hardware/Software Requirements

The PRS model is operational on the EPA National Computer Center on an IBM 370/168 computer under

MVS. The model may be accessed via WYLBUR for modification of the source code, creation or modification of input datasets, and submission of batch executions of the model.

The SWRRB program is written in standard FORTRAN 77 and has been installed on IBM PC/AT and compatibles. A hard disk is required for operation of the program and a math co-processor is highly recommended.

10. Experience

The SWRRB model has been used by the Exposure Assessment Branch, Hazard Evaluation Division, and the Office of Pesticide Programs of the USEPA (Arnold et al., 1989).

11. Validation/Review

SWRRB was tested on 11 large watersheds by Arnold and Williams (1987). These watersheds were located at eight Agricultural Research Service locations throughout the United States. The results showed that SWRRB can realistically simulate water and sediment yield under a wide range of soils, climate, land-use, topography, and management systems.

12. Contact

For copies of the SWRRB program and the user manual contact

Nancy Sammons
808 East Blackland Road
Temple, Texas 76502
(817) 770-6512

13. References

Arnold, J.G., J.R. Williams, A.D. Nicks and N.B. Sammons. 1989. ASWRRB, A Basin Scale Simulation Model for Soil and Water Resources Management.@ Texas A&M Press. 255 pp. (In Press).

Arnold, J.G. and J.R. Williams. 1987. AValidation of SWRRBCSimulator for Water Resources in Rural Basins.@ J. of Water Resources Planning and Management. 113(2):243-256.

Computer Science Corporation. 1980. Pesticide Runoff Simulator User's Manual. U.S. EPA, Office of Pesticides and Toxic Substances, Washington, D.C.

Holst, R.W. and L.L. Kutney. 1989. AU.S. EPA Simulator for Water Resources in Rural Basins.@ Exposure Assessment Branch, Hazard Evaluation Division, Office of Pesticide Programs, U.S. EPA (draft).

Knisel, W.G. (ed.). 1980. ACREAMS, A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems.@ USDA Conservation Research Report No. 26, 643 pp.

Smith, R.E. and J.R. Williams. 1980. ASimulation of the Surface Water Hydrology.@ In: CREAMS, A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. W.G. Knisel editor. USDA Conservation Research Report No. 26, pp. 13-35.

Williams, J.R. and H.D. Berndt. 1977. Sediment yield prediction based on watershed hydrology. Transactions of the ASAE. 20(6):1100-1104.

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Nonpoint Source Model Review

1. Name of the Method

Unified Transport Model for Toxic Materials—UTM-TOX

2. Type of Method

	Surface Water Model:	Simple Approach
xxx	Surface Water Model:	Refined Approach
	Air Model:	Simple Approach
xxx	Air Model:	Refined Approach
	Soil (Groundwater) Model:	Simple Approach
xxx	Soil (Groundwater) Model:	Refined Approach
	Multi-media Model:	Simple Approach
xxx	Multi-media Model:	Refined Approach

3. Purpose/Scope

Purpose: Predict concentrations of contaminants in

xxx runoff waters
xxx surface waters
ground waters (vadose and root zone)

Source/Release Types:

xxx Continuous
Single
Intermittent
xxx Multiple
xxx Diffuse

Level of Application:

Screening
Intermediate
xxx Detailed

Type of Chemicals:

xxx Conventional
xxx Organic
xxx Metals

Unique Features:

Addresses degradation products
Integral Database/Database manager
Integral Uncertainty Analysis Capabilities
Interactive Input/Execution Manager

4. Level of Effort

System setup:	xx mandays	xx manweeks	manmonths	manyear
Assessments:	mandays	xx manweeks	xx manmonths	manyear

(Estimates reflect order-of-magnitude values and depend heavily on the experience and ability of the assessor.)

