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FEATURES

A Model for Assessing the Impact of BMPs on Water Quality

IDEAL uses regional data to predict BMPs' effects on pollutants.

By John C. Hayes, Bill Barfield, K. Flint Holbrook, Jason Gillespie, Joe Fersner, and Brian Bates

'Best management practice' (BMP) is a buzzword that blankets a variety of industries and business disciplines. In the stormwater world, BMP generally relates to overall methods used to prevent, limit, or eliminate pollution in runoff. BMP, as a term, also applies specifically to the minimum control measures outlined in National Pollutant Discharge Elimination System (NPDES) permits.

What exactly is the 'best' BMP control measure for a given situation or geographic region? That hasn't been easy to answer. BMPs for stormwater-quality purposes other than for sediment control are relatively

Types of ponds the model can be used with

new; hence, federal and state environmental authorities have not been specific about these BMPs.

Historically, stormwater BMPs have been employed based on limited empirical data or trial and error, or by adopting another community's practices. That's added up to a lot of time and money wasted on BMPs what might not be 'best' at all. Communities easily have spent hundreds of thousands of dollars on, for example, silt fences, sediment ponds, straw bales, or riparian buffers, which had little discernible impact in reducing nonsediment pollution in source runoff.

A new spreadsheet model, however, is enabling engineers to determine, through quantifiable data, the best BMP for certain regions in South Carolina. Dubbed IDEAL (Integrated Design and Evaluation Assessment of Loadings), the physical process-based model, which includes region-specific rainfall and soil-type data, assesses the impact of BMPs on the discharge of sediment, nutrients, and bacteria contained in stormwater runoff.

IDEAL first was developed for the state's coastal region to help deal with rampant development. Between 1990 and 2000, more than one-fourth of South Carolina's population growth occurred in the counties adjacent the Atlantic Ocean, according to United States Census figures. Increased development has changed the hydrology of urban streams that feed into coastal wetlands and, ultimately, the ocean. The resulting increases in bacteria, suspended solids, phosphorus, and nitrogen have impacted animal and marine life, especially shellfish. Sources of bacteria also appear to be wildlife, pets in concentrated areas, poorly maintained septic tanks, cross connections, and leaking sanitary sewer lines. Moreover, high bacteria levels can result in beach closures, which might negatively affect tourism.

IDEAL was developed to be used along the state's coastline by the state's environmental regulatory authority, the South Carolina Department of Health and Environmental Control (specifically, DHEC's Ocean and Coastal Resource Management Division), to help meet antidegradation requirements.

To meet these requirements, DHEC staff must determine whether runoff from a proposed activity is expected to contain pollutants that already are causing impairment of the adjacent water body. This varies from project to project. Section 303 of the Clean Water Act requires DHEC to report every two years to EPA with a list of which waterways are impaired based on available sampling data. In addition, further analysis by South Carolina DHEC is ongoing to ultimately develop total maximum daily loads (TMDLs, the total amount of a pollutant a water body can receive from all sources and still meet water-quality standards) for these water bodies.

If stormwater runoff from the site will contribute pollutants that can cause water-quality impairment, the applicant must provide assurance that this project will not add further to the impairment or to the established TMDL.

DHEC states in *Antidegradation for Activities Contributing Non-Point-Source Pollution to Impaired Waters:* 'We believe this assurance can be provided with a demonstration of the efficiencies of a combination of BMPs.Š There is no specific methodology which must be followed; however, the demonstration must show that the BMPs to be installed will ensure that runoff from this site will not cause or contribute to further degradation of the water body.'

That's what makes IDEAL ideal: It generates BMP pollutant removal efficiencies that allow an engineer to design a system to meet the antidegradation requirements.

