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Evaluation of Detention Basins for Controlling Urban Runoff and Sedimentation

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EVALUATION OF DETENTION BASINS FOR

CONTROLLING URBAN RUNOFF AND SEDIMENTATION

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ABSTRACT

This report summarizes the work completed under the research project "Evaluation of Dentention Basins for Controlling Urban Runoff and Sedimentation." The main project accomplishments were:

(1) a demonstration of the desirability of considering systems of urban stormwater detention basins as opposed to individual basin design,

(2) the development of a systems analysis approach for least cost selection of a system of dentention basins for meeting a preset hydrologic objective,

(3) the development of a mathematical, computer-based simulation model of the performance of sediment retention basins,

(4) partial verification of the sediment basin model and

(5) the development of design recommendations for sediment basins based on simulations made with the sediment basin model.

Descriptors: Detention basin, urban hydrology, storm water management, sediment basin, simulation

Preface

This report serves as the final report for the research project "Evaluation of Detention Basins for Controlling Urban Runoff and Sedimentation". The research was supported in part by the Kentucky Agricultural Experiment Station and in part by the Office of Water Research and Technology, the United States Department of the Interior as authorized under the Water Resources Act of 1964, Public Law 88-379, as amended. Late stages of the project also received partial funding from the University of Kentucky Institute for Mining and Minerals Research.

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INTRODUCTION

Rapidly expanding urban areas, increased public input into urban development decisions through planning agencies, new programs of federal flood insurace, more stringent water quality laws, increased public concern about the environment and a lessening of public tolerance for even minor urban flooding and sediment pollution all point to the need for improved measures that can be used to control urban storm water runoff and sediment pollution. Generally the urbanization process results in a loss of natural water storage on a watershed. This loss of storage promotes increased runoff rates. Thus one method commonly employed for controlling urban storm water runoff is by the construction of additional storage in the form of detention basins.

Urban development typically severely disturbs rather large tracts of land. This disturbed land is exposed to rainfall for periods of time varying from a few months to several years. During this time tremendous quantities of erosion and sediment pollution can be produced. Recognizing that some exposed areas during construction activities and the subsequent erosion products cannot be completely eliminated, many times sediment trapping basins are installed immediately below the construction site. The purpose of these basins is to trap eroded sediments and prevent them from entering and polluting surface streams.

It is not uncommon to find that available sites for storm water

detention basins and sediment retention basins are very limited. Many times a single site is used to construct a basin that serves both purposes – storm water storage and control and sediment trapping. The criteria used in designing detention basins vary from locality to locality, developer to developer and engineer to engineer, not so much because of changing hydrologic and watershed conditions, but because of the lack of well documented design procedures.

With the importance of urban storm water management and sediment control in mind, the objectives of this project were:

1. Evaluate various criteria used to design detention basins used for controlling urban runoff and/or sediment pollution.

2. Evaluate the performance of detention basins used for controlling urban runoff and/or sediment pollution.

3. Develop improved techniques where needed for designing detention basins for controlling urban runoff and/or sediment pollution.

Background

Many rapidly developing areas are experiencing problems brought about by increased flood flows and sediment production caused by the urbanization process. Some of the larger metropolitan areas are attempting to meet these problems head on. In the case of storm water runoff a common requirement is that new development not aggravate any existing flooding problem. For example, both Jefferson County and Lexington-Fayette County in Kentucky have adopted this guideline and

are actively pursuing it. The design of a storm drain system for
an urban area that does not increase peak runoff rates above those
existing prior to development, in many cases, requires the inclusion
of a storm water detention basin.

Increased public awareness of environmental problems, new water
quality regulations and the federal flood insurance program have
focused attention on the sediment pollution that many times results
from urban construction. To combat this problem many communities
are adopting sediment control ordinances. Lexington-Fayette County
Kentucky, has developed such an ordinance. One of the most common
techniques employed to combat sediment pollution from construction
sites is through the use of sediment retention basins.

Two major considerations in designing sediment retention basins
are providing sufficient storage for the sediment that is produced
and providing the proper hydraulic environment so that sediment is
trapped rather than passing through the structure. Currently the
Universal Soil Loss Equation (USLE) is used to arrive at expected
sediment volumes and empirical capacity/inflow-trap efficiency
curves are used for hydraulic design. Both of these techniques need
serious evaluation for urban areas.

