THE DEPOSITS MODEL (DEPOSITION PERFORMANCE OF SEDIMENT IN TRAP STRUCTURES)

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ABSTRACT

DEPOSITS is a conceptual model which simulates the sedimentation process in reservoirs and sediment detention structures. Damages associated with water borne sediment have escalated due to the rapid increase in urban development and strip mining in the last decade. The economic and recreational life of many reservoirs has been greatly reduced due to silting and pollution. The DEPOSITS Model provides a viable design method suitable for determining the impact of these detrimental factors. It may also be used in the design of sediment detention structures downstream of disturbed areas. Recent Federal and state legislation requires provision of detention structures in most disturbed areas and limitations on effluent sediment concentrations. Currently employed methods do not adequately account for the factors affecting sedimentation and give no estimate of effluent sediment concentrations. This paper presents a description of the simulation model, the environmental impact and benefits obtained from use of the DEPOSITS Model and an outline of its application as a design method. The model has been tested on five sediment detention basins and gave good predictions of their performance. The model is being used to study the factors affecting sediment deposition in urban and strip mine areas.

INTRODUCTION

The control of waterborne sediment is a major economic and environmental concern in the world today. The annual cost, in America, of the damages associated with waterborne sediment has been estimated to be several hundred million dollars. [7] Loss of storage space in reservoirs and an increased emphasis on water quality and pollution control has led to much legislation and research on the control of erosion and sedimentation.

Although agriculture and silviculture account for more than fifty percent of the sediment reaching streams and reservoirs, considerable damage is caused by construction and surface mining activities. The rate of erosion from these activities has been estimated as ten times that from cropland and two thousand times that from a forest area. [7] Onsite sediment control structures usually do not succeed in removing all sediment from the runoff and in several states provision must be made for a sediment detention basin. [6] These basins are usually designed using trap efficiency methods developed for steady state flow conditions or empirical curves developed from large reservoir data. These curves do not consider such basic factors as sediment concentrations, sediment particle size distributions, and the instantaneous values of inflow and outflow to the basin. Current federal and state legislation call for limitations on effluent sediment concentrations thus indicating the need for a method which also predicts effluent sediment concentrations. During ongoing research at the Agricultural Engineering Department, University of Kentucky, a conceptual model has been developed which simulates the sedimentation process in reservoirs and sediment detention structures.

The model estimates the trap efficiency of the reservoir and simulates sediment concentrations as a function of basin geometry, sediment physical properties, and inflow sedimentgraph, basin hydraulic characteristics and inflow hydrograph. Sediment accumulations in the basin and the effects of reduced storage space on the basin performance may also be simulated. The object of this paper will be to present a description of the simulation model, the environmental impact and benefits obtained from use of the DEPOSITS Model and an outline of its application as a design method. The model has been tested on five detention basins and gave good predictions of their performance. A brief summary of these tests is contained in the paper.

Reservoir Sedimentology

The erosion and deposition of sediment is dependent on many factors. Estimating the delivery of sediment to a resevoir or detention structure is dependent on the following factors:

1) Watershed geometry.
2) Rainfall intensity and distribution.
3) Vegetative and ground cover.
4) Soil characteristics.
5) Watershed sediment control structures.
6) Channel characteristics.

The most frequently used method is the Universal Soil Loss Equation (USLE), developed by Wischmeier and Smith. [15] The use of such predictive equations, however, requires a knowledge of the delivery ratio to the downstream sediment structure. Frequently detached coarse grained material is quickly redeposited and determination of the volume of sediment and the sediment concentrations of sediment laden flow entering a reservoir or detention structure remains a difficult problem.

The transport of sediment through a reservoir is dependent on the following factors:

1) The inflow sedimentgraph.
2) The inflow hydrograph.
3) The hydraulic characteristics of the basin.
4) The basin geometry.
5) The particle size distribution of the sediment.
6) Viscosity of the flow and the settling characteristics of the soil particles.

The hydraulic characteristics of the basin are determined by the inflow structure and the nature of the outlet spillway. Most reservoirs and detention structures are designed on the basis of flood and hydraulic performance and little regard is given to the effects of removal of sediment. Even in the design of sediment detention structures, basin and riser design is normally controlled by state codes specifying a minimum capacity required in the basin and the size of spillway necessary for safe passage of the design flood storm.

Most of the design methods currently available use very little information on the factors affecting sediment transport. A description of these methods may be found in several publications. [1], [3], [16] Sediment storage in reservoirs and dams is frequently determined by use of Brune's empirical curves.[1] Sediment control structures are normally designed using either Brune's trap efficiency curves or Camp's mathematical methods. These methods provide poor indicators of the effects of basin geometry, the inflow sedimentgraph, the particle size distribution and the outflow discharge distribution on the effluent water quality or on the volume of sediment deposited.

THE DEPOSITS SIMULATION MODEL

Basic Concepts

The DEPOSITS Model is a FORTRAN program suitable for use on most computer systems. It has been run successfully as a WATFIV program on the IBM370-165 computer system at the University of Kentucky. A complete description of the model together with a listing of the model program is contained in the Kentucky Water Resources Technical Report 103. [16]

In order to develop a model sufficiently general to be applicable to most reservoirs, the flow within a detention basin is idealized by the PLUG flow concept. Plug flow assumes no mixing between plugs and routes the flow on a first in, first out basis. Although this type of flow does not allow for turbulence or short circuiting, provision for a correction factor has been incorporated in the model.

