Water Erosion and Water Quality

D.K. McCool and K.G. Renard

I. Introduction

Water erosion at some level is inevitable. Geological erosion transforms rugged mountains into rounded hills and produces fertile valleys and lowlands. Only by massive engineering structures is geological erosion reduced at a point, and in terms of geological time even then it is only temporarily averted.

Accelerated erosion reflects the activity of man. It occurs because of cultivation of sloping lands or vegetation alteration caused by a concentration of domesticated animals. Generally, accelerated erosion is detrimental. It results in movement of topsoil from hillslopes to valley bottoms that may already have an adequate depth of topsoil, or to streams and reservoirs. Subsoil is usually less hospitable to plant growth than topsoil because of a lack of nutrients and lower available water-holding capacity.

Erosion was recognized as a problem in early civilizations and various attempts were made to deal with it (Bennett, 1939). Literally thousands of years of

Advances in Soil Science, Volume 13

labor were spent constructing canals, dikes, and elaborate bench terrace systems. The remnants of these can still be seen, and some are still in use in certain parts of the world.

In the United States, erosion was recognized as a severe problem within a few years of settlement. Frequently the solution for the farmer of eroded and depleted land was to abandon the property and move to a new area because new land was readily available. There were a few conservationists in the 18th and 19th centuries, but their efforts were not extensive and there was no way to communicate effectively with a large number of farmers.

It was not until the start of the 20th century that erosion in the United States received national attention. In 1930, federal appropriations were made for investigations as to causes of erosion. This and subsequent legislation established 10 soil erosion experiment stations across the country (Bennett, 1939). The need for additional emphasis on soil erosion was heightened by the drought and dust bowl period of the 1930s. Since that time, farming practices have changed dramatically, with larger, more economically efficient farming units and larger tillage and harvesting equipment. These changes in farming practices have made it difficult to use traditional erosion control practices and placed more emphasis on cultural practices such as mulching and residue management. In the late 1960s and the 1970s, reduced and no-till seeding techniques were developed, first for row crops and then for small grains.

Reduced tillage and no-till systems result in higher quantities of crop residues remaining on the surface, which reduces runoff and erosion. However, these systems generally require higher application rates of insecticides and herbicides. Thus, there is a possibility that improved erosion control associated with conservation tillage systems may lead to decreased water quality because of increased chemical usage and the accompanying greater losses in the runoff or to groundwater.

Developing nations are frequently faced with problems of severe soil erosion and depletion of the soil resource base. As they struggle to feed an increasing population, steeper and less suitable lands come under cultivation. The result is increased soil erosion, greater fluctuations in runoff, and increased sediment damage. Erosion control practices such as mulching with crop residues are often not used because of tradition, use of the residue for other purposes, insect problems, or the additional labor needed to manage the residue.

The erosion problem in some parts of the world is unrecognized or ignored, with the assumption that erosion is a problem only where it is well publicized such as in the United States or in areas where erosion-depleted soil combined with drought have caused widespread famine and suffering. In reality, it is under only the most benign climatic, topographic, and soil conditions that accelerated erosion has no potential for damaging the natural resource base.

Assessing the status of the soil resource base and its change with time is an important activity in developing as well as developed nations. These assessments are necessary to predict capability of meeting food and fiber needs of the near and distant future. Properly conducted and used, assessments can assist planners and policy makers to make good decisions regarding land use and to design programs to control soil erosion.

The purpose of this chapter is to discuss water erosion and water quality impacts, to describe methodology to answer questions of interactions between erosion control and water quality, and to describe methodology for assessing soil erosion.

II. Impacts

A. Erosion

The effect of erosion on productivity received much attention in the United States from the 1930s through the early 1950s. Research sometimes involved topsoil scalping to simulate a severely eroded area for comparison with an adjacent noneroded area. Some researchers compared eroded phases of the soil with those with greater topsoil depth, while others initiated long-term projects to erode a plot area more naturally. Results from these studies of the detrimental impact of erosion on crop productivity were so conclusive that research emphasis was shifted to measuring erosion rates under different cropping practices, developing erosion-control practices, and predicting erosion (Meyer et al., 1985).