Early in the project it became obvious that current methods for
evaluating sediment basin performance were wholly inadequate. The
need for a model describing the sedimentation process in a basin that
accounted for such factors as time varying inflows and outflows,
particle size distribution of the incoming sediment, volume and time

distribution of incoming sediment and physical characteristics of the basin and spillway was apparent.

With these factors in mind, this research project gradually developed along two lines (1) the development of a methodology for sizing systems of storm water detention basins, and (2) the develoopement of a model for describing the performance of sediment basins.

PROJECT ACCOMPLISHMENTS

All of the significant project accomplishments have been and are

being reported in appropriate journals and as technical reports.

A complete list of publications resulting from the project is con-

tained in this report. It is not the intent of this summary to

duplicate previously published material. Rather some of the more

significant findings will be summarized. More detail can be obtained

by consulting other project publications. The discussion will be broken

into two parts - one dealing with storm water detention basins and one

dealing with sediment retention basins.

Storm-Water Detention Basins

Many urban development authorities now require some type of

control of storm water runoff so that the development process does

not cause increased peak runoff rates. Generally this criterion is

applied to each development site individually. The most common

storm water control method is a detention basin. This means that

many detention basins are built and there is generally no coordination

among the flow control exercised by these many individually designed

basins.

The first item considered was a cost minimization of an individual

basin to meet a preset hydrologic objective. The costs considered were

land costs, construction costs and spillway costs. The optimum deten-

tion basin size was taken as the one that met a flow objective for the

least cost. Figure 1 is a schematic representation of some of the costs involved.

In the field of flood control for large river basins, it has long been known that the most effective control is obtained by designing individual flood control reservoirs as a part of a system of reservoirs. The same is true on a smaller scale for urban storm water detention basins. Smiley and Haan (1976) demonstrate that placing retarding structures on downstream tributaries may aggravate flooding by holding the flow back sufficiently so that it coincides with flows from more upstream areas. Thus not only might individually designed detention basins increase flooding, but a considerable sum of money might be spent as well.

Mynear and Haan (1977, 1978) developed a procedure for sizing a system of urban storm water detention basins that accomplished a pre-set downstream flow objective at the lowest cost. It is shown that a systems approach can provide better flood control at a greatly reduced cost in comparison to the case where all detention basins are designed as individual entities without regard to other basins emptying into the same drainage system.