Settling of the sediment particles is described by Stokes' Law of Settling and particles are considered "trapped" as soon as they reach the reservoir bed. A correction is made for the nonspherical nature of colloidal particles and for hinderence due to high sediment concentrations. Each plug is subdivided into four layers allowing for stratification of the sediment and selective withdrawal at the outlet structure.

Basic inputs to the model are:

1) Stage-area curve.
2) Inflow hydrograph.
3) Sediment inflow graph.
4) Particle size distribution and specific gravity of suspended sediment.
5) Viscosity of the fluid.
6) Stage-discharge curve.
7) Stage-discharge distribution curve.

The stage is defined in the model as the depth of water at the riser. The basin geometry is completely defined by the stage-area curve and detailed knowledge of the basin geometry is not required.

If knowledge of the inflow sedimentgraph is not available, the model assumes the inflow sediment concentrations are proportional to the inflow rate. The total mass of sediment entering the basin is not required by the model to determine trap efficiencies but most be specified if effluent sediment concentrations or sediment accumulations in the basin are desired.

If a stage-discharge distribution curve is not specified, the model assumes that the outflow rate is uniform with depth. For a perforated riser outlet this assumption is a good approximation. For a drop inlet, weir or sluice structure however a stage-discharge distribution curve is desirable. The type of distribution typically found with a drop inlet or perforated riser is shown in figure 1 and 2.

The model is also capable of predicting the sediment concentration of the effluent and the sediment deposition pattern in the reservoir. The model determines the volume of sediment deposited in each plug and makes a corresponding adjustment in the stage-area curve. If this option is desired, the specific weight of the sediment deposits is required. The model assumes the same unit weight of deposits throughout the basin and does not provide for later consolidation of the deposits. If consolidation is a design criteria, an adjustment to the initial specific weight should be made.

Model Mathematics

The capacity of the basin is determined by the trapezoidal method illustrated in figure 3. Stage-area determinations may be made either from topographic maps or from site surveys. It was felt that the accuracy of these methods did not warrant the use of more sophisticated conic procedures for

TYPICAL OUTFLOW-DEPTH DISTRIBUTIONS

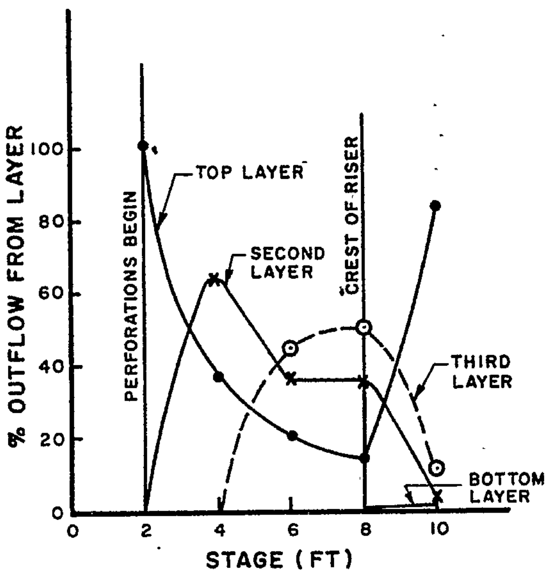


Figure 1: Perforated riser

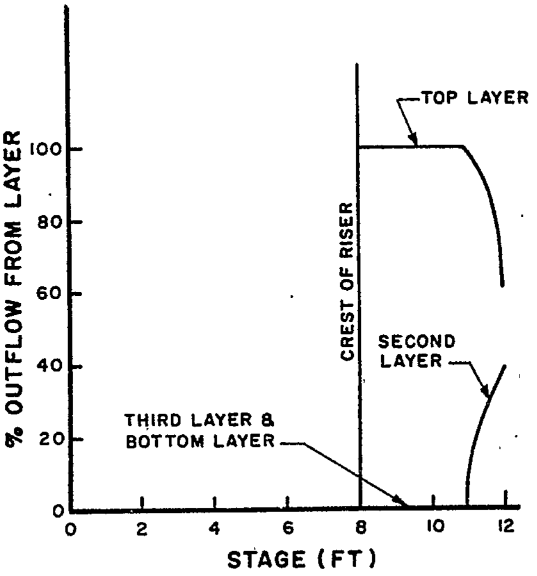
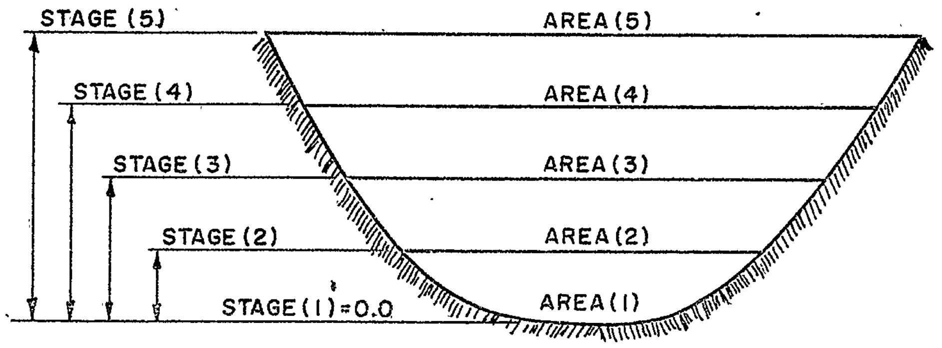


