Modeling Impacts of Post Development Water Quality BMPs

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Abstract. IDEAL (Integrated Design, Evaluation and Assessment of Loadings)is an innovative, object based model developed to predict water quality benefits of LID (Low Impact Development) and/or BMPs (Best Management Practices) in urban post construction watersheds. The paper will describe scenarios from Greenville County, SC, USA using local rainfall and soils information. Results of this modeling effort are intended to show the effectiveness of various treatment trains. LID concepts and BMPs modeled include disconnecting storm drains, use of water barrels, bioretention cells, bioswales, sand filters, and VFS. Comparison is made with the use of LID concepts and BMPs with traditional wet and dry ponds. IDEAL features the capability of predicting distributed source area generation of runoff, sediment, nutrients, and pathogens in post construction watersheds. Procedures are also available to apply the model to the urban fringe with construction and agricultural source areas as well. The graphical user interface features drop and drag capability and works for large numbers of subwatershed source areas, conveyances, and BMPs arranged in treatment trains. Numbers and sizes of subwatersheds are limited only by computational time and appropriateness of the conveyance objects. BMPs are modeled with process based algorithms that take into account mass continuity and the processes of infiltration, settling, and sorption for chemicals and pathogens as well as mortality and growth for pathogens. Interarrival time of storms is considered, and rainfall input can either be single storm or a matrix of conditional probability of rainfall amounts, seasons, and infiltration or curve numbers.

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Keywords. Water quality model, urban development, best management practices, low impact development, stormwater, sediment control, urban hydrology, bacteria, nutrients

Introduction

To adequately address water quality concerns as they relate to storm water discharges, it is important to understand the types of pollutants that are present. or expected to exist, as well as their potential impacts on receiving water bodies. It is equally important that the origins of the various pollutants and how they may change be identified such that source controls and appropriate downstream measures can be applied.

IDEAL (Integrated Design, Evaluation and Assessment of Loadings) is a model developed in response to needs of both regulatory personnel, as well as the regulated community, to have a method that could enable them to evaluate loadings from rural and urban areas as they change in order to understand their potential for downstream impacts. The control of runoff can usually be classified into two categories: runoff quantity control and runoff quality control. Quantity control techniques are relatively well established and are based on the physical laws of conservation and momentum. Such measures seek to attenuate peak runoff flow rates and to reduce hydrograph volumes to mitigate flooding and the potential for erosion downstream. A much more difficult task is the water quality control of urban runoff. This problem is confounded by the intermittent nature of rainfall, the variability of rainfall characteristics such as volume and intensity, changing land cover, and the variability of constituent concentrations.

IDEAL considers a variety of post construction best management practices (BMPs) including both wet or dry detention ponds, vegetative filter strips, bioswales, bioretention cells, and sand filters.

An extensive set of outputs, including both text and graphs to show hydrographs, sedigraphs, chemigraphs, and pollutographs, are available for each object as well as at the discharge (outlet) from the watershed.

Model Development

User Interface

The graphical input/output interface provides drag-and-drop capabilities so that subwatersheds, best management practices, engineered devices, and conveyances can be easily added, deleted, and modified together with existing practices. The graphical input/output allows objects like subwatersheds, best management practices and connectors to be easily added, moved, deleted, copied and pasted for "What if…?" scenarios. One of the unique capabilities is the ability to evaluate the same watershed with two or more different treatment trains simultaneously, and to even look at the loadings at intermediate points in the watershed so that the benefit of a specific practice can be defined. A critical aspect is that a watershed can have multiple subwatersheds in order to deal with highly complex arrangements of land use and best management practices arranged throughout the subwatershed.

Storms and Rainfall Probability

Rainfall data bases are required for each location to be modeled. The user inputs location which triggers rainfall probability related inputs from data base or parameters for a single design storm. This information considers the probability of daily rainfall depth falling in one of 12 rainfall depth classes if rainfall occurs, the probability that it occurs during the growing or dormant season, and the probability that it occurs when conditions are dry, average, or wet. Hyetographs based on NRCS Type Storms I, IA, II, and III are determined from geographic location.