Mynear and Haan (1978) compare the systems approach to the traditional, individual basin approach in terms of the costs involved to provide a given degree of flood protection. They consider a watershed with three possible detention basin locations. By optimizing the individual basins, the total costs for the three basins was $239,975.
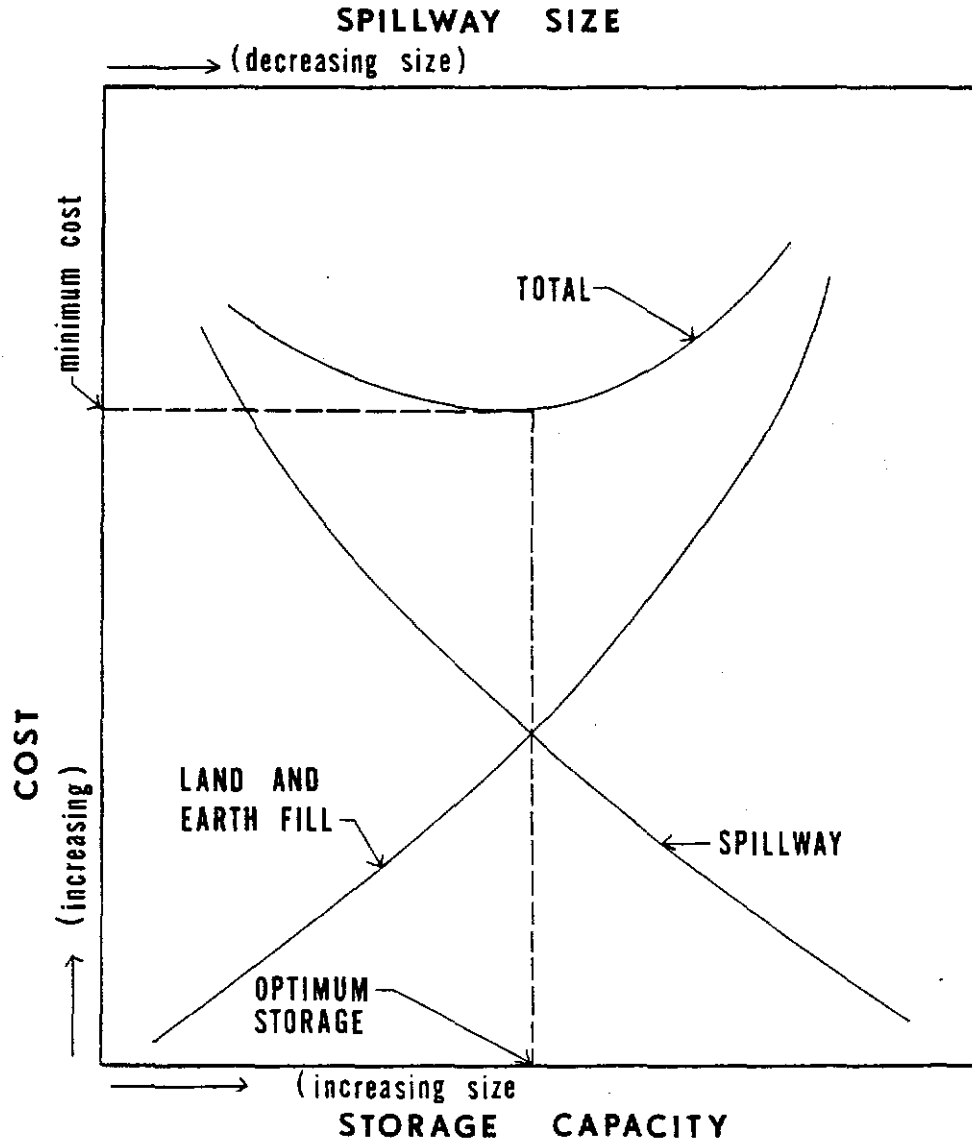
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Figure 1.   Land, dam, and spillway relationships with storage
            and spillway size

Sediment Retention Basins

Sediment basins have been used for many years to slow the velocity and reduce the turbulence in flowing water and thus allow suspended particles to settle out. For basins with rapidly changing flow rates such as are produced by storm water runoff, adequate design procedures were not available. Existing techniques either assumed a constant flow rate and predicted basin performance from Stokes Law of settling or assumed that sediment trapping in small detention basins could be estimated from empirical data collected on large, multipurpose reservoirs. Obviously the smaller detention basins below construction sites and urban areas do not fall in either of these categories.

In recognition of the lack of any design procedures for sediment basins whose purpose is to control sediment pollution below construciton sites, a simulation model called DEPOSITS (DEposition Performance Of Sediment In Trap Structures) was developed (Ward, Haan and Barfield 1977b).

The DEPOSITS Model

An attempt has been made to incorporate in DEPOSITS the basic factors affecting sediment transport and deposition in a reservoir. Although dependent on many factors, it is generally recognized that the major factors controlling sediment transport through a reservoir are:

1.   The inflow sedimentgraph.

2.   The inflow hydrograph.

3.   The basin geometry.

4.   The hydraulic characteristics of the basin.

5. Viscosity of the flow.

6. The physical characteristics of the sediment.

The DEPOSITS model requires the input of either an inflow sedimentgraph or a mass of sediment associated with the storm event. If only an estimate of the inflow sediment mass is given, the model assumes that the inflow sediment concentration is proportional to the water inflow rate. An important feature of the model is that knowledge of the sediment inflow is not required to estimate basin trap efficiency. The inflow hydrograph may either be simulated using the many methods currently available or may be determined from watershed records. The sediment basin geometry is defined in the model by the input of a stage-area curve. The hydraulic characteristics of the basin are determined by the inflow structure and the nature of the outlet spillway. The model requires the input of a stage-discharge curve and an outflow distribution-stage curve. If an outflow distribution-stage curve is not specified, the model assumes the outflow rate is uniform with depth. For a perforated riser outlet designed under current Kentucky state codes for surface mines, this assumption is a good approximation. For a drop inlet, weir or sluice structure, however, a stage-outflow distribution curve is desirable. The effects of outflow distribution on trap efficiency are described in Ward, Haan and Barfield (1978 a).

