A Review of Sediment Predictive Techniques as Viewed from the Perspective of Nonpoint Pollution Management

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ABSTRACT / User-oriented criteria for the evaluation of physically based management models are presented. These criteria emphasize the utility rather than the elegance of the model. The standards are then applied to efforts at predicting non-point pollutant loadings. In particular a critical review of sediment pollution is used as the basis for the evaluation of sediment yield models as management tools. A wide range of sediment yield models are rated and recommendations for their use are made.

Introduction

Efforts for the abatement of pollution have been spurred by the passage of Public Law 92–500 in the United States of America. However, until recently the primary emphasis has been on point source pollutants. The development of the 208 planning process has placed the emphasis on nonpoint pollutants. Sediment stands out as a key link in the chain of understanding, predicting, and controlling nonpoint pollution. However, the role that sediment may play in augmenting or mitigating the effects of other pollutants has not always been clear. Ultimately the level of water quality will depend to a large extent on this interaction. The effect of sediment on water quality is twofold: a physical effect and as a locus for chemical interactions. Management of water quality demands reliable tools for the prediction of sediment loadings and transport to the stream. To date, the procedures available have been borrowed and adapted to serve the 208 planning process. What is needed is a systematic review of existing procedures and an examination of alternative approaches within the context of managing water quality. The present paper fulfills this need.

In order to realize this approach a framework for analysis must be established. The first and second sections of this paper discuss the water quality impacts of sediment and techniques for the rapid identification and evaluation of sediment problems. The third section describes the characteristics of an ideal management-oriented sediment delivery model. This will be used as the basis for the critique of the remaining two sections, which describe existing quantitative predictive techniques and potential alternatives. Ultimately, no single procedure will be adopted as the final solution.

This paper presents a first approximation of objective criteria for physically based management models. This makes possible a critical evaluation of the usefulness of sediment yield prediction techniques as management tools.

KEY WORDS: Nonpoint pollution, Sediment, Modeling, 208 planning, Sediment yield

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Impacts

Sediment is classed as a pollutant becuase of its physical properties and potential chemical interactions. In this section we will establish those water quality parameters that are well defined functions of sediment load. A clear understanding of these relationships will guide us in selecting predictive techniques for evaluating alternative control strategies.

Physical Effects

The most readily identifiable effect of sediment is simply its presence. Whether in harbors, stream channels or reservoirs, sediment poses a significant problem by impairing the expected function of both natural and man-made structures.

Curtis and others (1973) estimate that over 445 million metric tons of sediment per year are delivered to the Gulf of Mexico, Atlantic and Pacific Oceans, excluding the Great Lakes. This averages about 64.7 metric tons per square kilometer per year. While these values are within geologic rates of denudation (Schumm 1963), they do not reflect local extremes or inland deposition rates. In addition, the Great Lakes have an estimated gross erosion rate of 151 million metric tons per year (G.L.B.C. 1975). A recent evaluation of dredging quantities in the Great Lakes has been made by Raphael and others (1974). This study indicates that 4.76 million metric tons of sediment is dredged for the maintenance of existing facilities. In addition, a number of smaller ports are no longer being dredged because of insufficient usage. However, the most startling figure in