Loadings

As a watershed model that deals with complex issues of both water quantity and water quality, IDEAL contains diverse methods to predict loadings as a result of land use and BMPs (Best Management Practices). Loading functions were developed for IDEAL for each of the following constituents: sediment, total nitrogen, and total phosphorus. Bacterial loadings have also been developed but are not considered in this paper.

Loading – Pervious Areas

Watershed Characteristics are input into IDEAL and allow each subwatershed to have pervious, impervious, and/or combined subareas. The user can right click on subareas to edit and add characteristics for the pervious and impervious areas including area, length, slope and depth of the exposed soil layer.

<u>Hydrology and Soil.</u> Hydrology characteristics allow the user to provide inputs that are based on local rainfall characteristics as well as land cover properties. These characteristics include NRCS Storm Types (I, Ia, II, III), precipitation depth for the design storm(s), storm duration, rainfall data for each location including probabilities associated with depth.

Additional soil and hydrology user inputs are used either directly or to link specific data for that soil or hydrologic condition in order to minimize data input by the user. These values are typical of many other runoff related programs. The NRCS curve number method is used to estimate runoff volume with the Green and Ampt method as an alternative, which is particularly important for infiltration-based low impact development BMPs. IDEAL uses the unit hydrograph method with a rainfall excess hyetograph to compute the total runoff hydrograph. The additional inputs are land use, soil series, depth range, NRCS curve number, time of concentration, watershed drainage area, peak rate factor (based on land use), slope, and slope length.

<u>Sediment Yield</u>. Sediment yield loading for pervious areas is based on the Modified Universal Soil Loss Equation (MUSLE) with hydrology calculations as previously described using the curve number method and unit hydrograph to get peak flow and surface runoff depth. Sediment yield user inputs for the pervious areas include soil erodibility, cover and practice factor, tendency to rill, power function coefficient “a” for time distribution of sediment, soil texture information (% sand, silt and clay) for parent material which is used to estimate eroded sizes.

Erosion particle sizes are estimated using the CREAMS size distribution which predicts fractions that occur in five classes (sand, silt, clay, large aggregates, and small aggregates). It is particularly important to identify clay that is contained within aggregates in order to predict trapping of nutrients attached to the clay when the clay is trapped. The CREAMS estimates are the only generally accepted predictor currently available although local data are preferred and can replace these predictions.

<u>Sediment Size Distribution.</u> The typical way to represent particle size distributions in sediment models is to have a composite size distribution with varying equivalent particle settling diameters. In IDEAL, mass of sediment is divided into primary particles and aggregates to account for differences in specific gravity. The two are treated as separate size distributions, and their identity maintained as a storm moves through the watershed. For a given watershed, fractions of clay, silt, and sand in the parent material are used to estimate fractions of primary clay, silt and sand, and small and large aggregates (as well as average diameters of each), specific gravity of each particle class, and fraction of clay in each particle class. After obtaining this information, equivalent settling diameters for the small or large aggregates are determined based on specific gravity.

For primary particles, average diameters are fixed. For aggregates, diameters vary as a function of clay content of parent material. Since the CREAMS equations do not define break points between particle classes, we assume that breakpoint between two adjacent classes is the log mean diameter of the two.

Since average diameters of clay, silt, and sand do not vary with clay content of parent material, the lower and upper diameters for clay and sand, respectively, do not change. Conversely, average diameters of small and large aggregates change dramatically with clay content. This causes problems making calculations that identify particles as small or large aggregates. To overcome this problem for the aggregate group, computations were made of the values. This analysis established limits that should be reasonable when applied across a broad range of soils with varying clay content.

Accurate calculation of trapping in BMPs requires that particle sizes be subdivided into smaller increments. Therefore, particle sizes are discretized uniformly for both primary particles and aggregates, using logarithmic scales. An important parameter is to identify number of particle subdivision segment that contains lower and upper diameters for primary particles and aggregated particles. Likewise, number of particle subdivision segment that contains breakpoint diameters between particle classes is also important.

Subclasses were defined for both primary particles and aggregates. Total mass for each size increment for the sediment being eroded must be specified in order to combine upslope areas as the model moves downstream. Further, this must be divided into aggregates and primary particles. Total eroded sediment on a segment is calculated from the sum of predictions.

Fraction of eroded sediment in each particle class is calculated. Once number of log increments in each particle class is known, amount of sediment detached is assumed to be uniformly distributed across each subclass.