In order to make the model sufficiently general to be applicable to most sediment basins, the hydraulic characteristics of the flow through the basin is idealized by the plug flow concept. Plug flow assumes delivery of the flow in a first in, first out basis and

allows no mixing between plugs. Although this concept does not account for short-circuiting or turbulent flow, a correction factor has been incorporated in the model to allow for some adjustment.

The physical characteristics of the sediment are described by the input of a particle size distribution and specific gravity. Settling is described by Stokes Law and a correction is made for hindrance due to high sediment concentrations settling in close proximity and also for the non-spherical nature of colloidal particles. Preliminary results indicate that trap efficiency is dependent on the percent of the particles finer than 20 microns. Each plug is subdivided into four layers allowing for stratification of the sediment and selective withdrawal at the outlet structure. Particles are considered 'trapped' when they reach the basin bed. If the reduction in basin capacity due to sediment accumultions is desired, the specific gravity of the sediment deposits must be specified. Provision is made for making the incoming particle size distribution a function of increasing flow rate.

The model mathematics are complex and only a brief outline is contained in this paper. Flow through the basin is routed by conventional methods. A plug flow concept is used. The volume of each plug is determined as the volume of outflow contained under the discharge hydrograph for each plug time increment. The plug time increment is specified by the program user and should not exceed $\frac{1}{4}$ the time to peak of the inflow hydrograph. The location of each plug on the inflow hydrograph is ascertained and the initial sediment content determined from the sediment concentrations associated with this period of time. This procedure is illustrated schematically in Figure 2.
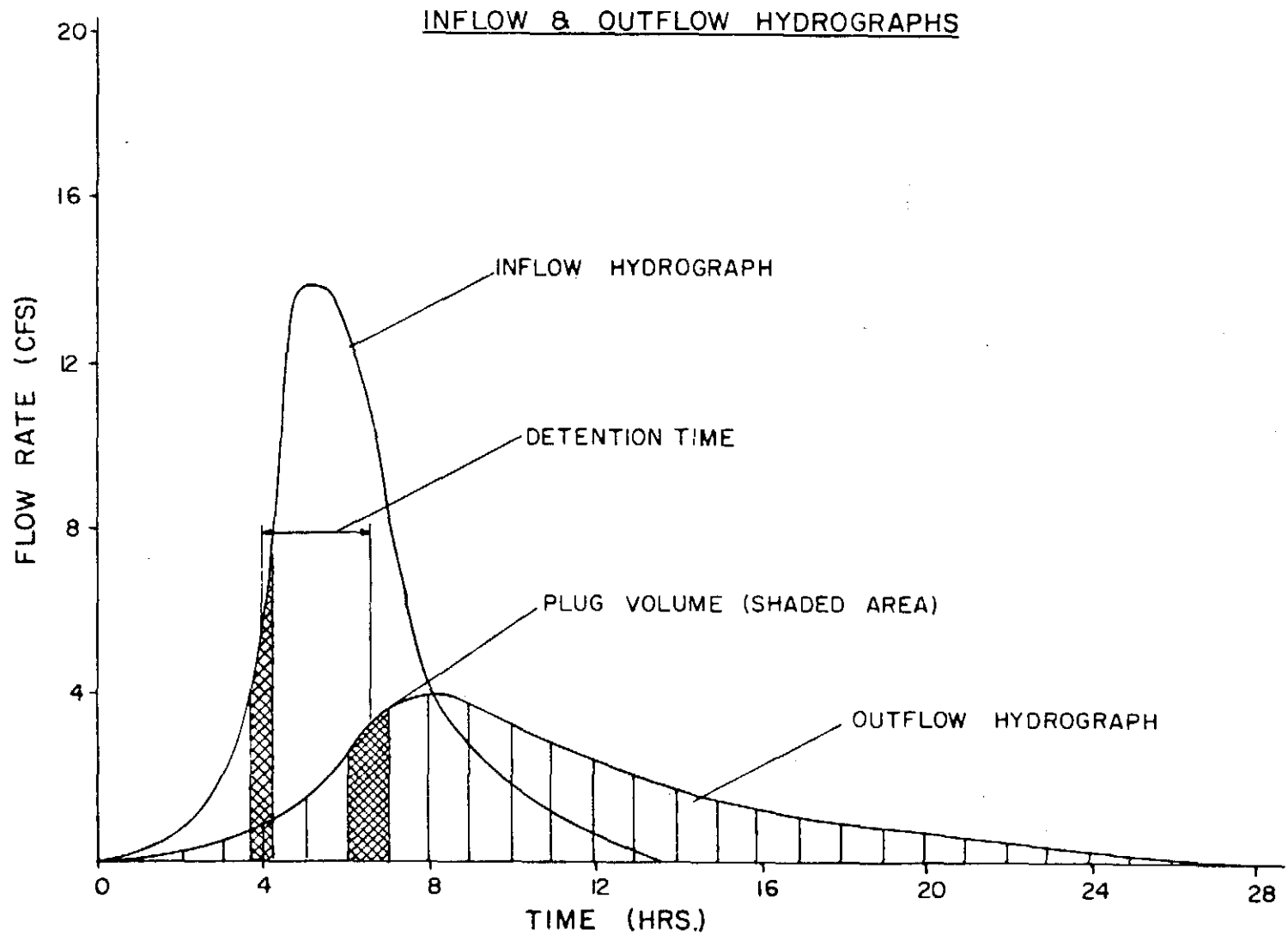
INFLOW & OUTFLOW HYDROGRAPHS