In the early 1980s renewed interest developed in relationships between soil erosion and productivity, largely as a result of Public Law 95-192, the Soil and Water Resources Conservation Act of 1977 (RCA). The RCA emphasized the need for better quantification of erosion-induced productivity losses, their economic impacts, and their short-term and long-term impacts on the ability of the United States to produce food, feed, and fiber. Because of different crop varieties, fertilization techniques, and tillage practices, it was not possible to extrapolate results of the earlier studies to current conditions (Williams et al., 1981). Studies linking soil erosion to productivity were undertaken. In nearly all cases, because of funding requirements and other constraints, the research was designed to be short term. These erosion/productivity concerns and the requirements of RCA also led to development of models linking soil erosion and productivity. The most widely used of these models is the Erosion-Productivity Impact Calculator (EPIC) (Williams and Renard, 1985).

In early 1983 a Symposium on Soil Erosion and Crop Productivity focused on appraisals, policies, economics, and prediction techniques (Follett and Stewart, 1985). By late 1984 sufficient current experimental data were available that a National Symposium on Erosion and Soil Productivity was held at which several researchers presented their results (ASAE, 1985). Nearly all the results showed a significant impact of soil erosion on productivity. The impact was a function of erosion rates and soil characteristics; in some cases crop yield would be changed significantly over a long period of time while in others the changes would be more rapid. Researchers in some areas found landscape position to be a factor of greater importance than topsoil depth, largely because of soil variations and moisture-holding capacity related to landscape position (Gilliam et al., 1985).

The studies cited previously all concentrated on the effect of erosion on productivity. They did not address the issue of off-site damages, such as filling of roadside ditches, reduced channel flow capacity, reservoir siltation, loss of fish habitat, aesthetic considerations, and lost recreational potential.

That off-site damages could exceed productivity losses was emphasized by Crosson (1984), who cited results of the 1977 National Resources Inventory (NRI), results from studies at the University of Minnesota, and from studies of Resources for the Future that indicated, respectively, yield losses of 8% in 50 years, 5 to 10% in 100 years, and 2 to 3% in 30 years. The annual cost of these yield losses was estimated at $40 million in 1984 and $80 million in 1985; annual costs would increase by about $40 million each year. In contrast, Crosson cited a study by the Conservation Foundation that indicated off-site damages from sediment were about $3.1 billion per year, many times the cost of the productivity losses. Since then, off-site impact has been an important consideration in nearly all soil erosion studies and projects.

B. Water Quality

Surface water quality can be affected by a number of factors, the most obvious and visible being suspended sediment. However, the most troublesome are not the visible factors, but rather the invisible that render the water unsafe for livestock, irrigation, recreation, and human consumption. Water can be made unsafe by a number of chemical and biological agents. These include excess plant nutrients, animal wastes, municipal or household wastes, agricultural chemicals, and other materials.

Water quality has been a matter of a public concern for some time. In the United States, federal legislation addressing water quality appeared before 1900. The Refuse Act of 1899, the Public Health Act of 1912, and the Oil Pollution Act of 1912 all dealt with water quality. The first federal legislation having a major impact on U.S. agriculture was the Federal Water Pollution Control Act Amendments of 1972, which, among other items, addressed non-point source pollution from such sources as farm fields.

Major water quality problems of concern to agriculture are nutrients and pesticides. Nutrients make water unsafe for humans, animals, or fish when the concentration of certain forms exceeds a critical level; excessive nutrients can also accelerate eutrophication. Nitrogen has perhaps received the most attention as a threat to water quality (Wadleigh, 1968). Nitrite is the most toxic form of nitrogen, but children, young animals, and cattle convert some of the more common nitrates to nitrites in their stomachs and can develop methemoglobinemia. In 1962 the U.S. Public Health Service set an upper limit on nitrate in drinking water at 10 mg N per liter (45 ppm nitrate) (Frere, 1976).

Eutrophication, a natural process, is accelerated by the enrichment of water by excess nutrients. The ensuring luxuriant growth of algae and plants and their decay removes oxygen from the water. Rapid growth of algae is the greatest and most widespread problem in most of the United States (Frere, 1976). High levels of nitrogen and phosphorus appear to be the nutrients accounting for most of the excessive algae growth. Frere cited Sawyer (1947), who concluded concentrations of 0.3 ppm of inorganic nitrogen and 0.015 ppm for inorganic phosphorus were levels at which eutrophication would become a problem.

On a nationwide level, fertilizer is a major and manure a minor input of nutrients to streams. The relative role of these factors may be reversed for a given area, such as those with a high concentration of livestock (Frere, 1976).