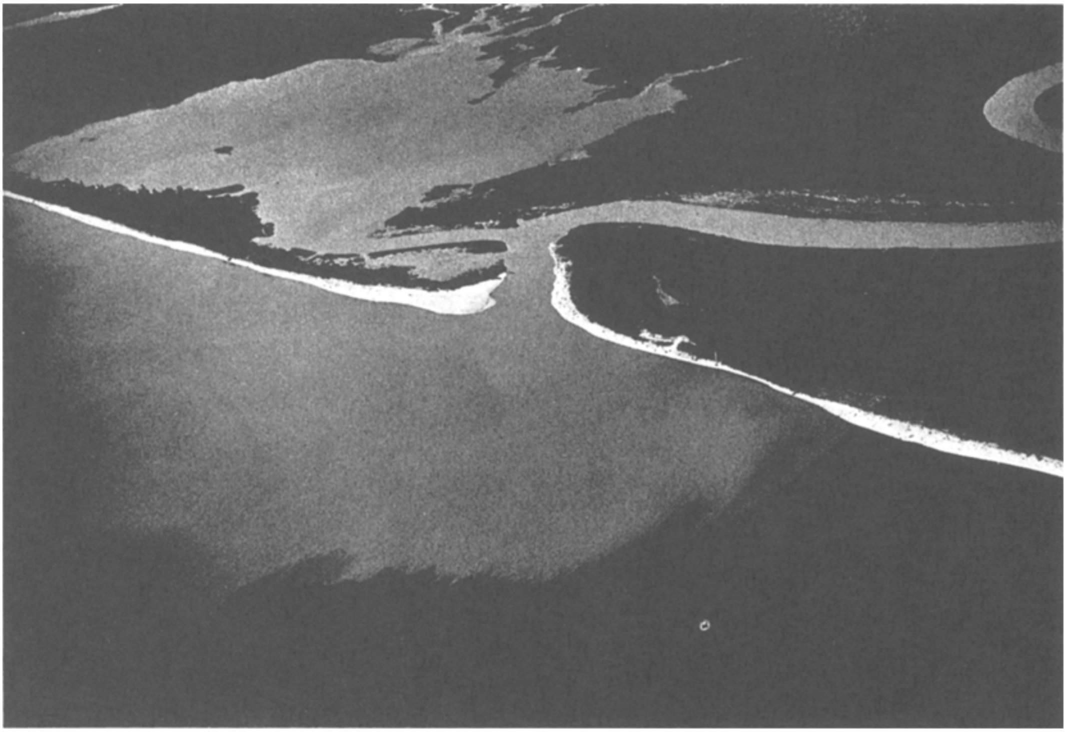

Fig 1 An aerial view of a stream mouth emptying sediment laden waters into a lake. High turbidity causes a distinct visible separation at the boundary between the mixing water bodies. Photo by J. Larison.

this report is that about 83 percent of this dredged material is considered polluted for it exceeds criteria for either volatile solids, chemical oxygen demand, total Kjeldahl nitrogen, oil and grease, mercury, zinc, or lead.

Dendy (1968) evaluated the rate of depletion of storage capacity for reservoirs. His results indicated that the highest rates of sedimentation exist for the smaller reservoirs. Within 30 years about 20 percent will be half filled and many others impaired.

Next to the sheer volume of material transported, the most obvious effect of sediment is on the turbidity of the water. While turbidity is easily measured (Breston 1970, EPA 1974), it is not always easily related to total sediment load (Truhlar 1976). The two most common methods employ either a light scattering detector or the depth of visibility of a Sechhi disc. The difficulty of relating turbidity to sediment load results in part to the varying light scattering properties of different sized particles. Work by McSweeney (1971) using a fiber-optic system may represent a possible solution to the problem and at the same time give information about the size distribution of the suspended sediment.

A more detailed discussion of physical effects can be obtained from Oschwald (1972). Gottschalk (1962) analyzes the nature of the damages that may be incurred.

Chemical Effects

General Properties. Some general properties of sediments are important in understanding their chemical reactivity. The speed and extent of the reaction of a substance with sediment depend upon the surface area of the sediment. The greater surface area per unit volume smaller sized sediment particles makes them especially important. Significant changes in the quality of water can be expected with changes in the size distribution even if the total sediment concentration remains fixed. Such changes of size distribution have been reported by Wildung and others (1972). The ability to predict and control particle size distribution can be a key factor in modeling the impact of sediment on chemical water quality parameters.

Another important property of sediments is their chemical heterogeneity. Like the soils from which they are derived, sediment frequently is associated with coatings of various oxides and hydroxides of aluminum and iron (Jenne 1968) as well as calcareous substances. These substances greatly enhance the ability of soils to react with or adsorb other chemicals (Korte and others 1976), and the same can be expected for sediments. The importance of these coatings suggests their measurement should supercede that of the presently used cation exchange capacity (Kennedy 1965, Wang 1975).

Sediment may react with, carry and/or release, any of a large number of chemicals. We can distinguish three broad groups: nutrients, trace metals, and organics. Each interacts with sediment in a characteristic fashion.

Nutrients. The most important class of chemicals associated with sediment is the nutrients (McKee and others 1970, Harms and others 1974) particularly nitrogen and phosphorus. Reviews of nitrogen (Keeney 1973) and phosphorus (Syers and others 1973) interactions with sediment are available. The fact that the erosion process tends to select for finer particles means that sediments tend to be more enriched in nutrients than the native soil (Schuman and others 1976). Such an increase in finer particles means a disproportionate increase in nutrients. Again we see the imporance of particle size distribution in determining the impact of sediment on water quality. This is particularly important for phosphorus, which tends to be strongly attached to sediment. Here the role of calcareous materials can be very important in attenuating the capacity of sediment to react with phosphorus (Williams and others 1971).

Trace Metals and Organics. The second class of chemicals associated with sediment is the trace metals (Oschwald 1972). These may be associated with the cation exchange capacity or the hydrous oxide and hydroxide coatings. Perhac (1972) described the distribution of trace metals between solution and adsorbed phases. Since natural levels of trace metals are usually not significant (Livingstone 1963), the influence of sediment is primarily that of a sink to point sources of pollution.