Nutrients and Other Chemicals. An isotherm approach is used to divide the concentration of pollutants (Total N or Total P) between the concentration that is in the liquid phase and the solid phase which is found on the clay. The isotherm distributes the nutrient of interest between the sorbed and dissolved states based on empirical data assuming equilibrium. To simplify the process, a linear isotherm is used to approximate the actual isotherm.

Pathogens. Bacteria considered in the model will be referred to as reference bacteria as it would be very difficult to consider all types of bacteria individually. In the current application, Ecoli are considered to be the reference. The loading of bacteria, like nutrients, is based on event mean concentrations (EMC) in this version of IDEAL since the alternative is to estimate bacterial loadings based on numerous, ill-defined functions. The event mean concentration is assumed to be distributed among the active clay and the dissolved phase with the distribution defined by an empirical isotherm. The procedures for developing isotherms for bacteria are being refined, and limited soils have been tested. The results will be incorporated into the program as they become available.

Loading – Impervious Areas

Hydrology. Hydrology information for impervious areas follows the same general methodology as used in pervious areas. However, soils information is not required, and drains can either be connected or not.

Sediment Yield and Sediment Size Distribution. The loading function for sediment yield from impervious areas uses a size distribution assuming that only primary particle sizes (clay, silt, and sand) occur. Their fractions and sizes are based on the NURP data base. Local data collection is recommended but often is not readily available. Sediment yield loading from impervious areas is based on event mean concentration (EMC) times the runoff volume where EMC is typically statistically determined based on land cover/use.

Nutrients and other chemicals. An isotherm approach is used to divide the concentration of pollutants (Total N or Total P) between the concentration that is in the liquid phase and the solid phase which is found on the clay. The isotherm distributes the nutrient of interest between the sorbed and dissolved states based on empirical data assuming equilibrium. To simplify the process, a linear isotherm is used to approximate the actual isotherm.

Pathogens. Pathogen loadings from impervious areas are treated using the same EMC/isotherm approach as used for the pervious areas. The major differences are caused by the differences in source and the eroded particle size distribution.

Logical Devices and Conveyances

Logical devices are objects that are included in IDEAL in order to connect structures with the watershed. They are points at which flows and loadings are calculated and where output can be viewed, enabling users to evaluate the effectiveness of individual structures. Conveyances direct flow to structures and can include routing. IDEAL does not currently account for deposition/erosion in conveyances. Logical devices include the following items.

Open Channels. Open channels generally have defined channel shapes and sizes and can vary from vegetated, roadside ditches to concrete channels to natural streams.

Closed Conduits. Closed conduits are simply pipes that may be flowing as open channels or under pipe flow.

Diversions. Diversions which allow flow splitting into different downstream structures. Junctions which provide for combining from multiple connectors.

Diffuse Connector. Diffuse connectors are similar to level spreaders in that they distribute the flow over a relatively wide flow width (similar to sheet flow) in order to avoid concentrated flow problems.
Nonrouted Connectors. Non-routed connectors simply connect structures but have no effective travel time so that hydrographs do not change from the inflow to outflow of a non-routed connector.
Outlet. The outlet provides an end point for the system (only one outlet per watershed is allowed).

BMPs

For this paper, the only BMPs considered will be dry ponds and vegetative filters.
Ponds. Dry and Permanent Pools (including forebays). IDEAL estimates efficacy of a variety of structural practices including wet or dry ponds. Trapping is based on the detention time within the pond as a result of routing flows.
Vegetative Filter Strips (VFSs). Substantial interest has been shown in Low Impact Development BMPs that promote infiltration and nutrient uptake with more being added in response to demand. As an example, this paper will use vegetative filters as described below, but bioswales, bioretention cells, sand filters and other practices follow similar approaches. In addition to the hydrograph and pollutant loadings routed from previous upstream areas, BMP structures, and connectors, vegetative filters require the inputs pertaining to their size, soils and infiltration, vegetation.