Pesticides move into surface waters with either runoff or sediment. In general, soluble compounds move with the runoff and adsorbed compounds move with the sediment. However, some very water-soluble compounds have strong irreversible adsorption to soil particles and move only with the sediment. Movement of pesticides is very complex and is a function of the soil characteristics as well as those of the pesticide itself (Caro, 1976).

Subsurface water quality is mainly impacted by mobile nutrients and pesticides, although, through cracks in initially dry soil, those forms normally associated with surface flow can also enter the groundwater. Pesticides are usually applied on or near the soil surface. Fertilizers can be surface applied, incorporated by tillage, or injected into the soil. Common application rates of N are 112 kg per hectare or more in high producing areas, but 60 kg per hectare or less in drier areas. In addition, through mineralization of organic nitrogen to nitrate, 135 kg N per hectare or more can be released in fertile soil (Frere, 1976). Similarly to movement with runoff water and sediment, movement of nutrients and pesticides into and through the soil is governed by characteristics of both the soil and the nutrient or pesticide. Soluble materials move rapidly with infiltrated water in sandy soils with more organic matter or clay, even if the soil is so well structured as to maintain high permeability. According to Caro (1976) adsorption is a better indicator of overall potential movement than solubility, because strongly adsorbed materials will not move.

III. Prediction

A. Erosion

Erosion prediction has progressed from data collection to compare practices, to simple empirical models, to complex empirical models, and most recently toward process-based models. The most widely used empirical model at present is the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1965; 1978), a predictor of long-term soil loss. Soil loss is calculated as mass per unit of area based on the product of six factors: rainfall and runoff erosivity factor, R; soil erodibility factor, K; slope length factor, L; slope steepness factor, S; crop management factor, C; and erosion control practice factor, P. Various adaptations of the USLE replaced the rainfall and runoff erosivity factor, R, with parameters designed to predict more accurately on an event basis or to predict sediment yield. The Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) replaced the USLE R factor with a factor based on peak rate and total runoff volume for an event in an effort to predict watershed sediment yield. Onstad and Foster (1975) developed an adaptation of the USLE for predicting soil loss from events, based on a combination of the traditional R and the MUSLE peak rate and runoff volume. The Agricultural Chemical Transport Model (ACTMO; Frere et al., 1975) was an early attempt to add a hydrologic model to erosion prediction. Both ACTMO and the Chemicals, Runoff, and Erosion from Agricultural Management Systems Model (CREAMS; Foster et al., 1980) use certain factors from the USLE along with runoff prediction techniques. CREAMS includes channel processes and is suitable for small watersheds.

A revision of the USLE, called the Revised Universal Soil Loss Equation (RUSLE) is currently being developed. It retains the use of the six factors and predicts hillslope soil loss on an average annual basis, but it has improved values of the R factor for western states in the United States, takes into account variation of soil erodibility with time, has new slope length and steepness relationships, uses a subfactor system for calculating crop management factors, and has new erosion control practice factor values developed by CREAMS technology. It is programmed and operational on a personal computer.

A number of rather complex watershed erosion-sediment yield models have been developed. In general, these models were intended for watershed-size areas and are not suited to farm planning because of the data requirements and the need for mainframe computers to solve the flow equations. Frequently these models are research oriented and intended for investigating the influence of a particular parameter on the runoff and soil erosion process. Foster (1982) compares these models and is the source of much of the following discussion. A number of the earlier models linked an erosion and sediment transport model to an existing runoff model such as the Stanford model. Examples of models using the Stanford model are those of Negev (1967), David and Beer (1975), the ARM model (Donigan and Crawford, 1976; Donigan and Davis, 1978; Fleming and Leytham, 1976). In more recent modeling efforts, the modeler has tended to develop the runoff as well as the detachment and transport relationships. Examples include Smith's model (1977), the CSU model (Li, 1977), ANSWERS (Beasley, 1977), and OPUS (Smith and Ferreira, 1986). Some models such as the Ground Water Loading Effects of Agricultural Management Systems Model (GLEAMS; Leonard et al., 1987) include components for routing infiltrated water and selected chemicals through the root zone. Inclusion of this component is essential if movement of nutrients and pesticides to groundwater is to be considered, as discussed in a following section.