Table 1. Output for Greenville, SC, Example Problem — Runoff and Peak Discharge

Runoff and Peak Discharges	Avg. Storm	Annual Storm	Total Annual
Average Annual Single Storm			
Rainfall (in.)	0.4611	4.0000	53.94
Flow From Watershed to BMPs (if BMPs are specified)			
Q (ac.-ft.)	0.1907	3.7088	22.31
Q (in.)	0.1144	2.2253	13.38
qp (cfs)	2.5536	51.3446	
Fraction of Rainfall That Becomes Runoff	0.2481	0.5563	0.25
Volume of Rainfall on the Filters (if specified) (ac.-ft.)	0.0083	0.0765	1.03
Volume of Water Infiltrated in VFS (if specified) (ac.-ft.)	0.0000	0.0000	0.00
Flow From VFS Into Pond (if VFS is specified)	*VFS not specified*		
Flow From Pond (if pond is specified)			
qp (cfs)	1.5744	12.5610	
Peak Stage (ft.)	0.6137	10.8532	
Fraction of Runoff in per Pool	0.0000	0.0000	
Avg. qpo/qpi calib.	0.6166	0.2446	

In addition, a second version of the model was regionalized for Greenville County, SC, which is an inland NPDES Phase I community. Greenville County currently is using the model to address both antidegradation and municipal NPDES postconstruction requirements.

The model particularly has been helpful in identifying BMPs that deal with fecal coliform bacteria. Before IDEAL, Ocean and Coastal Resource Management staff found it very difficult to suggest analysis procedures that could demonstrate whether a development project discharge would further degrade the impaired water body by bacteria. This especially was difficult because the in-stream water-quality standard to meet for shellfish waters is 14 counts per 100 ml. Consequently, it was not uncommon to require an overall BMP pollutant removal efficiency to be the range of 98-99% in order to meet that standard.

To make the calculations, the spreadsheet requires user input on BMP, watershed, precipitation, and pollutant characteristics; however, default data have been provided based on a literature review. Traditional methods are utilized to develop peak flow rates and to determine total sediment yield. The spreadsheet then uses event mean concentrations (EMCs) for impervious areas and known particle sizes for pervious areas to determine total particulates entering the respective BMP. Because EMCs for constituents can fluctuate dramatically depending on local conditions, the program allows the user to input site- or watershed-specific EMCs if the data are available. The program then uses a combination of experimental isotherms, settling theory, and infiltration relationships to determine resulting trapping efficiencies for vegetative buffers, as well as dry detention and wet detention basins. The impact of variable interarrival times between storms on trapping in wet detention is accounted for by using the EPA model. In addition, trapping efficiencies for bacteria include calculations for removal because of natural mortality and mortality as a result of light penetration.

Calculating the annual runoff and loadings is based on a probabilistic approach. Calculations are made for 12 precipitation categories that are further subdivided into the growing and dormant seasons, with variations into wet, average, and dry antecedent moisture conditions. Derived from the joint probabilities of precipitation, growing season, and antecedent moisture condition, values of runoff and loading at each point on the watershed and exit points from the BMPs are statistically averaged and an annual value is calculated.

This user-friendly program can be calibrated and used for any locale within the US by adding site-specific climatic and soils information. Local EMCs are encouraged, but first estimates can be obtained by using the National Urban Runoff Program (NURP) dataset.

What follows is a more technical description of the IDEAL model. However, a detailed description of the equations used in IDEAL is not possible in the limited space in this article. The reader is referred to Barfield et al. (2002, 2003) for model details and to Hayes et al. (2003) for additional examples.

The Model in Summary

IDEAL is a spreadsheet model for assessing the impact of BMPs on the discharge of sediment, nutrients, and bacteria contained in stormwater runoff into local receiving waters. Effluent loads and concentrations of the above constituents are predicted to be influenced by vegetative filter strips, as well as by dry or wet detention ponds. Using regional probabilities of varying rainfall amounts, loadings, and yields from BMPs for individual storms are predicted and converted to average annual stream constituent loadings. In addition, IDEAL predicts two-year, single-storm loads.