Applications of IDEAL to Urban Watersheds

IDEAL is flexible so that a wide range of scenarios can be addressed ranging from a single subwatershed without any best management practices (BMPs) to many subwatersheds having the same or a different treatment train on each. For example, the setup for a relatively simple scenario might consist of a pervious subwatershed draining either through a channel to a vegetative filter strip (VFS) or draining directly through a channel to a wet detention pond. A more complex situation that is used as the basis for this paper is the one contained in Figure 1. In this situation, there are eight identical subwatersheds each consisting of 2.5 acres of pervious area for a total of 20 acres. Each subwatershed is shown to drain through a diffuse channel to a VFS, and then each of the VFSs drain through an open channel to a common dry detention pond that drains through a circular conduit to the outlet where loadings are estimated. The following six scenarios are considered in this paper:

1. Loadings at the outlet only with no BMPs in place,
2. Loadings from the outlet with only the VFSs in place,
3. Loadings from the outlet with only the detention pond in place,
4. Loadings from the outlet with only the detention pond in place, but it is twice as large,
5. Loadings from the outlet with all VFSs and the detention pond, and
6. Loadings from the outlet with all VFSs and the detention pond is twice as large.

Precipitation Data. IDEAL uses a variety of information which is included in databases contained within the model. A particularly critical component is the precipitation data for the location of interest. By clicking on the cloud icon in the upper left of the IDEAL workspace as shown in Figure 1, the user can select either single storm or multiple storm scenarios. If multiple storms are selected, conditional probabilities of 72 storms are used to estimate loadings on an average annual basis. The dormant season was defined for each year of the historical record as the period between the first low temperature less than 33^{o}F in the fall and the last day in the spring having a low temperature less than 33^{o}F. However for purposes of illustration in this paper, single storm scenarios using either a 2-yr, 24-hr storm or a 10-yr, 24-hr storm were selected for precipitation in order to demonstrate that load reductions are significantly impacted by the storm size. In all scenarios, the storm was assumed to occur during the growing season under average moisture conditions.
Subwatershed Description. Each of the subwatersheds used in the scenarios is considered to be an identical pervious area consisting of 2.5 ac with a CN of 72, peak rate factor of 325, and a time of concentration of 0.16 hr. The soil consists of 12.5, 21.5 and 66 percent clay, silt and sand, respectively, with a soil erodibility of 0.28. Average annual event mean concentrations for nutrients are assumed to be 2.06 mg/l for total nitrogen and 0.28 mg/l for total phosphorus. The subwatershed, VFS and pond conditions remain constant so that the impact of storm events is evident. Clearly, the model allows for differences in soil conditions, event mean concentrations, grasses selected for VFSs, and pond size/configuration from one scenario to another.
Vegetative Filter Strip (VFS) Description. Each of the VFSs was assumed to be 40 ft wide by 100 ft long in the direction of flow with a slope of 0.02 ft/ft. Soil texture, as used to estimated infiltration, was assumed to be sandy clay loam in all cases. The vegetation was taken to be a lawn which could be either mowed or unmowed and having vegetative characteristics similar to those of fescue.
Dry Detention Pond Description. The stormwater detention pond was assumed to be a dry pond with very good performance. The stage at 4 ft for Pond 1 provides a pond area of 1/2 ac. The pond has a low flow

orifice near the bottom having a diameter of 4 in. The outlet is a circular 24 in. riser connected to a 16 in. barrel having a length equal to 80 ft. There is also an emergency spillway to prevent overtopping. In scenarios 4 and 6, the pond area at all stages is double the size of the pond in scenarios 3 and 5; i.e., at a stage of 4 ft, the area is 1.0 ac. All other features have the same size.

Scenario Results

Considerable variation was found between results from the various BMP scenarios as shown in Tables 1 and 2, as well as Figures 2-5. This result was anticipated, but the purpose was to demonstrate that the model captures this variation and allows the user to easily evaluate the usefulness of various management practices using local inputs and can do so for a wide range of conditions. Table 1 shows the loadings resulting from each of the scenarios at Greenville for the 2-yr, 24 storm (3.7 in.) and the 10-yr, 24-hr storm (5.6 in.). Similarly, Table 2 shows the percent load reduction for the two storms. Figures 2 and 3 show the results from Table 1 graphically, and Figures 4 and 5 graphically present Table 2.