Figure 2: Drop inlet



$$\text{CAPAC}(5) = \sum_{J=2}^{5} \left(\text{AREA}(J) + \text{AREA}(J-1)\right)\left(\text{STAGE}(J) - \text{STAGE}(J-1)\right)/2 \quad \text{....} 13$$

Figure 3: Determination of the basin capacity

determining the stage-area relationship. An average depth-stage curve is also determined for the reservoir. The average depth is defined as the average depth of the water surface from the reservoir bed. This volume weighted average of the water depth for each stage point given by

$$\mathrm{AVDPTH(I)} = \frac{\sum_{J=2}^{J=I} \mathrm{DEPO}^{2.0} * (\mathrm{AREA(J)}-\mathrm{AREA(J-1)})}{\sum_{J=2}^{J=I} \mathrm{DEPO} * (\mathrm{AREA(J)}-\mathrm{AREA(J-1)})} \qquad (1)$$

where DEPO = STAGE(I)-(STAGE(J)+STAGE(J-1))/2.0; AREA(J) is the surface area, in acres, at the stage point (J); STAGE(J) is the stage, in feet, at the stage point (J); and AVDPTH(I) is the average depth, in feet, at each stage point (I). An alternative method is used if the basin geometry is such that two consecutive stage points show no increase in surface area.

Inflow to the basin is defined by the input of an inflow hydrograph. The number of inflow points and the time increment between points must be specified. Inflow hydrographs are normally simulated from rainfall data collected from watershed gauging stations. The flow is routed through the reservoir by a method based on Kao's Four-Quadrant Graph-Method [9] and in simulation studies the procedure developed by Mynear and Haan was used for developing the inflow hydrographs. [12]

The sediment concentration variation with time may either be specified as an input or simulated by the model. If specified, the concentrations must be given for the same time points as the inflow hydrograph. If the influent concentrations are not specified, the sediment concentration is assumed proportional to the volume of flow during each time increment. If the total mass of sediment inflow is specified, influent concentrations are determined by

$$\mathrm{NFLNT(JS)} = \frac{\mathrm{SEDMNT(JS)*SG*MASS*735.48}}{\mathrm{VOLUME(JS)*SEDTOT(M)}} \qquad (2)$$

where NFLNT(JS) is the influent sediment concentration (mg/l) at time JS, $\mathrm{SEDMNT(JS)}=\mathrm{VOLUME(JS)}^{2.0}$, MASS = mass of sediment in tons and SEDTOT(M) is the sum of the M values of SEDMNT(JS). VOLUME(JS) is the incremental inflow at time JS and M is the number of inflow points specified in the input of the inflow hydrograph.

Based on several studies it appears that considering the sediment concentrations proportional to the flow rate gives a reasonable approximation for small moderately sloping watersheds. [4], [13] The actual correlation is dependent on the rainfall intensity, the particle characteristics and the watershed geometry and ground cover conditions. On some watersheds the peak of the sedimentgraph may preceed that of the inflow hydrograph. [8]

Effluent concentrations are determined by

$$\mathrm{EFLNT(NN)}=(\mathrm{SEDPLG(NN)}/\mathrm{PLGVOL(NN)})*\mathrm{MASS}*7.3548 \qquad (3)$$

where EFLNT(NN) is the average effluent concentration for plug (NN), SEDPLG(NN) is the percent of the total sediment volume contained in the plug outflow and PLGVOL(NN) is the volume of the plug. The effluent concentration is determined only if the mass of sediment is specified either by the input of influent concentrations or a total mass of sediment. All influent and effluent values are in mg/1.

PLUG ROUTING

The flow is subdivided into seperate plugs of flow of equal time increment. The plug time increment is denoted by DELPLG, and must be specified in hours in the input. Each plug is subsequently subdivided into four layers of strata of equal depth and the following factors determined:

1) The plug volume.
2) The fraction of the total sediment inflow initially contained in the plug.
3) The detention time.
4) The average stage during outflow.
5) The average depth of flow of the plug during detention.

The initial routing of the inflow by the Four Quadrant method gives the discharge rate for each time increment DELTAT thus enabling the computation of the accumulated outflow. The initial point of entry to the basin of each plug is determined by first ascertaining the points at which the accumulated inflow is equal to the accumulated outflow on the respective hydrographs as shown in figure 4. The times at which these points occur on the inflow hydrograph are determined by linear interpolation between the accumulated inflow points used in the initial routing. The sediment volumes at each of these points is derermined by interpolation between the values found on the sediment volume curve described by the equation

$$\mathrm{SEDMNT(J)}=(\mathrm{CONCED(J)}+\mathrm{CONCED(J-1)})\ (\mathrm{VOLUME(J)}/2000*\mathrm{SG}) \qquad (4)$$

where VOLUME(J) is the incremental inflow at time J, in acre-ft,, CONCED(J) is the concentration (mg/l) and SG the sediment specific gravity. The detention time, plug volume and fraction of sediment in each plug may then be calculated.