INFLOW HYDROGRAPH

DETENTION TIME

PLUG VOLUME (SHADED AREA)

OUTFLOW HYDROGRAPH

FLOW RATE (CFS)

TIME (HRS.)

Figure 2.   Inflow and outflow hydrographs

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The detention time for the plug is determined as the time interval between centers of the plug on the inflow and outflow hydrographs. Settling is determined based upon the average fall depth of the plug during detention. The average depth is ascertained as the area contained under the average depth-time curve developed during the initial routing divided by the detention time. The basin capacity is determined by the trapezoidal method illustrated in Figure 3. and 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 of each stage point is given by

$$\text{AVDPTH (I)} = \frac{\displaystyle\sum_{J=2}^{J=I} \text{DEPO}^{2.0}\,(\text{AREA(J)} - \text{AREA(J-1)})}{\displaystyle\sum_{J=2}^{J=I} \text{DEPO}*(\text{AREA(J)} - \text{AREA(J-1)})} \tag{1}$$

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.

This average depth gives a conceptual picture of the plug geometry during detention. Based upon this geometry, the plug is subdivided into four layers. Based on the settling criteria discussed earlier, the percent of particles capable of falling from one layer into the next is determined. Provision is made for trapping of the particles on the sides of the layers. This procedure determines
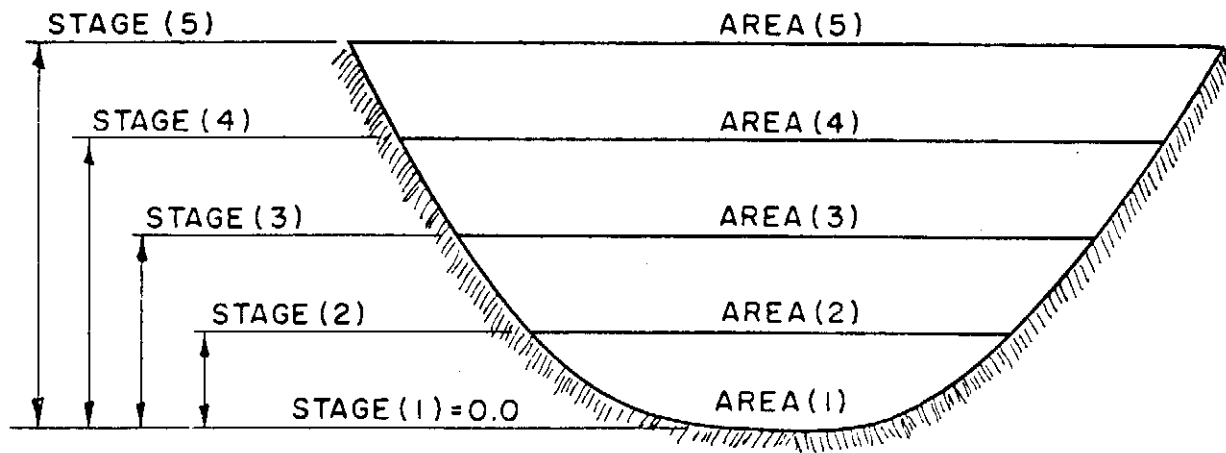
$$CAPAC\ (5) = \sum_{J=2}^{5} \Big(AREA\ (J) + AREA\ (J-1)\Big)\Big(STAGE\ (J) - STAGE\ (J-1)\Big)/2 \ \text{----}\ 13$$