Table 2. Output for Example Problem — Sediment Loading, Dry Detention

Sediment Loading and Trapping	Avg. Storm	Annual Storm	Total Annual
Watershed Yield			
Total TSS Yield From Watershed Into VFS or Drain (lb.)	113.34	13260.71	13260.71
Average Concentration (mg/l)	218.71	218.71	218.71
Clay-Size Particles (lb.)	19.33	514.44	2261.11
Settleable Nitrogen (lb.)	0.34	7.33	39.28
Settleable Phosphorus (lb.)	0.05	1.20	5.49
Active Fraction (clay) (lb.)	18.94	505.90	2216.34
Trapping in Pond - Dry Detention/Storm Flow			
Pond Specified and Type Detention	*Pond Specified*	*Dry*	
Total Sediment Trapped (lb.)	63.4545	2771.1677	7424.18
Clay-Size Particles (lb.)	3.0552	148.8143	357.4598
Settleable Nitrogen (lb.)	0.0326	1.5649	3.8155
Settleable Phosphorus (lb.)	0.0326	1.5649	3.8155
Active Fraction (clay) (lb.)	3.0171	146.9370	352.9965
Total Sediment Discharged (lb.)	49.8849	1223.2790	5836.5349
Clay-Size Particles (lb.)	16.2705	365.6212	1903.6510
Settleable Nitrogen (lb.)	0.3032	5.7695	35.4693
Settleable Phosphorus (lb.)	0.0401	0.8685	4.6942
Active Fraction (clay) (lb.)	15.9260	358.9669	1863.3439
Trapping Efficiency (Total Sediment)	0.5599	0.6938	0.5699
Trapping Efficiency (Active Fraction)	0.1593	0.2904	0.1593

Computations are made separately for impervious areas directly connected to drains and pervious areas with impervious areas not connected directly to drains. Each has the possibility of draining through vegetated buffer/filter strips. Flows and loadings are summed and then directed to a pond that can be either dry (no permanent pool) or wet (permanent pool).

Statistical average values for runoff, sediment, nutrient, and bacteria loadings are calculated based on the probability distribution of precipitation, season, and antecedent moisture for the region of interest to determine the probabilities of a given storm having a specified precipitation, that the event will occur in the growing season, and of a specific antecedent moisture condition.

Runoff volume at the outlet is calculated separately for each area using the Natural Resources Conservation Service (NRCS) Curve Number (CN) approach (Soil Conservation Service, 1972, 1973; 1985). The CN for average antecedent moisture conditions (AMC II) for each area is a user input with values for AMC I (dry condition) and AMC III (wet condition) calculated.

Runoff rates at area outlets also are calculated separately for each area using the NRCS TR-55 equations, which predict unit peak discharge as a function of time of concentration and ratio of initial abstraction to precipitation (Soil Conservation Service, 1975, 1986).

Total yield of sediment is calculated differently for impervious and pervious areas. For pervious areas, the yield is calculated from the Modified Universal Soil Loss Equation (MUSLE) using runoff volume and peak discharge (Williams, 1975). The soil-erodibility factor K, topographic factor LS, cover-management factor C, and practice factor P from the Universal Soil Loss Equation are model inputs for the pervious area. For impervious areas, the sediment yield is calculated from a user input EMC for total suspended solids (TSS), which is multiplied by runoff volume and specific weight of water with appropriate unit conversion. The fraction of sediment is calculated for each particle size class using the Chemicals, Runoff and Erosion from Agricultural Management Systems equations (Foster et al., 1985). For each particle size class, an average diameter and a specific gravity are defined, typically as a function of the fraction of original clay. The fraction of clay within each particle size class is also defined by the size fraction of clay and silt in the parent material. Size fractions being predicted with this parent size distribution are for a combination of aggregates and primary particles. Particle size distributions for material in impervious areas are derived from information from the NURP database (Schueler and Lugbill, 1990). All sediment in impervious areas is assumed to be in primary particles that previously have been blown in by the wind or aggregates that have been crushed by traffic.

Nutrients considered in the model are limited to total phosphorus and total nitrogen. The loading of nutrients is based on EMCs defined by land uses. Event mean concentration is assumed to be distributed among the active clay and dissolved phase with the distribution defined by an empirical isotherm. Actual loading is given by multiplying the EMC times runoff volume and an appropriate conversion factor. A first estimate of EMCs can be obtained from the NURP database and other data. Isotherms are utilized to distribute total concentration of a nutrient between liquid and adsorbed phases. Actual values for isotherms are determined experimentally in the laboratory and are plots of concentration on the solid phase (µg/gm sediment) versus concentration in the dissolved phase (mg/l) for a given nutrient. The laboratory analysis is used to develop the linear isotherm constant K_s and the maximum concentration on the solid phase $C_{s,max}$, which should be based on an actual isotherm for the predominant local soil.