5. Description of the Method/Techniques

Unified Transport Model for Toxic Materials (UTM-TOX) was developed by Oak Ridge National Laboratory for the U.S. EPA Office of Pesticides and Toxic Substances, Washington, D.C. (Patterson et al., 1983). UTM-TOX is a multimedia model that combines hydrologic, atmospheric, and sediment transport in one computer code.

The model calculates rates of flux of a chemical from release to the atmosphere, through deposition on a watershed, infiltration and runoff from the soil, to flow in a stream channel and associated sediment transport. From these calculations mass balances can be established, chemical budgets made, and concentrations in the environment estimated.

The atmospheric transport model (ATM) portion of UTM-TOX is a Gaussian plume model that calculates dispersion of pollutants emitted from point (stack), area, or line sources. ATM operates on a monthly time step, which is longer than the hydrologic portion of the model and results in the use of an average chemical deposition falling on the watershed.

The Terrestrial Ecology and Hydrology Model (TEHM) describes soil-plant water fluxes, interception, infiltration, and storm and groundwater flow.

The hydrologic portion of the model is from the Wisconsin Hydrologic Transport Model (WHTM), which is a modified version of the Stanford Watershed Model (SWM). WHTM includes all of the hydrologic processes of the SWM and also simulates soluble chemical movement, litter and vegetation interception of the chemical, erosion of sorbed chemical, chemical degradation in soil and litter, and sorption in top layers of the soil. Stream transport includes transfer between three sediment components (suspended, bed, and resident bed).

6. Data Needs/Availability

The input data includes monthly wind, hourly precipitation, solar radiation, daily maximum and minimum temperatures, soil characteristics, topographic information, surface water characteristics, sediment characteristics, and the physiochemical properties and transformation rates associated with the chemical.

7. Output of the Assessment

The output can be obtained in terms of plots and tables summarizing the average monthly and annual chemical concentrations in the 8 wind sectors, in saturated and unsaturated soil layers, in runoff, out of each reach, and in the stems, leaves, roots and fruits of vegetation.

8. Limitations

The model ignores the interaction between chemicals and sediment in streams. There is a large time and spatial resolution of ATM portion of the model relative to the hydrologic processes. The model is quite complex and requires significant user expertise.

9. Hardware/Software Requirements

UTM-TOX is large computer program and is written is FORTRAN IV. The program was developed for IBM 370/3033 or VAX 11/780 systems.

10. Experience

An earlier version of the model has been applied by Munro et al. (1976) to evaluate the movement of lead, cadmium, zinc, copper and sulphur through Crooked Creek Watershed. This earlier version was also used by Huff et al. (1977) to Walker Branch Watershed. One of the current application of the model is reported by Patterson (1986) for estimating lead transport budget in the Crooked Creek Watershed. No current references since 1986 on the application of the model are available.

11. Validation/Review

The model components have been field validated by several researchers (Culkowski and Patterson, 1976; Munro et al., 1976; and Raridon, Fields, and Henderson, 1976).

12. Contact

To obtain copies of the model and the manual contact

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13. References

Culkowski, W.M. and M.R. Patterson. 1976. A Comprehensive Atmospheric Transport and

Diffusion Model. ORNL/NSF/EATC-17.

Huff, D.D., G.S. Henderson, C.L. Begovich, R.L. Luxmoore and J.R. Jones. 1977. The Application of Analytic and Mechanistic Hydrologic Models to the Study of Walker Branch Watershed. In: Watershed Research in Eastern North America. A Workshop to Compare Results. D.L. Corell (editor). Vol. II, pp. 741-766.

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Patterson, M.R. 1986. Lead Transport Budget in Crooked Creek Watershed. In: *Pollutants in Multimedia Environment*. Plenum Press. 1986. pp. 93-118.

Raridon, R.J., D.E. Fields and G.S. Henderson. 1976. Hydrologic and Chemical Budgets on Walker Branch WatershedCObservations and Modeling Applications. ORNL/NSF/EATC-24.