The last class of chemicals we are concerned with is the organic materials. While soil organic matter may be of concern in a few cases, pesticides are the pollutant of major concern. Even so, soil organic matter can play an important role as a secondary agent, complexing and transporting other pollutants (Schuman and others 1976). A review of pesticide sediment reactions has been presented by Pionke and Chesters (1973) and a more recent look is given by Willis and others (1976). In general, pesticide yields give excellent correlations to sediment yield.

Identification and Estimation

The simplest approach to sediment control involves the identification of specific compact areas that act as a source. The ability to locate such source areas would allow a concentration of effort, which is economically desirable. These source areas may contribute runoff, sediment, or nutrients. The source areas for different nonpoint pollutants may not be concurrent or even overlapping with themselves or the source area for runoff. Thus the source areas must be identified separately. Such knowledge is also advantageous in evaluating theoretically based models that should be in qualitative agreement with the delineation of these areas. The initial idea of source areas was developed by Betson (1964) and applied to runoff or hydrologically active areas. Subsequent work has been done by Ragan (1968), Betson and Marius (1969) and Engman and Rogowski (1974). While Engman and Rogowski suggest that such a model "may be suited to simulation of overland transport of sediment and agricultural chemicals," to date it has not been applied in this area. One of the problems (Engman 1974) is identifying the contributing areas conveniently, Ishaq (1974) has applied remote sensing technology for this task, but his assumption that hydrological source areas and sediment source areas are similar, is open to question. Similar work on remote sensing has been done (Abdel-Hady and Karbs 1971) for hydrologically active areas. Most of the work relating to sediment has concentrated on measurement of suspended sediment in water (Blanchard and Leamer 1973, Goldman and others 1974, Pionke and Blanchard 1975, Rosgen 1976). While this can be of value in detecting the point of impact or entry to the watercourse, it will not identify the primary source.

At the present we might expect remote sensing techniques will be used exclusively to identify watersheds with excessive stream loadings. Its extension to the identification of upland source areas will require advances in remote sensing technology, field measurement, and pattern recognition. In addition, an extensive period of validation will be necessary.

One other technique which comes under the broad category of identifying source areas deserves mention. That is the use of radioisotopes (in particular Cs-137) to study sediment delivery from and movement within watersheds. Much of this work is oriented towards estimating recent sedimentation rates. This can be of value in determining baseline rates. Other work is based on the uniform distribution of Cs-137 within a watershed as a result of aboveground nuclear testing (McHenry and others 1973). As a result all material eroded since the beginning of atmospheric testing contains Cs-137, or equivalently the amount of Cs-137 is directly related to the amount of soil eroded. Ritchie and others (1973) have used this to determine sedimentation rates in reservoirs. Ritchie and McHenry (1976), in a paper presented before the Ecological Society of Ameria, evaluate factors that control the variability of cesium measurements. Its major use to date has been estimating net erosion rates. Ultimately, for water quality purposes, its main impact will be to furnish qualitative ideas as to the movement of soil within field or watershed boundaries so that gross erosion may be related to net sediment yield, and source areas identified from physiographic correlations. Along these lines an intensive sampling program is required. McHenry and others (1977) have presented results of some preliminary activity at White Clay Lake, Wisconsin.

Modeling in the Management Context

Modeling as a discipline possesses certain well defined (or at least frequently discussed) criteria to insure fidelity to the physical world. Success or lack thereof is usually discussed solely in terms of the faithfulness with which reality can be replicated or predicted. Only secondarily will consideration be given its use to simulate alternative control strategies (England 1973). This aspect of modeling will be discussed in greater detail in the next section. Here we define certain constraints upon models arising from their use within the planning process in managing the environment. This demands an acceptability to a range of users who will place differing demands and expectations upon the model. Some of these are discussed in Lettenmaier and Burges (1975). These user-oriented problems are exacerbated in the study of sediment because of its indirect effects that often are not considered in traditional water quality planning (Burt and Gentry 1974) or else restricted to a very limited aspect, such as soil conservation.

Every management-oriented model should be evaluated on the basis of the following five criteria: 1) accuracy, 2) simplicity, 3) adaptability, 4) flexibility, and 5) viability. Typically, model selection and development has emphasized restricted interpretation of the first two criteria. We shall discuss each of these briefly and in particular note a different emphasis to be placed on the first two categories in the context of a management situation.

Accuracy. The accuracy that any model may attain in part reflects a trade-off with the other categories. This is particularly important since "water quality prediction" embraces a large variety of disciplines, not all of them used to interacting at the same level (Engman and others 1971). All too often a mythical accuracy becomes the *sine qua non* of modeling. It is not expected that small perturbations in the results of a predictive model will have large repercussions in the management choice. What the management conscious modeler should seek is the minimum accuracy that still reflects the basis characteristics of the system. Stated another way, all models with a greater accuracy than a fixed criterion should be treated indifferently. This selection rule excludes one class of models and ranks as equivalent another class from which the appropriate model must be selected on some other basis. This puts a premium on empiricism as opposed to a mechanistic approach in modeling. It also presupposes a great deal of insight into both the physical and management systems.