Bacteria considered in the model can be either *E. Coli* or fecal coliform and are considered to be the reference. Loading of bacteria, such as nutrients, is based on EMCs. EMC is assumed to be distributed among the active clay and dissolved phase with distribution defined by an empirical isotherm.

Event mean concentration has been defined from a national database reported by Schueler and Holland (2000), but local data collection is encouraged to develop more accurate information. The user must input an appropriate EMC for bacteria.

Vegetative Filter Strips

In addition, IDEAL contains a module for vegetative filters that considers trapping sediment by both settling and infiltration into the soil matrix. In the model, dissolved chemicals are trapped via the 'settleable' component of chemicals and trapping of chemicals sorbed on active clay particles and as a result of the infiltration of pollutant-laden water into the soil matrix. Pollutant reduction due to chemical reactions is not considered. Bacteria are trapped or die because of several phenomena, settling on the active phase of clay-size sediment, infiltration into the soil matrix, natural mortality, and light penetration into water. In the vegetative filter strip, it is assumed that natural mortality and light penetration are small and that trapping primarily is a result of settling. The approach to trapping is identical in concept to that of nutrients. Vegetative filter strips will not be considered further in this article because of space constraints.

Dry Detention Pond BMPs

A dry detention pond has no permanent pool; thus, the lowest outlet essentially is at the bottom of the pond. Calculating the trapping in a pond requires that flow be routed hydraulically through the reservoir with peak stage and discharge calculated. Sediment is routed through the reservoir, followed by nutrients and bacteria.

Stage area is defined using a power function for the stage-area relationship. IDEAL allows combinations of drop inlets, weir outlets, orifice outlets, and emergency spillway. Locations and sizes of these controls are user inputs. Hydraulics calculations are based on standard relationships.

Routing of sediment is based on trapping efficiency. IDEAL calculates trapping efficiency for each particle class using the EPA model (Driscol et al., 1986), which uses a settling velocity for each particle class, average area of the pond during inflow, peak discharge, and a pond inefficiency parameter that accounts for the impacts of short circuiting, dead storage, and nonideal settling. Values of the parameters and a discussion of the prediction methodologies are given in Driscol et al. (1986) and Haan et al. (1994). Hydraulic and geometric information are the only inputs needed to predict trapping in a dry detention reservoir.

The in-flow mass of nutrients divided by inflow volume of water yields concentration. The mass of nutrients trapped is calculated using isotherms with predictions of the mass of clay-size particles trapped plus an estimation of the settling of particulate nutrients.

The bacteria model used is by Chapra (1997). Bacteria are trapped or killed as a result of three processes: (1) the settling of soil particles with attached bacteria to the pond bed, (2) the natural mortality that occurs in the pond, and 3) exposure to light that penetrates the pond. Each process is considered in the model.

Wet Detention Pond BMPs

A wet detention pond has a permanent pool; therefore the lowest outlet is not at the bottom of the pond. Calculating the trapping in a pond during storm flow is the same as that for dry detention. The only difference between the two models is that some of the storm flow resides in the permanent pool after the storm flow has ceased and settling of sediment and nutrients, as well as attenuation of bacteria, continues between storms in the permanent pool for the wet detention. Conversely, all of the flow is discharged with dry detention. The only additional variables required for wet detention, other than changing the stage area and outlet structure information, are the average interarrival period between rainfall events and the coefficient of variation of the interarrival time. The coefficient of variation is used with the EPA model (Driscol et al., 1986) to estimate the impact of variations in the interarrival times of storms and, hence, variations in the settling and attenuation of bacteria that occur between storms.