Figure 5 illustrates how the stage in the basin varies with time. By linear interpolation on this curve the average stage during outflow of each plug is determined. The average depth, experienced by each plug during detention is then computed by the method illustrated in figure 6. Each plug is then subdivided into four layers of equal depth as shown in figure 7. The sediment remaining in suspension within each strata is computed and the percentage of the total outflow associated with each plug is calculated. The fraction of the initial sediment content that is removed by each plug is

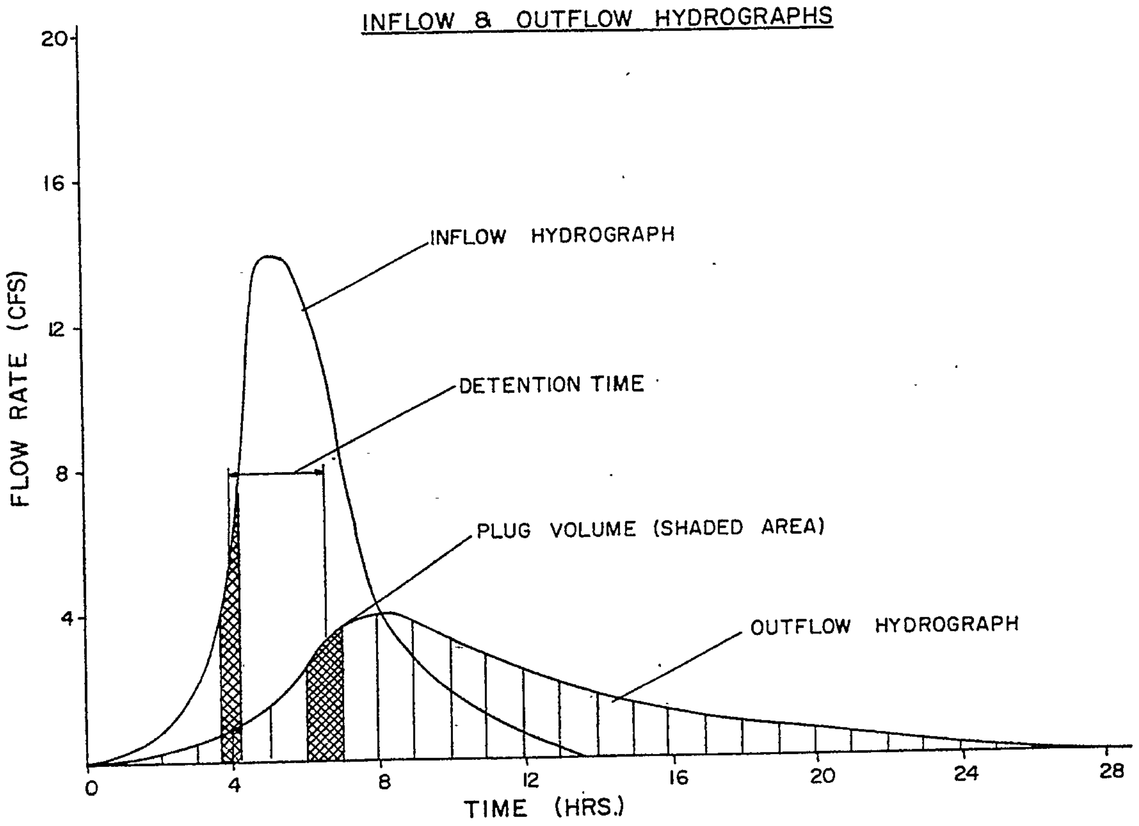


Figure 4: Inflow and outflow hydrographs

determined and the sum of these increments gives the total removal during the storm event. A brief description of these computations follows.

The sediment distribution in each plug is assumed uniform when the flow first enters the basin. The amount of sediment remaining in suspension, in each layer, is calculated by Stokes' Law. The fall velocity required for a particle to be removed from each layer is determined by

$$V_{fall}=\text{Fall distance}/(\text{detention time} \times (1-C)^{2.5}) \quad (5)$$

wher C is 50% of the initial sediment concentration expressed as a fraction. The factor $(1-C)^{2.5}$ accounts for hinderance due to several small particles falling in close proximity. Once the fall velocity is determined, the particle size associated with this velocity is determined from Stokes' Law. [2]

$$D=(V \times \mu/(51.5 \times (SG-1)))^{1/2} \quad (6)$$

where D is the particle size (mm), V the corrected fall velocity (feet/hour), SG the particle specific gravity and μ the fluid viscosity. The factor 51.5 is a conversion factor to account for the different units being used and also includes a correction for the non-spherical nature of colloidal particles. The concentration C was selected as half the original concentration because a large percent of the particles are usually coarse and settle very rapidly. Figure 8 demonstrates the typical changes in sediment concentration with time. It should be noted that hinderance is unlikely to be a major factor unless the model is adopted for use in the design of settling tanks.