Simplicity. The degree of detail incorporated within a model is a frequent point of departure for differing models. Typically, the use of a statistical approach or a mechanistically based one tends to be dependent in large part upon the training of the modeler. From the management context, detail should be dictated by two considerations. First is the number and desired accuracy of the water quality parameters. Here it should be emphasized that complexity and accuracy do not imply each other, although they are related. The second consideration is that sufficient alternatives or control variables are incorporated. The ideal management model has a continuous multidimensional array of possiblities. These can then be evaluated for some optimum policy. All too often the options given are limited not by the physical reality but by the assumptions used in the model (Rickert and others 1975).

Adaptability. Adaptability we will describe as the ability of a model to incorporate additional water quality features. Most of the models to be discussed in the next section deal exclusively with erosion and sediment transport. In some cases, adding additional features such as nutrient loadings can involve significant work and result in questionable accuracy. The inaccuracy results from the propagation of error when predictions of nutrient (or other chemical) flows are dependent upon uncertain values for sediment yield.

Flexibility. Flexibility refers to the ability of the model to evaluate alternate control strategies or situations. In addition, the input must readily relate to the alternatives as perceived by the manager. Adapting a research model to the needs of a manager frequently represents a considerable time cleaning up the computer program (for example, structuring the program to perform interactively).

Viability. The last criterion is in many cases the most important. The viability of a model reflects its economic and political acceptability. The latter implies that the model or its output is in a format that is accessible to a nontechnical person. Frequently the manager has several options as to the incorporation of a model into an economic analysis. If the manager opts for an optimal solution to alleviate a pollution problem then this places certain constraints upon the types of information needed (Schneider 1976). First, we need to be able to predict the magnitude of the nonpoint source. This in conjunction with a damage function will allow us to categorize the area as to the degree of hazard as well as the potential for improvement. In those areas where the nonpoint loading is minimal, no further effort is needed. This can be important when the expense of developing or applying the model is not justified by the expected benefits. In this case either some of the qualitative techniques discussed in the previous section will be used, or recommendations can be made on the strength of previous experience (for example, regulating all earth-moving activities in urbanizing areas). Otherwise a more detailed analysis is required, leading to the second phase of work, that of delineating the response of loadings to changes in management or level of control. Ideally, we would like to classify areas on the basis of their response curves and an optimal control strategy. An alternate approach is to use a "satisficing" approximation (Monarchi and others 1973).

The five criteria discussed here represent one level of concern in evaluating the use of models for water quality management. Other more technical considerations will be reviewed in the next section.

Existing Quantitative Techniques

Technical Considerations

The central characteristic of all modeling is approximation. The ideal model consists of the accurate description of all processes occurring within the system (here taken to mean watershed). This means starting from a fundamental knowledge of these processes and their interactions. The number of equations necessary to describe a complex system such as a watershed would be enormous (as well as nonlinear with random inputs). In order to deal with such systems, simplified forms of the relevant equations are used. The validity and extent of such approximations are the determining factors in the usefulness of a given approach. The selection of assumptions depends on the objectives of the modeling effort, the possible approaches, and the criteria of success. Let's look at the objectives in greater detail. In specifying the objectives we also implicitly determine the limitations of the model. The more limited our objective, the better our chances of accomplishing it with standard techniques.

It is frequently assumed that the greater the detail in the description of the physical system, the greater the fidelity in the response of the model. However, different concurrent approximation may have deleterious effects that cancel or reinforce. This implies that added detail in a model does not guarantee a corresponding increase in the precision or accuracy of the model. Finally the incorporation of untested descriptions of physical processes in a model may not give any better results than a model without any description of the process. Detail in and of itself does not inevitably result in success.

After having determined the objectives of the modeling effort, we can begin to survey the possible approaches for its achievement. Kisiel and Duckstein (1972) outline six basic techniques: 1) FSM—finite state machine or cell model; 2) PDE—partial differential equations; 3) ODE—ordinary differential equations; 4) Stochastic; 5) MLR—multiple linear regression analysis or other statistical techniques; and 6) No model—estimation based on experience.

In the "finite state machine" (FSM) model of sediment movement, the watershed is divided by a grid into cells. One of the main advantages of the FSM is its simplicity, which allows its use by people without extensive mathematical or computer background. While many such models do not have a time dependence, one can be incorporated in a FSM to allow kinetic effects to become significant. One problem with the FSM is the proper choice of cell size and time increment; frequently these are chosen on the basis of convenience.