Scenario 1: No BMPs. Scenario 1 results are for the situation where there are eight, 2.5 ac subwatersheds with no BMPs and are shown in Table 1 for both the 2-yr and 10-yr storms. The magnitude of the differences in loadings is generally much greater than the difference between the design storms; i.e., while the smaller storm depth is 66% of the larger one, the runoff volume is only 47% as much. Sediment, nitrogen and phosphorus follow this same trend. Since no BMPs are included, no load reduction is shown in Table 2 for this scenario.

Scenario 2: VFS Only. Scenario 2 results include the benefit of having a VFS associated with each of the subwatersheds. Tables 1 and 2 show a reduction in sediment yield is about 74 and 84% for the 10-yr and 2-yr storms, respectively. Runoff volume is only reduced about 4-6% because of some infiltration within the VFS. Total nitrogen is reduced slightly by about 3-7%, and total phosphorus is reduced approximately 4-11% as a result of phosphorus that settles along with clay particles. In all cases, the smaller storm resulted in a larger reduction in loadings.

Scenario 3: Pond 1 Only. Scenario 3 includes the benefit of having the eight subwatersheds drain directly through a single dry detention pond before exiting the watershed. The pond provides substantial reduction in peak flow, but also provides significant reductions in volume of 8-15%. Hence, trapping of sediment leads to a reduction in sediment yield of 89-96%. Total phosphorus exhibits slight reductions ranging from about 3-11% while total nitrogen ranges from about 3-11%. Again, nitrogen is expected to be trapped primarily as a result of infiltration whereas phosphorus will be captured as a result of particle settling.

Scenario 4: Pond 2 Only. Scenario 4 is identical to that of Scenario 3 except the pond is twice as large at each stage. This pond is clearly oversized as compared to what is required by current regulations, but it does exhibit significantly reduced runoff volume (about 2.5 times more) compared to the Pond 1 scenario. Sediment reduction is somewhat higher as compared to the smaller pond, but nutrient loadings are reduced by a factor of 4.

Scenario 5: Pond 1 and VFSs. Scenario 5 demonstrates the benefits of having both VFSs directly connected to each subwatershed as well as a downstream detention pond. Runoff volume is reduced about 4 or 5% more than with Pond 1 only. Similarly, sediment and nutrients also are reduced slightly compared to the Pond 1 only scenario. In all cases shown, the pond has a much greater impact than do VFSs alone.

Scenario 6: Pond 2 and VFSs. Scenario 6 is again similar to Scenario 5 except the pond is twice as large as in Scenario 4. Again, the VFSs reduce the runoff volume by about 4% over Scenario 4 with Pond 2 only. Other constituents behave similarly to the Scenario 5. Comparing these scenarios, the user would be able to evaluate whether the extra expense and maintenance of the VFSs justify their usage. Also, the user might wish to look at a slightly larger pond than Pond 1 in order to determine whether that might be a better alternative as compared to the VFSs.

Conclusions

As shown, IDEAL provides an organized system for evaluating the effectiveness of a single management practice or a treatment train for reducing loadings from a watershed. Combinations of low impact development and traditional management practices can be evaluated quickly to determine whether practices are providing desired benefits. In cases where a specific problem exists such as phosphorus issues, IDEAL can also be used to easily make decisions as to whether a particular BMP or combination of BMPs is actually worthwhile in reducing the critical pollutant. Questions remain about the cost/benefit of small structures scattered around a development as compared to larger structures located near the outlet point, but IDEAL provides a method to compare various scenarios quickly. As additional economic data is incorporated, the intent is to be able to optimize design based on the water quantity/quality needs. Additional future plans for IDEAL include improvements to the user interfaces following suggestions by end users, refinements in the loading functions, and inclusion of additional BMPs such as extended bioswales and engineered devices.