The parameters depicted in Figure 7 give a conceptual picture of the average plug parameters during detention. The typical geometry of each plug will probably vary considerabley as it flows through the basin. In the model the average depth geometry is employed only to determine the suspended sediment concentrations remaining at outflow. The volume of outflow associated with each layer is determined from the outflow distribution obtained from the average stage at the riser during outflow. Typical outflow distribution curves are shown in Figure 1 and 2. The volume of sediment actually deposited on the basin sides from each layer is

$$DEP_{vol}=\frac{MASS\text{x}0.000736\text{x}(100-P_{lay})\text{x}SED_{total}\text{x}Q_{lay}}{10000.0 \text{ x } DENSITY} \quad (7)$$

where DEP_{vol} is the volume of the sediment deposit, SED_{total} is the fraction of the total sediment

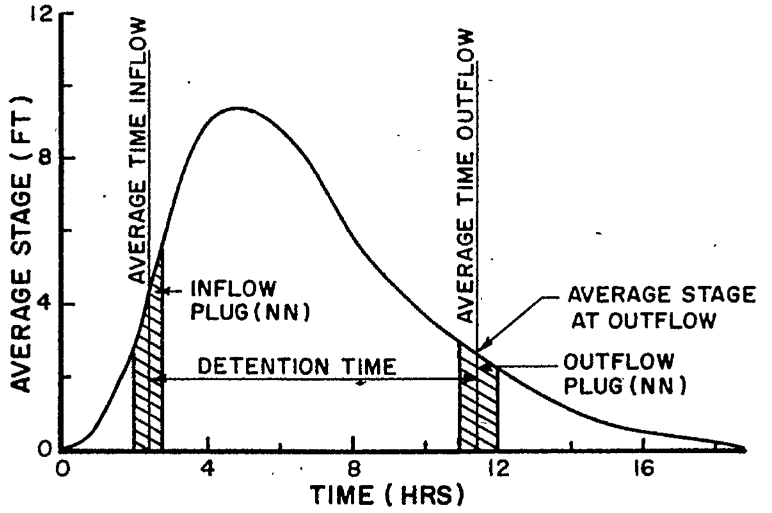


Figure 5: Stage-time curve

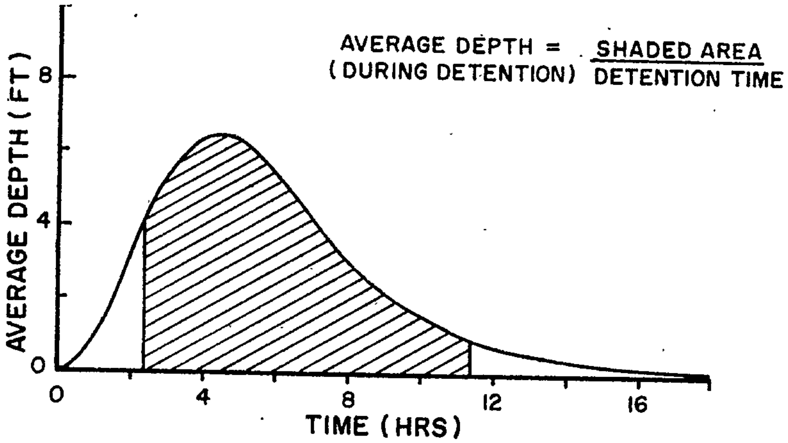


Figure 6: Average depth-time curve

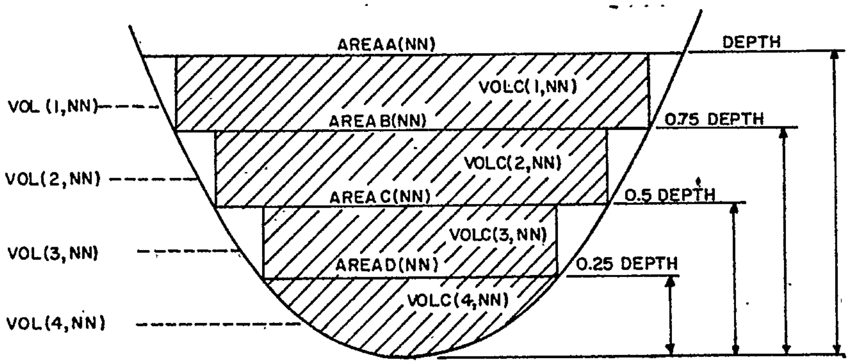


Figure 7: Layer sediment concentration determination

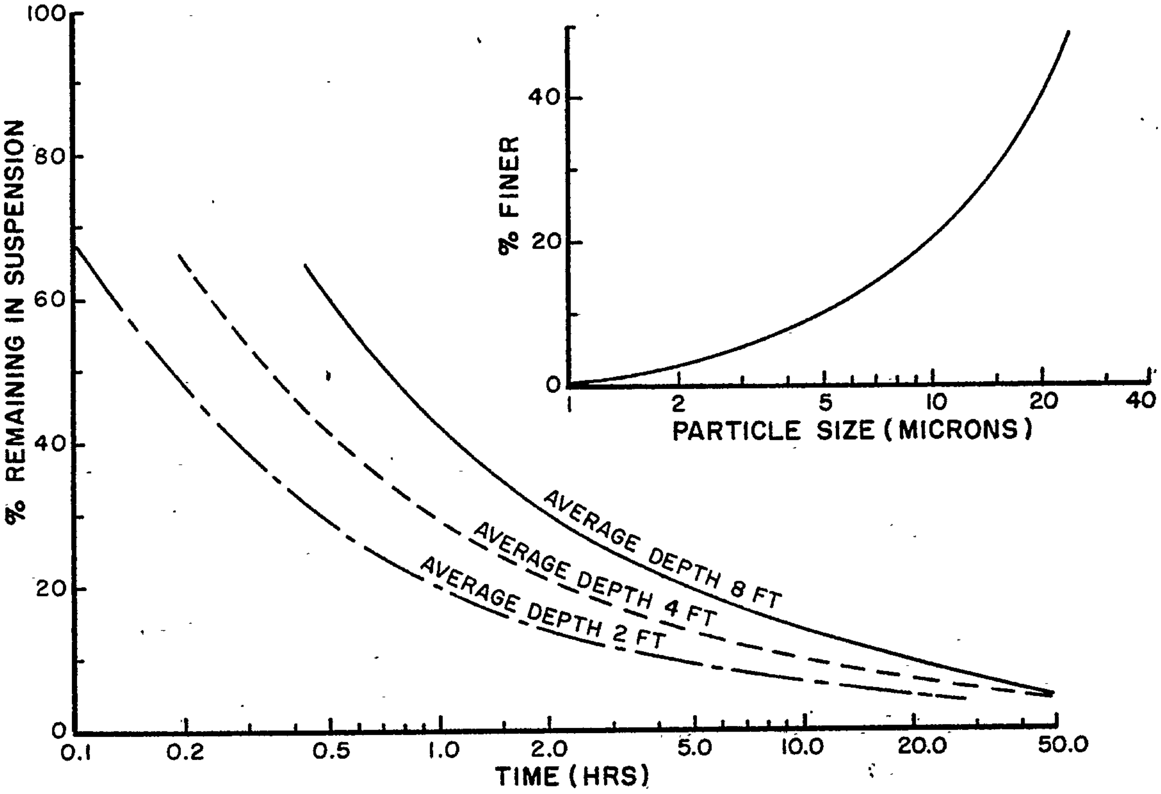


Figure 8: Sediment content variation with time

volume initially contained in the plug and DENSTY is the specific gravity of the sediment deposit.

The change in volume and area due to deposition are calculated by assuming the sediment deposited is uniformly distributed in each layer. The capacity of the basin is reduced at each stage point corresponding to the average depth point at which the increment of deposition occurs. This accounting cycle is repeated for each plug. Physically this process does not give the actual location of deposition in the basin. The area-stage curve is then determined from the new capacity stage curve. Typical results are shown in figures 9 and 10. The model is based upon the assumption that the area increases with an increase in stage. When the area-stage curve is determined numerically from the capacity-stage curve, this condition may be violated. If this should occur the area-stage curve is smoothed by maintaining the criteria that the area increase with depth and the new area at each stage be the same or less than that prior to deposition. A further correction is then made to ensure that the "smoothing" has not altered the volume of deposition. It is recommended that if the deposition option is employed, that the stage points be defined every 0.5 feet in a shallow basin and every 1.0 feet in a deep basin.

MODEL VERIFICATION