The partial differential equation (PDE) is generally obtained via conservation equations (mass, energy, and/or momentum). The computation may become time-consuming and involved if nonlinearities appear or distributed parameters are present. In cases where ana-

Fig. 2 Erosion, deposition (sedimentation), and overland flow are seen here on the plowed land of a farm exposed to a rain storm. It represents the overall complexity encountered when attempting to estimate sediment yields. Photo by J. Larison.

lytical solutions are not available, numerical techniques can be used (for example, finite difference or finite element). Depending on the complexity of the equations used in the model, this may become expensive and unwieldy. It is interesting to note that under some conditions the FSM and numerical solutions to PDEs are identical. However, in general the latter approach provides guidelines for choice of cell size and time increment as well as information on the stability and convergence of the procedure. In addition, its theoretical development inspires greater confidence in its potential to describe complex nonequilibrium systems accurately.

The use of the stochastic approach to modeling is probably the most exacting in terms of the skills necessary for the development of predictive formulas. The data requirements are fairly large for its use. Usually the processes of erosion and deposition are assumed to follow a normal or Poisson or other well defined distribution. This is integrated over the watershed and event to obtain the net sediment transported. Repeated simulation and averaging of the basic stochastic process is common. The use of analytical expressions is also possible although theoretically involved. In either case, there is the problem of relating the parameters of the stochastic process to physically measured variables.

The last specific technique is the general one of statistical analysis. Our discussion here excludes problems of parameter estimation. Regression equations have the advantage of being simple to use; however, the applicability is usually limited to the conditions for which the analysis was performed. The success or failure of this approach depends to a large extent on being able to ascertain *a priori* the relevant parameters to attempt a correlation. These are not always easily identified.

Some mention should be made of eclectic modeling efforts. Typically, one approach is used to describe the movement of water in the watershed. This may be interfaced with a different approach for sediment production. A third approach describes nutrient loading. These models attempt to use the technique best suited for that particular phase of the physical process.

One general problem arises for those approaches which introduce unknown parameters. These models require a preliminary calibration to obtain these values (Snyder and Wallace 1974). This requires careful experimental design to insure the ability to determine all such parameters. In some cases, parameters are interrelated, resulting in an inability to estimate them separately. Then no advantage is gained by using a model incorporating the parameters separately. For more information about techniques of parameter estimation and problems associated with them, see Bard (1974).

In many modeling situations the best approach is not immediately apparent. The experience, ability, and bias of the modeler determines the approach used. Frequently, constraints of time, money, and complexity limit the type of approach, and an extensive search is not necessary. In a review Kisiel (1971) presented the following criteria: a) accuracy; b) computational efficiency; c) simplicity; and d) flexibility. In any case some form of validation is desirable. The degree to which any model can be validated is obviously dependent on the data available. It should be noted that the data used in validation should not have been used in the calibration of the model. Ideally, validation utilizes some objective criteria of the agreement between the model predictions and the data. Possible criteria that can be used are sum of squares and likelihood functions (Bard and Lapidus 1968). On occasion even a careful analysis will not discriminate between two models. In this case other considerations will dictate the choice of model to be used.

An important final step in the development of a model is an evaluation of its response to perturbations of its parameters and inputs (McCuen 1973). This performance of a sensitivity analysis allows a careful evaluation of the initial assumptions and physical intuition about the system.

The use of several models may yield a pattern of results that can be abstracted from the models. This has been expressed by Levins (1966) as the idea that if several models with "different assumptions, lead to similar results we have what we can call a robust theorem which is relatively free of the details of the model." This concept could be of importance in the development of qualitative relationships between watersheds. However, to date no systematic work has been done along these lines. An example of what we might expect is the observation that the relative importance of rainfall intensity versus total runoff is dependent on the watershed area (McGuiness and others, 1971). We might expect this qualitative result from any detailed model.

Review Literature

For many modeling efforts a discussion of sediment yield must be preceded by one of hydrograph synthesis and overland flow. It is not possible to broadly summarize this area of research here; instead the reader is referred to Chow (1964) for an excellent review of this material as well as an introduction to upland erosion phenomena. A more recent review is presented by Novotny (1976). One interesting line of work that has been developed since is with the use of kinematic cascade models (Lane and others 1975). This approach starts from the basic differential equations but introduces several simplifying approximations. Whereas the kinematic wave approach characterizes the watershed by a single plane, the cascade model uses two or more planes. To date this model has not been incorporated in a water quality model.