Appendix

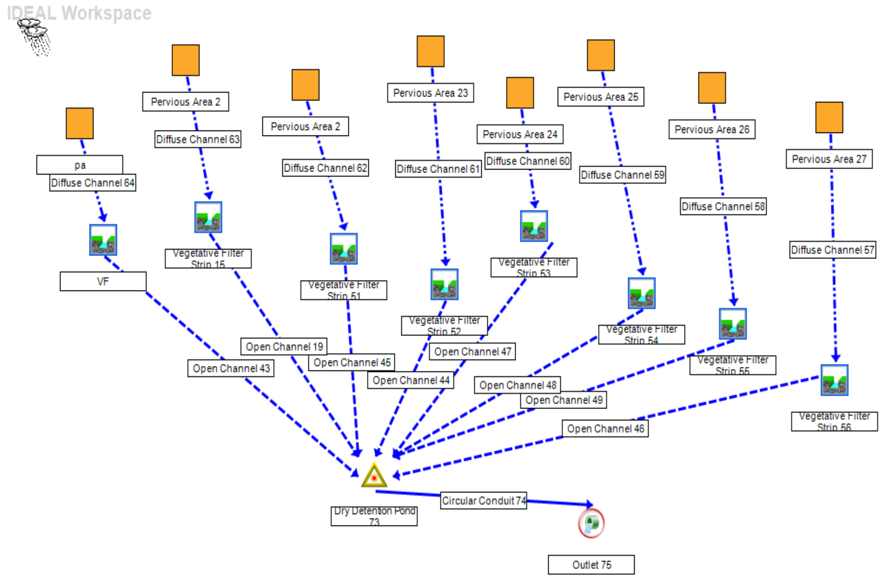

Figure 1. Scenario showing multiple subwatersheds, vegetative filters and wet pond connected to the outlet.

Table 1. Loadings with and without BMPs for six scenarios in Greenville, SC for both 2-yr and 10-yr, 24-hr storms, 3.7 in. and 5.6 in., respectively.

Yields from Single 2-yr, 24 Storm						
Scenario	1 - No BMPs	2 - VFS only	3 - P1 only	4 - P2 only	5 - P1+VFSs	6 - P2+VFSs
Runoff Volume	2.09	1.96	1.77	1.32	1.64	1.24
Sediment	34.3	5.5	1.4	0.5	1.1	0.5
Nitrogen	11.70	10.92	10.46	7.33	9.65	6.84
Phosphorus	1.59	1.42	1.42	1.00	1.26	0.89
Yields from Single 10-yr, 24 Storm						
Scenario	1 - No BMPs	2 - VFS only	3 - P1 only	4 - P2 only	5 - P1+VFSs	6 - P2+VFSs
Runoff Volume	4.45	4.29	4.10	3.61	3.94	3.44
Sediment	81.0	21.3	8.9	3.4	7.9	3.1
Nitrogen	24.92	24.22	24.23	22.10	23.51	21.28
Phosphorus	3.39	3.25	3.29	3.00	3.14	2.85

Table 2. Percent reductions with and without BMPs for six scenarios in Greenville, SC for both 2-yr and 10-yr, 24-hr storms, 3.7 in. and 5.6 in., respectively.

Percent Reductions for Single 2-yr, 24 Storm						
Scenario	1 - No BMPs	2 - VFS only	3 - P1 only	4 - P2 only	5 - P1+VFSs	6 - P2+VFSs
Runoff Volume	0.00	6.41	15.41	36.91	21.40	40.83
Sediment	0.00	84.00	95.84	98.52	96.71	98.57
Nitrogen	0.00	6.67	10.60	37.37	17.49	41.51
Phosphorus	0.00	10.56	10.69	37.40	20.99	43.95
Percent Reductions for Single 10-yr, 24 Storm						
Scenario	1 - No BMPs	2 - VFS only	3 - P1 only	4 - P2 only	5 - P1+VFSs	6 - P2+VFSs
Runoff Volume	0.00	3.57	7.82	18.97	11.37	22.61
Sediment	0.00	73.73	89.05	95.78	90.30	96.14
Nitrogen	0.00	2.81	2.77	11.32	5.66	14.61
Phosphorus	0.00	4.19	2.89	11.40	7.17	15.88

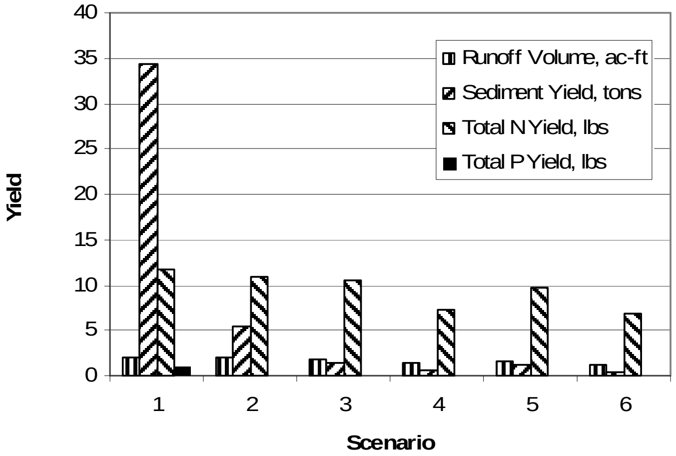

Figure 2. Runoff, sediment, total nitrogen and total phosphorus loadings for 2-yr, 24 hr storm at Greenville, SC example scenarios.