The performance of the model was studied on data provided through the kind assistance of the Environmental Protection Agency. Four strip mine basins and one urban basin were studied. A summary of the simulation results is contained in Table 1. At present there is very little good data available and although a vast amount of data had been collected on these basins, several basic assumptions and approximations had to be made.

Influent and effluent data was only collected over periods of 2-4 hours and it is the opinion of the authors that the actual measured efficiencies are incorrect. The mass balance equation [10]

$$R(\%\text{ solids removed}) = \left[1 - \frac{\frac{10^6}{C_1} - 1}{\frac{10^6}{C_2} - 1} \right] 100 \qquad (8)$$

where C_1 = solids concentration of influent, mg/l
C_2 = solids concentration of effluent, mg/l
was used to determine the actual performance of the basin. The periods of monitoring however are not of sufficient length to reflect the effect of a measured influent concentrations on the effluent concentrations. An alternative method based on the minimum and maximum sized particles likely to be trapped during the predicted detention time has been presented in table 1.

Considerable deposition had occured in most of the basins and the geometry at the time of monitoring was estimated based on the geometry at construction and measured sediment accumulations. The sensitivity of the studies to some of the basic assumptions was tested and a variation of 1-3% was found in the figures presented in table 1. Most of the events presented had fairly steady flow conditions due to monitoring of only part of a storm event or baseline pumping from the strip mine areas. These steady conditions account for the good correlation obtained with the EPA modification of Camp's method for steady flow conditions. Basin 7 however illustrates the difficulty of using this method in conditions of widely varying flow rates. The efficiency of 67% is for the peak observed outflow and 83% for the minimum flow conditions observed. Steady state conditions seldom occur in urban areas or in areas experiencing high intensity rainfall.

It appears from the initial simulation studies that the model gives good predictions of actual basin performance and is a viable design method.

MODEL APPLICATION

Enactment of "208" environmental control legislation has led to much research into the development of better water quality design methods. Frequent problems are:

1) Design of sediment storage in reservoirs and dams.
2) Control of sediment from disturbed areas.
3) Removal of sediment from existing structures
4) Control of deposited sediment during storm events.
5) Control of solid waste and sediment in agricultural areas.