A number of review papers exist on aspects of modeling sediment movement. The broadest perspectives are given by Dury (1969) and Kirkby (1974), whose orientation is geomorphology. Much of the current work, in particular field studies, is described by Heinemann and

Table 1 Comparison of watershed model types by management criteria

	Accuracy	Simplicity	Adaptability	Flexibility	Viability
1. USLE-Derived					
SDR	3	2	2	3	4
Williams	4	2	2	3	3
Onstad & Foster	4	2	2	3	3
2. Other Statistical	3	2	2	2	4
3. Cell Models					
Kling & Olsen	3	3	3	3	3
OKI	3	3	3	3	4
4. Flow Duration-Rating Curve					
Bureau of Reclamation	4	4	3	2	3
Betson & McMaster	4	4	4	2	4
5. Deterministic					
Smith	?	1	3	4	2
David & Beer	3	1	4	3	2
Renard	3	2	3	3	2
ACTMO	?	1	4	4	3
6. Parametric	?	3	3	3	3
7. Stochastic	?	1	2	2	1

Note: 1 = Undesirable, 5 = Desirable, Question mark indicates uncertainty.

Piest (1975). Their work tends to be uncritical but is broader in scope than this paper. A broad based interpretive review of erosion mechanics is given by Massie (1975). Deposition is analyzed by Partheniades (1972), and sediment transport in streams is reviewed by White (1975). The material in the last three papers in combination with that of Bennett (1974) forms the basis for many modeling efforts.

Specific Cases

We shall examine seven classes of models that have been used or developed for predicting sediment yield. In some cases they fit neatly into the categorization developed under "Technical Considerations." However, many modeling efforts are hybrids, and this is reflected here. Each class will be characterized and then evaluated using the criteria established in the preceding section and "Technical Considerations." Unfortunately, no quantitative scale exists with which the models can be rigorously compared. Instead, a subjective evaluation will be made based upon a review of the available literature and experience of the authors. This should provide some insight into the relative merits of different approaches. These results are summarized in Tables 1 and 2. The model categories of Tables 1 and 2 and their evaluation will be elaborated in the following sections.

1. *Universal Soil Loss Equation (USLE).* Many of the modeling approaches use the USLE (Wischmeier and Smith 1965) in some form as the basis for predictions (McElroy and others 1976). The basic approach is to divide the watershed into distinct land-use categories. Each of these is in turn assigned a gross erosion value based on the USLE. These are added up and then adjusted to a net sediment yield by the use of a sediment delivery ratio (SDR). This is an empirical approach much popularized by the appearance of Roehl's paper (1962). He made it possible to assign a SDR on the basis of drainage area. This is the approach that many 208 planning organizations use. Frequently the land-use characteristics are estimated rather than precisely inventoried. This allows a quick rough estimate of sediment yields from a watershed.

The original development of the equation was for average yearly estimates of soil erosion from a field. Many workers have attempted to avoid these limitations implicit in the use of the USLE for watersheds by modifying the rainfall factor. There are two basic modifications: 1) replace the rainfall factor by a runoff factor (Williams and Berndt 1972, Williams 1975a), or 2) use some combination of rainfall and runoff (Onstad and Foster 1975). The main advantage of these techniques is the elimination of the SDR. This is particularly desirable as the SDR may vary considerably even for the same watershed (Mutchler and Bowie 1976).

The major advantages of the USLE related techniques are their widespread acceptance and ability to evaluate the effect of specific cropping systems or conservation practices. As a result they have been widely

Table 2 Comparison of watershed model types by technical criteria

	Requires Calibration	Goodness of Fit	Ease of Use	Expense
1. USLE-Derived				
SDR	No	2	4	4
Williams	No	3	4	4
Onstad & Foster	Yes	3	4	4
2. Other Statistical	No	3	5	5
3. Cell Models				
Kling & Olsen	No	3	4	4
OLI	No	3	4	4
4. Flow Duration-Rating Curve				
Bureau of Reclamation	Yes	4	4	4
Betson & McMaster	Yes	4	4	4
5. Deterministic				
Smith	Yes	4	2	3
David & Beer	No	4	2	3
Renard	Yes	3	2	3
ACTMO	Yes	4	3	3
6. Parametric	Yes	NA	2	3
7. Stochastic	Yes	NA	1	2

Note: 1 = Undesirable, 5 = Desirable, NA = Not applicable due to insufficient model use. All comparisons on event basis.

used in economic studies (Narayanan and others, 1974). The disadvantages are the accuracy that can be obtained and the inability to distinguish between sediment derived from different fields (for a field adjacent to a stream and one on the upland a single SDR or run-off factor assumes both contribute the same fraction of eroded material). Another negative factor has been the lack of information about the eroded material such as its particular size distribution. Williams (1975b) has shown that for a simple routing model of a complex watershed, particle size is a determining factor in net sediment yield.

2. *Statistical.* The statistical approach, as we shall discuss it, involves standard regression and correlation analysis. This is basic to all other work in that it provides an intuitive base as to the processes influencing sediment yield. A great deal of preliminary work has gone into identifying what are the significant independent variables characterizing a watershed (Overton 1969, Shelton and Sewell 1969). These can be used as a starting point for the analysis of sediment yield data (Flaxman 1972, Hindall 1976, McPherson 1975, Williams and others, 1971).