Figure 3.

the distribution of sediment remaining in suspension and the location of deposition. The actual volume of deposition and the sediment discharge rate is determined by the nature of the outflow distribution with depth. As might be expected, most of the withdrawal will be more uniformly distributed with a perforated riser.

Model Verification

Unfortunately little data, if any, are in existence for a complete verification study of the DEPOSITS model. Ward, Haan and Barfield (1977c) reports on efforts to verify the model based on data supplied by the Environmental Protection Agency. A paper is currently being prepared based on a verification study conducted using data supplied by the U. S. Department of Agriculture Watershed Research Station at Columbia, Missouri. Numerous computer runs have been analyzed to ascertain their reasonableness and consistency.

All of these verifications indicate the DEPOSITS model is performing satisfactorily. Trapping efficiencies and outflow sediment concentrations agree well with the expected and where available observed results. A rigorous evaluation awaits the collection of complete data sets.

Instruments for collecting data concerning the performance of a detention basin in Lexington, Kentucky, were installed in 1976 and operated continuously for a two-year period. Detention basins in Lexington are designed to control flooding from 100-year runoff events. They have little effect on runoff from the more frequent

and smaller events. During the monitoring period, no storms of
sufficient magnitude to cause appreciable ponding of water in the
basin and trapping of sediment was recorded.

In May and June of 1978 instrumentation was installed on two
sediment basins below surface mines in Eastern Kentucky. These
basins do function during small runoff events and hopefully will
provide data needed for a more complete evaluation of the DEPOSITS
model.

Model Simulations

Several simulation studies have been made with the DEPOSITS
model. Based on the results of these simulations, simplified
prediction equations for basin trap efficiency and outflow sediment
concentrations have been developed (Ward, Haan and Barfield, 1978a,
1978b). Figure 4 is an example of the type of information generated
from the simulation studies. From this figure it is possible to
predict the peak outflow sediment concentration from a knowledge of
the inflowing sediment load, the peak runoff rate into the basin
and the basin trap efficiency. Trap efficiency can be estimated
from this equation

$$E = 89.2 + 25.4(S/Q) + 1.77(P_{20}^* - P_5^*)(t_d/t_{st}) - 1.23P_{20}^*(q_0/q_{in})^{0.3}$$