Example Calculations

A 20-ac. watershed in Greenville, SC, is being analyzed for effluent TSS, nitrogen, phosphorus, and fecal coliform. The watershed has 30% pervious areas, 30% impervious areas not connected to drains, and 40% impervious areas directly connected to drainage networks. Local rainfall data are from the Greenville-Spartanburg Airport. Soil is a Cecil sandy clay loam (hydrologic soil group B) with 54% sand, 34% silt, and 12% clay. Pervious areas are lawns in good condition. Impervious areas not connected to drains are residential homes. Impervious areas connected to drains are strip malls. The curve number for pervious areas is 61; for unconnected, impervious areas it is 98; and for impervious, connected areas it is 98. The time of concentration for pervious and unconnected, impervious areas is 0.2 hour, and for connected, impervious area to drains it is 0.25 hour. Soil erodibility for the watershed is 0.28, slope is 4%, average slope length is 100 ft., cover factor for lawns is 0.02, and the areas have no conservation practices, such as terraces.

Table 3. Output for Example Problem — Pollutant Loading, Dry Detention

Pollutant Loading and Trapping	Avg. Storm	Annual Storm	Total Annual
Vegetative Filter Strips Specified	*No Filter Specified*		
Pond Specified and Type Pond		*Dry Detention Pond Specified*	
Dry Detention (Stormwater Flow If Wet Detention Specified) & VFS			
Nitrogen			
From Watershed (lb.)	0.9742	11.6181	113.99
From Watershed (mg/l)	1.8800	1.1675	1.88
Discharged From Pond (if specified) (lb.)	0.9415	11.6128	110.16
Discharged From Pond (if specified) (mg/l)	1.8169	1.1670	1.82
Fraction Trapped VFS (if specified)	----	----	----
Fraction Trapped Dry Detention Pond (if specified)	0.0336	0.0005	0.03
Fraction Trapped Dry Detention Pond + VFS (if specified)	0.0336	0.0005	0.03
Phosphorus			
FromWatershed (lb.)	0.1327	8.6204	15.53
From Watershed (mg/l)	0.2561	0.2867	0.26
Discharged From Pond (if specified) (lb.)	0.1258	2.5977	14.72
Discharged From Pond (if specified) (mg/l)	0.2428	0.2553	0.24
Fraction Trapped VFS (if specified)	----	----	----
Fraction Trapped Dry Detention Pond (if specified)	0.0517	0.1136	0.05
Fraction Trapped Dry Detention Pond + VFS (if specified)	0.0517	0.6987	0.05
Bacterial Indicator			
From Watershed (number)	3.5278E+10	6.8629E+11	4.1276E+12
From Watershed (number/100 ml)	1.5000E+04	1.5011E+04	15000.00
Discharged From Pond (if specified) (number)	1.6808E+10	2.6769E+11	1.9666E+12
Discharged From Pond (if specified) (number/100 ml)	7.1467E+03	6.1475E+03	7146.70
Fraction Trapped VFS (if specified)	----	----	----
Fraction Trapped Dry Detention Pond (if specified)	0.5236	0.6099	0.52
Fraction Trapped Dry Detention Pond + VFS (if specified)	0.5236	0.6099	0.52

EMCs for the impervious areas directly connected to drains are 115 mg/l for TSS, 1.88 mg/l for nitrogen, 0.23 mg/l for phosphorus, and 15,000 counts/100 ml for bacteria. For pervious areas, the EMCs are 1.88 mg/l for nitrogen, 0.40 mg/l for phosphorus, and 15,000 counts/100 ml for bacteria. Although IDEAL can consider vegetative filters, a vegetative filter is not included in this example.

A dry detention pond controls runoff from both areas. The pond has a drop inlet with a riser of 18 in. in diameter with a crest located 0 ft. above the bottom of the pond, a barrel diameter of 12 in. and a length of 50 ft., Manning's roughness of 0.024, an entrance loss and bend-loss coefficient of 0.5, a weir coefficient of 3.1, and an orifice coefficient of 0.64. An emergency spillway is utilized with its crest at a stage of 12 ft., a length of crest of 20 ft. (parallel to flow path), a width of 30 ft. (perpendicular to the flow path), and a weir coefficient of 3.087. The pond area at a 5-ft. elevation above the pond bottom is 0.25 ac., and pond area at the crest of the emergency spillway (12 ft. above the pond bottom) is 0.5 ac. For comparison purposes, the outlet consists of an 18-in.-diameter drop inlet connected to a 12-in.-diameter barrel. The inlet location can vary depending on whether the pond is a wet or dry pond and the final design criteria. The crest of the emergency spillway is 12 ft. above the pond bottom.