The major advantage of these techniques is their simplicity. However, they are severely limited by those variables included in the analysis. If controllable variables are not included in the regression equations, they are of little value to the manager. Occasionally overlooked is the fact that the exact form of the regression equation can affect the "goodness of fit" (Weber and others 1976). This can result in a poor predictive capacity. Because of these limitations most regression equations developed are only useful in the specific geographical areas for which they were developed.

3. *Cell Models.* The two cell models to be discussed here represent extensions of the USLE to a complex watershed. They result from a need to avoid the problems of a single SDR for a watershed. This is done by dividing the watershed into cells. Erosion in each cell is calculated from the USLE. In the model developed by the Ohio-Kentucky-Indiana Regional Council of Government (1975) or OKI, the cell represents land-use units. These units may be irregular in shape. Each cell has a unique delivery ratio that may be a function of the soil type. All calculations are done on an event basis, with sediment yield computed simultaneously with runoff.

A second approach is that of Kling and Olsen (1975). Here the cells are of uniform size, laid out in a grid pattern. Again, gross erosion is calculated using the USLE, but deposition is explicitly taken into account. This is done by routing the sediment through adjacent cells. Only a fraction of the incoming sediment is passed through the adjacent cell. Kling (1974) uses the ratio of slopes of the two cells as an estimate for this fraction. All of the calculations are done on a yearly basis.

Generally, these cell models retain most of the advantages and disadvantages of the USLE. The major increased advantage is their use of an alternative to a single SDR. In addition, their structure allows for spatial heterogeneity. The only additional limitations stem from the particular nature of sediment routing used. These may or may not be a realistic representation of overland transport and deposition of sediment.

4. *Flow Duration, Rating Curve.* One of the few techniques that does not rely on the USLE is used by the Bureau of Reclamation (Strand 1975). It is based on the use of flow duration curves in conjunction with sediment concentration. The sediment concentration is obtained from a sediment rating curve, or power function. Both curves are empirical and must be determined on site. The procedure described by the Bureau of Reclamation is basically the following integration:

$$SY = \int_{t_1}^{t_2} QC \, dt$$

where SY is sediment yield, Q volumetric flow rate, C concentration of sediment, and t time. The integration from t_1 to t_2 may represent either an event or a year. The rating curve takes the form of $C = aQ^b$, where "a" and "b" are constants characteristic of the stream and watershed. Substituting into the first equation results in:

$$SY = \int_{t_1}^{t_2} aQ^{b+1} \, dt$$

Given "a" and "b" from regression analysis (Flaxman 1975) and a flow duration curve the integration can be performed. Alternatively the time history of Q can be used to obtain a similar result.

Besides its use on an event basis or expected yearly basis, it has also been used to look at the effect of extreme events on long term sediment yields (Neff 1967).

An extension of this basic idea to other water quality parameters has been made by Betson and McMaster (1975). They propose a general form of rating function (similar to that of the Bureau of Reclamation) to be used with any water quality index. They use this only for estimating concentrations rather than loadings. But there is nothing limiting in their method provided streamflow data are available. They go on to look for correlations of the coefficients to geologic characteristics of the watershed. This allows them to predict the coefficients for any unmonitored watershed.

The basic advantage of this technique is its simplicity. It is also one of the more difficult to work into a management scheme. This results because the only controllable variables are streamflow and the coefficients "a" and "b." To date, little work has been done on how land-use practices may affect these values. Runoff control through land-use manipulation (Fogel and others, 1974) may have potential as a pollutant management strategy, but it presupposes that nonpoint pollutants are transport limited.

5. *Deterministic.* A great deal of work has been done in the development of detailed mechanistic models to describe the erosion and sediment transport processes (Bennet 1974). The work of many groups tends to overlap in methodology. In this review we shall evaluate only those approaches that are in some sense unique.

The first group of deterministic models attempts to solve the governing differential equations of erosion and sediment transport. In order to obtain solutions, certain broad assumptions must be made to allow either an exact solution (Foster and Meyer 1972) or a numerical one (Smith 1976). These models possess the aesthetic satisfaction of starting from fundamental conservation equations that describe the whole sediment yield process. They suffer from the problems of being difficult to work with and insufficiently developed to be applied in diverse environments. This results in part from the presence of coefficients of the differential equation which cannot be determined independently. Thus, extensive calibration and validation is required.

The second group of deterministic models takes a synthetic approach. The component processes are predicted on the basis of detailed submodels. These submodels usually are derived from fundamental fluid mechanical descriptions of the erosion and transport phenomena. David and Beer (1975a,b) as well as Meyer and Wischmeier (1969) are indicative of this school of thought. Their major advantage is the relative ease of construction and their ability to handle a wide variety of physical situations. Their major drawbacks are their bulkiness and lack of experience on a watershed basis. It is not always clear with such models what management alternatives can be explored.