for basins with a permanent pool where E is the trap efficiency (%),
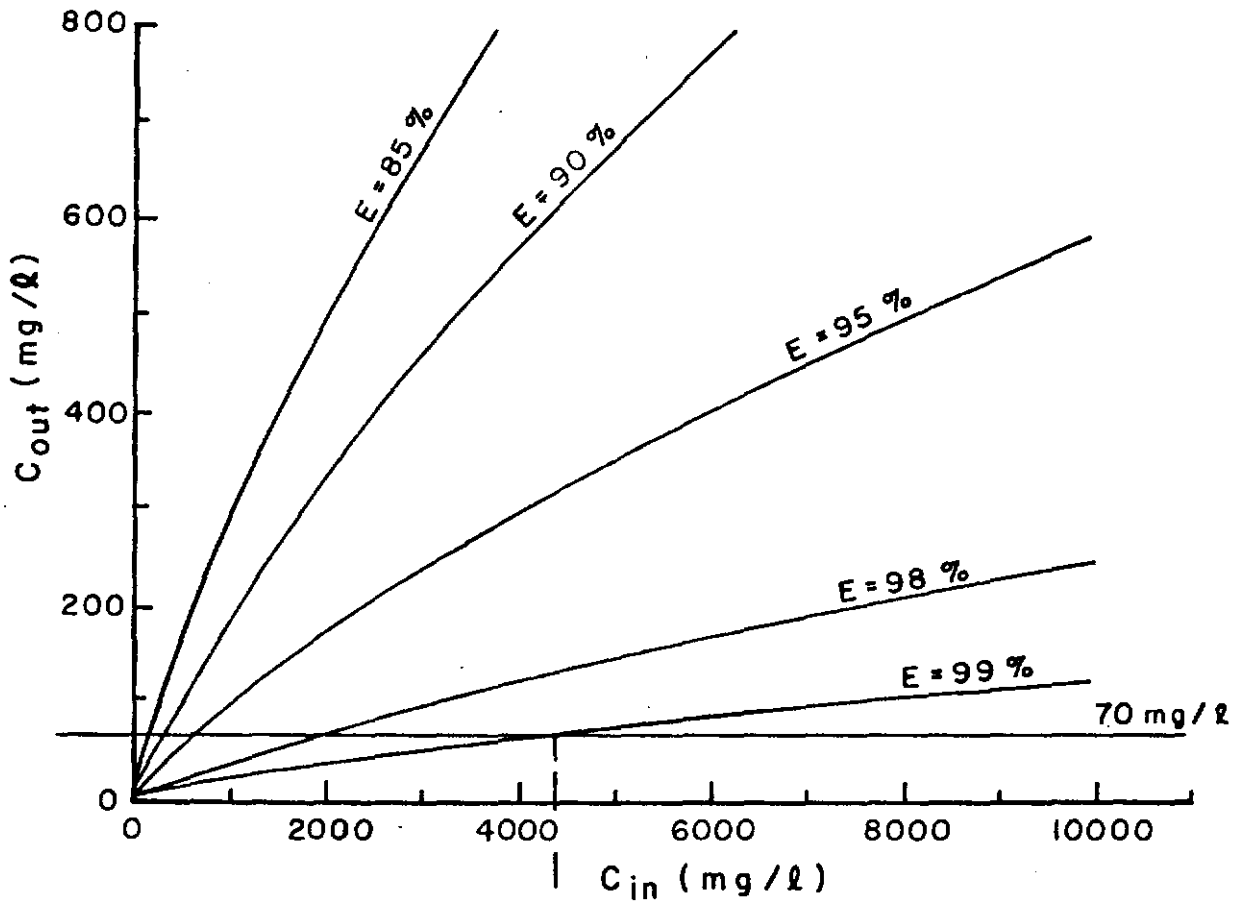
Estimation of Peak Outflow Concentration.
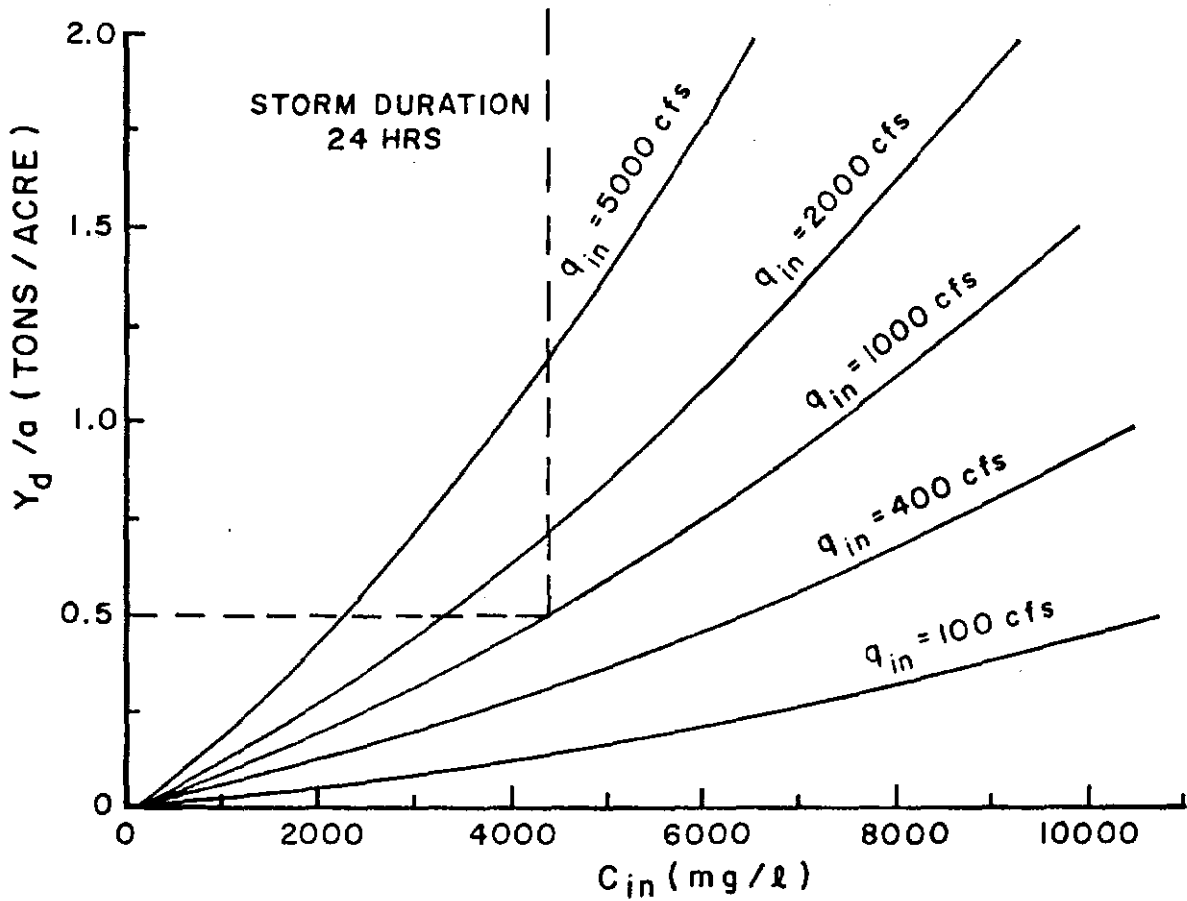
Determination of Peak Inflow Concentration.