Example outputs follow with runoff results summarized for the dry pond scenario in Table 1, sediment loading in Table 2, and pollutant loading from the dry detention pond shown in Table 3. As indicated in these tables, the spreadsheet provides extensive details about the trapping and loading of each constituent. While these details cannot be adequately explained in this article because of space limitations, the results provide the user with abundant information for decision-making regarding stormwater design. Several values have particular significance. From Table 1, the peak stage for the annual storm is 10.85 ft. (less than the emergency spillway elevation). Table 2 shows fraction trapped on an annual basis for the dry pond to be 0.56. Similarly, Table 3 shows fractions trapped for nitrogen and phosphorus as 0.03 and 0.05, respectively. These results allow the designer or regulator to determine quickly whether or not the design meets design requirements.

Table 4. Annual Loading Results of Fraction Trapped for TSS, Total Nitrogen, and Total Phosphorus Exiting the Dry Detention Pond in the Example Problem

Constituent	Elevation from Pond Bottom to Riser Crest (ft.)				
	0.0	0.5	2	4	6
TSS (mg/l)	0.56	0.61	0.71	0.80	0.86
Total N (mg/l)	0.07	0.05	0.08	0.11	0.16
Total P (mg/l)	0.10	0.07	0.11	0.14	0.19

Users can change one or more inputs (i.e., pond characteristics) and see the results promptly. This capability allows options to be explored quickly and allows designers to rapidly move toward a design based on local requirements. For example, the user can rapidly consider a wet pond having the same dimensions as the dry pond but with a riser located at 0.5, 2, 4, or 6 ft. above the pond bottom. Results shown in Table 4 show the annual loading results for fraction trapped of TSS, total nitrogen (total N), and total phosphorus (total P) for each of the five possible locations of the riser inlet ranging from the 0.0-ft. elevation corresponding to a dry pond to a wet pond having up to 6 ft. of permanent pool. If the design needs to meet a specific criterion, such as trapping 80% of TSS, it easily can be determined that the wet pond with 4-ft. elevation for the inlet is most appropriate. Similar comparisons of other design parameters can also be made. It should be noted that the results in Table 4 show that trapping efficiency for TSS improves as riser elevation increases, but trapping both total N and total P decreases with the low permanent pool (0.5-ft. elevation riser).

Conclusion

IDEAL is a process-based, spreadsheet model for urban areas that predicts and routes runoff and pollutant loads through BMPs. Model outputs are expected runoff, sediment, nutrient, and bacteria loadings based on statistical averages. IDEAL calculates statistical averages for runoff, sediment, nutrient, and bacteria loadings based on probability distributions of precipitation, season, and antecedent moisture. Runoff volume and peak discharge are calculated by the NRCS curve number and TR-55. Total watershed area is input along with percentages of pervious, impervious directly connected to drainage system, and impervious not connected to drains. Sediment is generated differently for pervious and impervious areas. Each can drain through vegetated filter strips. Flows and loadings are summed and then directed to either a dry or wet pond. For pervious areas, Williams's MUSLE is used. For impervious areas, an EMC for TSS is used. For each area, particle size distribution and percent clay in the sediment is estimated. Nutrients considered are limited to total P and total N, and isotherms distribute the total concentration of a nutrient between the liquid and adsorbed phases. Loading of bacteria, such as nutrients, is based on EMC and isotherms. Local engineers and regulators have shown considerable interest in using the program, particularly to meet antidegradation rules. IDEAL provides a framework so the model itself contains much of the regional, site-specific information. This provides consistency between design information so that engineers and regulators quickly can agree on appropriate input values and designs.

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