A third type of model ignores the details of erosion and concentrates on transport. The critical tractive force technique is used by Renard (1974) to evaluate total sediment yield for ephemeral streams. One advantage of the procedure is it allows the evaluation of the particle size distribution of the suspended load. Work has also been done using this approach coupled with a stochastic model of runoff events (Renard and Lane 1975). Disadvantages are the difficulty of determining parameters and its primary applicability to semiarid environments.

The last type of deterministic model we will discuss emphasizes the hydrology of the watershed. In general, these start from a sophisticated runoff model and attach an erosion component (usually the USLE). The hydrograph generation usually involves considerable data requirements and expertise in adjusting parameters. Once calibrated they usually respond well to attempts at simulating the effect of watershed modifications. Unfortunately, this quality of response is usually limited to runoff. The Hydrocomp model is one example which has been widely used (Hydrocomp International 1969, Donigian and Crawford 1976) despite their problems in sediment prediction (Fleming and Leytham 1976). A more recent development is ACTMO (Frere and others, 1975). Its hydrological component is a revision of the USDA Hydrograph Lab model (Holtan and Lopez 1971). One advantage of this model is its calculation of particle size distribution of eroded material and using this in evaluating nutrient yields.

These models are the most complex but also the most versatile. Unfortunately their accuracy is not well established and there is considerable difficulty in using the model on uncalibrated watersheds. They are probably best used to obtain qualitative results about watershed response.

6. *Parametric.* The use of parametric models has been defined (Snyder 1971) as the "development and analysis of relationships among the hydrologic and physical characteristics of the drainage area contributing streamflow." The functional relationships are characterized by unknown quantities or parameters which cannot *a priori* be determined. Snyder (1975) has suggested possible applications to sediment yield. One limitation of parametric modeling is the extensive calibration required. Usually parameters must be estimated using non linear least squares, an involved and expensive procedure. As more powerful and less expensive mathematical techniques become available, this approach could become important.

7. *Stochastic.* "A stochastic process is the mathematical abstraction of an empirical process whose development is governed by probabilistic laws" (Doob 1953). Stochastic processes can be used in conjunction with hydrologic models to either "generate synthetic sequences of hydrologic data" or "add a random element equal to the unexplained variance" (DeCoursey 1971). While there has been considerable interest in applying such concepts to hydrologic modeling, their use in nonpoint pollution problems has been negligible. Some interest has existed in the effect of random rainfall events on sediment transport (Murota and Hashino 1969, Renard and Lane 1975). The only serious attempt at describing the details of the erosion and transport process using a stochastic model is by Woolhiser and Blinco (1975). Unfortunately, this work is a restatement of the problem couched in probabilistic terms. No work has been done in trying to apply it to actual field data. In fact little or no effort is presently being expended along these lines (Woolhiser, personal communication).

It is worthwhile to point out here that scant attention in the planning process is given to uncertainty in climate (Knox and others, 1975) or rainfall estimates (Curry and others, 1966). This can influence the selection of a control strategy indirectly (Wells and others, 1973). The prediction process for all models requires the input of rainfall data on an event or yearly basis. Unless a range of climatic situations are evaluated any policy developed may be biased.

Discussion

Our initial goal was to evaluate models in a management context. This led to a new set of criteria. While their aplication to specific models are given in Table 1, this remains at an abstract level. We now turn to some specific recommendations to planners and modelers.

At the present time, deterministic, parametric, and stochastic models are basically research tools. They are expensive to use (both in manpower and computing costs) and, at present, of uncertain accuracy. Their major rôle is expected to be the elucidation of watershed response characteristics. This could be especially important in delineating source areas. Only in a very limited number of cases (primarily large urban areas) is it worth considering their use.

The easiest approach that can be used is the statistical one. If such relationships have been established for the planning area, they should be used. The major drawback is that they may present only limited control options. Most areas will probably rely on USLE-derived techniques. These are important because there exists a large manpower and information base related to their use.

There is a broad gap between the USLE-related techniques and the most complex modeling efforts. Only recently has this begun to be breeched. The development of cell models or modified rating curve techniques represents a significant contribution. They have the potential of combining most of the advantages and few of the disadvantages of the other procedures. Two major research needs must be satisfied to realize this potential: first, a better description of the process of deposition, and second, an extensive evaluation of the dependence of rating curves on land-use (and temporal) characteristics.

Many options are open to modelers and planners. Only by recognizing their limitations and needs can there be a productive interaction. With this review we hope to stimulate an awareness in modelers that they are not working exclusively under technical constraints. Rather there are distinct nontechnical criteria by which the utility of their work must be judged.

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