Figure 4

S is the basin capacity up to the riser crest (acre-feet), Q is the inflow volume (acre-feet), t_d is the average detention time (volume weighted in hours), t_{st} is the storm duration (hours), q_0 and q_{in} are the peak outflow and inflow rates (cfs), and P_5^* and P_{20}^* are the percent of the sediment particles finer than 5 and 20 microns, respectively, at the peak inflow rate.

The sediment yield in tons/acre can be estimated using the Universal Soil Loss Equation. The peak inflow rate can be estimated from runoff hydrograph procedures. The peak outflow rate is determined by routing the inflow hydrograph through the detention basin. The peak inflowing sediment concentration was estimated based on the total sediment yield and the assumption that the inflowing sediment concentration is proportional to the inflowing runoff rate as depicted by the runoff hydrograph.

One significant finding of the simulation studies is that sediment basin trap efficiency is extremely dependent on the sediment particle size distribution, especially in the 5 to 20 micron range.

CONCLUSIONS AND RECOMMENDATIONS

Based on the work under this project concerning the design of urban storm water detention basins, it appears that urban areas could provide greater flood protection at a lower cost by a coordinated, systems approach to the design of storm water detention basins. When compared to an approach based only on individual site analysis, the systems approach may result in less costly basins that more effectively control flood flows.

The development of the DEPOSITS model for sediment basin simulation and design represents a significant advancement in techniques available for analyzing the performance of sediment basins. The DEPOSITS model takes into account the main factors affecting sediment basin performance in a manner that is conceptually much more acceptable than currently available alternative procedures. Simulations with the model show that the particle size distribution in the 5 to 20 micron range is the single most important factor affecting sediment trapping in basins of the size normally found in urban areas and below surface mines. Particles smaller than 5 microns are extremely unlikely to be trapped without the aid of some type of flocculation. The biggest remaining hurdles to predicting sediment trapping are accurate estimates of total sediment inflow into a basin and an accurate estimate of the particle size distribution of sediments entering a basin.

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