The DEPOSITS Model may be used to study the factors affecting sediment transport and deposition in most catchment areas. Together with good field data or predictive equations to estimate inflow hydrographs and sedimentgraphs, the model may be used to predict the performance of existing structures and also in the design stage of projected reservoirs and basins. The effects of soil conditions, basin geometry and outlet design may readily be determined.

Most basin design is usually determined on a particular design storm. Little regard is given to the basin performance during other flow conditions. Figure 11 illustrates the effect of storm magnitude and basin capacity on trap efficiency. Typically the design storm might be that event which has a maximum stage at the riser crest. It can be seen that for the large basin represented by curve A the basin performance is almost the same during any storm event. The basins B and C however will probably be undersized as they have much higher trap efficiencies, than the design efficiency, during the more frequent small storm or baseline events.

The effects of riser or outlet design have also been studied and preliminary results indicate that

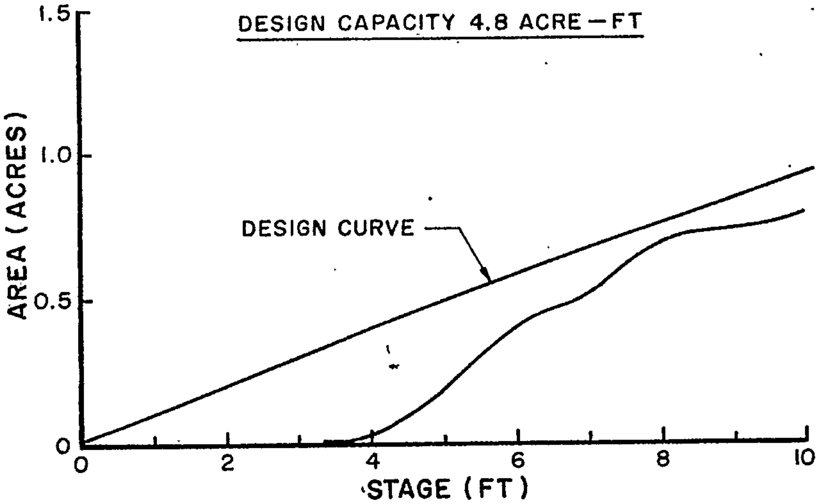


Figure 9 Change in stage-area curve due to sediment accumulation

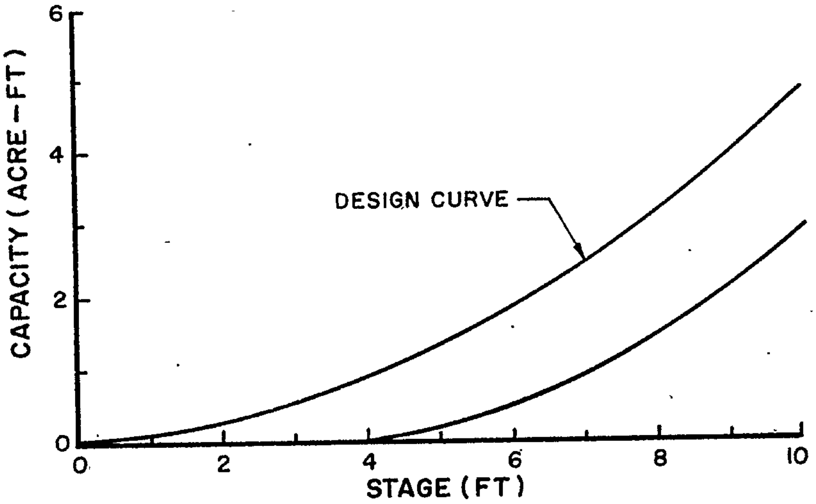


Figure 10 Change in capacity curve due to sediment accumulation

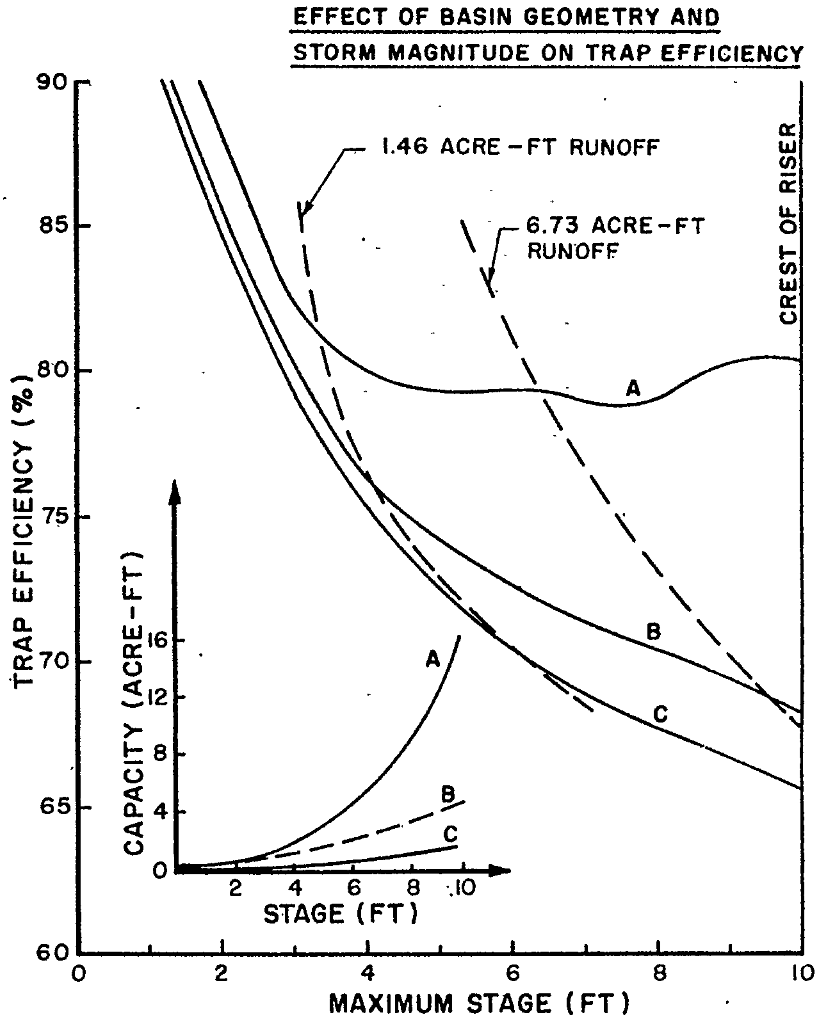


Figure 11: Effect of basin geometry and storm magnitude on trap efficiency

TABLE 1

RESULTS OF VERIFICATION STUDY

Location	Principal Spillway	Flow Condition	Trap Efficiency (Percent) EPA Method 1)	DEPOSITS Model	Actual 2)
Breathitt Co. Kentucky (EPA Pond 4)	Perforated 14" diameter riser	Baseline 0.7 cfs	95	94	97.5 < 97 3)
Kanawaha Co. West Virginia (EPA Pond 8)	Drop Inlet 3 ft. square	Storm 0.47 cfs	97	95	92.3 < 97 3)
Monongalia Co. West Virginia (EPA Pond 7)	Perforated 24" diameter riser	Storm Peak 1.01 cfs	67 83	82	91.3 < 90 3)
Perry Co. Kentucky (EPA Pond 3)	Perforated 24" diameter riser	Baseline 0.99 cfs.	90	90	89.3 < 93 3)
Columbia Maryland 4)	15" Perforated riser & 42" diameter drop inlet.	Storm Peak 5.4 cfs	Not Measured	95	95+

1) References 6 & 7
2) Using equation 8
3) Based on % finer of smallest particles trapped.
4) Source. Joint Construction Sediment Control Project. EPA-660/2-73-035.

trap efficiencies may be improved considerably by selective withdrawal at the outlet. In some cases it may be desirable to increase the removal of sediment from the reservoir and outflow from the sediment laden flow near the reservoir bed may be simulated. Multiple storm events may be simulated with the model thus allowing for the study of the effects of sediment accumulations in the basin. An estimate of the reservoir life and the changing performance of the basin may be ascertained.