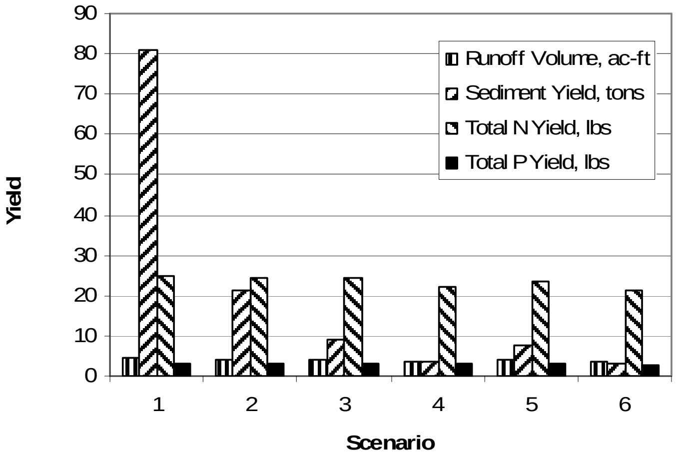

Figure 3. Runoff, sediment, total nitrogen and total phosphorus loadings for 10-yr, 24 hr storm at Greenville, SC example scenarios.

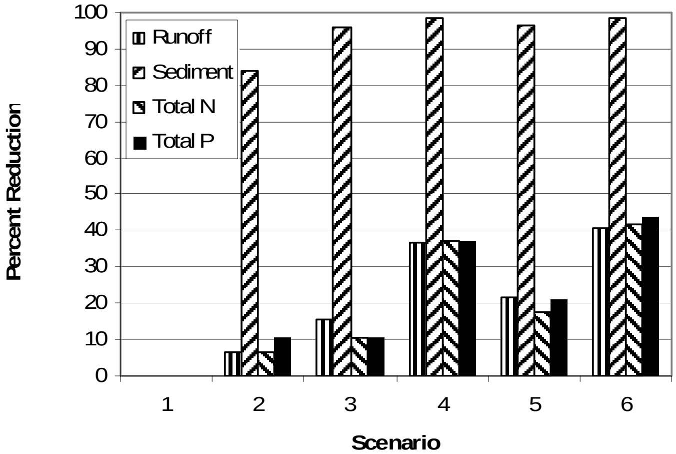

Figure 4. Percent reduction in runoff, sediment, total nitrogen and total phosphorus loadings for 2-yr, 24 hr storm at Greenville, SC example scenarios.

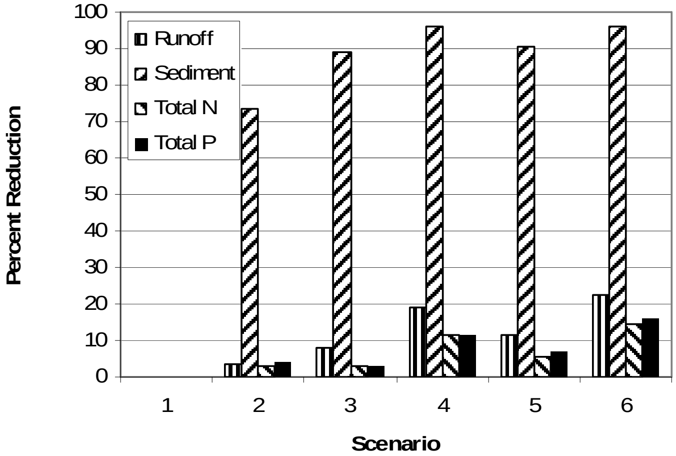

Figure 5. Percent reduction in runoff, sediment, total nitrogen and total phosphorus loadings for 10-yr, 24 hr storm at Greenville, SC example scenarios.