A major benifit of the model is the capability to estimate effluent sediment concentrations. Most federal and state codes are written in terms of effluent water quality rather than trap efficiency. The ability to estimate effluent concentrations also allows for design and routing through multi-basin systems. Frequently several small basins or reservoirs are constructed on the same catchment area and predictions of the impact of each basin on the other is made difficult due to a lack of knowledge of sediment concentrations and praticle size distribution. This difficulty may now be overcome through use of the DEPOSITS model.

CONCLUSIONS AND RECOMMENDATIONS

The DEPOSITS Model is a viable design method which may be used in the design of sediment detention basins, lagoons and reservoirs. Its application is not limited to steady flow conditions or to a particular basin geometry. One of its major advantages over other currently adopted methods is that it provides knowledge of effluent sediment concentrations. It may also be used to obtain a composite prediction of a basin's performance during its design life and will also simulate sediment accumulations within the basin. Input to the model is minimal and extensive site surveys are not required. The cost of the program is small. In simulation studies of a 32 storm cycle the CPU time was 0.0079 hours and the total cost $9.19.

Based on results obtained with the DEPOSITS Model, it appears that the codes controlling sediment basin design need to be revised to meet effluent quality controls as well as the hydraulic flood requirements.

Self flushing sluice systems need to be evaluated for use in water resource reservoirs and dams. At present estimation of required storage space for sediment deposition are normally made based on little information and provide for poor sizing.

Considerably more data is required similar to that obtained by the EPA and Hittman Associates.[5], [6] The basin monitoring however should cover several storms and be of longer duration. Determination of sediment delivery to downstream structures

DEPOSITS - - - Continued

is usually poorly defined by the available predictive equations. More research is required on watershed washloads. The effects of flocculation and aggregation need to be studied and a composite watershed model which allows for partial mixing within the basin developed.

Research of this nature on both urban and strip mine areas is being conducted at the University of Kentucky and it is anticipated that a more sophisticated method will be developed in the next few years. The DEPOSITS Model however is a valueable aid to the design engineer and it is hoped that design models of this nature will be used by agencies and engineers in the design of better hydraulic structures.

ACKNOWLEDGEMENTS

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