In 1985 a coordinated effort was started by the Agricultural Research Service, Soil Conservation Service, Forest Service, Bureau of Land Management, U.S. Geological Survey, and other federal and state agencies to replace the USLE with a process-driven field-usable erosion/sedimentation model (Foster and Lane, 1987). The effort is called the Water Erosion Prediction Project (WEPP). The model will be available in three versions – a hillslope version for farm planning, a watershed version, and a grid version. Target date for completion of the hillslope version was late 1989. This version will apply to hillslopes without concentrated flow channels or gullies, that is, as a replacement for the USLE. It computes interrill and rill erosion along selected landscape profiles and includes sediment deposition at energy gradient decreases or in impoundments. Gully erosion is considered only in the watershed and grid versions. WEPP includes components for climate generation, infiltration, water balance, crop growth and residue decomposition, surface runoff, and erosion. It calculates spatial and temporal variations of soil loss in continuous simulation or single-event mode.

B. Water Quality

Movement of nutrients and pesticides in surface runoff is modeled by routing the material with the water or sediment as appropriate. Because the nutrients and pesticides are more readily adsorbed to the finer soil particles, it is necessary for the erosion and transport portion of the model to be selective; that is, different particle sizes should be considered separately.

ACTMO (Frere et al., 1975) routes pesticides and nitrates with surface runoff and sediment. The pesticide option considers adsorption, breakdown, and movement. The nitrate option deals with mineralization, plant uptake, and movement. CREAMS (Knisel, 1980) uses a plant nutrient submodel with a nitrogen component that considers mineralization, nitrification, and denitrification processes. Enrichment ratios provide the basis for computing nitrogen and phosphorus movement with sediment. The pesticide component considers foliar interception, degradation, and washoff, along with adsorption, desorption, and degradation in the soil. A grid-based single-event model, the Agricultural Non-Point-Source Pollution Model (AGNPS; Young et al., 1987), uses a standard runoff prediction technique, certain factors from the USLE, and channel parameters. It predicts runoff, sediment, and nitrogen, phosphorus, and chemical oxygen demand concentrations in the runoff and in the sediment for all points in the watershed.

Movement of nutrients and pesticides to groundwater is currently accomplished by use of a leaching model coupled to the infiltration component of the main hydrologic model. Both ACTMO (Frere et al., 1975) and CREAMS (Knisel, 1980) consider nitrate leaching but not pesticide movement into and through the soil. GLEAMS (Leonard et al., 1987) deals with pesticide and metabolite movement into and through the root zone. The Leaching Estimation and Chemistry Model (LEACHM; Wagenet and Hutson, 1987) considers pesticide and metabolic movement through the root zone. The CMLS model (Nofziger and Hornsby, 1986) assumes no surface runoff and routes pesticides through the root zone for single events. Another pesticide leaching model is the Pesticide Root Zone Model (PRZM; Carsel et al., 1984; 1985), which is coupled to a hydrologic/erosion model and considers pesticide movement through the root zone.

IV. Research Needs

There is pressing need for a field-usable process-based erosion and water quality model. WEPP is targeted to meet a part of that need. However, whereas the hydrology and hydraulics are process-driven, many of the soil, biological, and cropping relationships are largely empirical, and the model may be quite sensitive to some of these components. If USLE relationships are a guide, residue effect and residue decomposition will be very important, as will crop growth and cover. Also, readily available soils information may not be in sufficient detail or may be too broad or general to enable accurate prediction of infiltration and percolation and hence of runoff, soil loss, and chemical movement.

Given that erosion at some level is associated with cultivation and livestock production, and that some soils are more susceptible to erosion damage than others, the concept of a soil loss tolerance was introduced into erosion work. The soil loss tolerance, T, is defined as the maximum soil loss, in mass per unit area, that can be sustained without productivity loss. This concept has been attacked frequently. Objections include that no firm relationship exists between topsoil depth and yield and that, in some situations, productivity is much better related to available soil water than to topsoil depth (Gilliam et al., 1985). Others feel that currently used values are based on social and economic considerations rather than on sustainability of long-term productivity (Johnson, 1987).

It is likely that, in fact, whereas one of these extreme viewpoints may be correct for a given field in one area, the other may be correct for another site at some other place. The need for a better and more complete definition is evident from the controversy that has developed around T. This controversy stresses the need for a more complete concept of erosion tolerance that includes soil formation rates, suitability of the subsoil as a medium for plant growth, depth of topsoil, and potential for off-site damage.

Predicting effects of management practices on surface water quality as well as on soil loss is essential. Inasmuch as pollutants may be either carried in solution or adsorbed to soil particles, an erosion predictor such as the USLE is inadequate to address water quality. Models must also include runoff prediction. Certainly off-site impacts are of concern, so hillside models must provide input to routing models that will consider the fate of pollutants that leave the hillslope area and enter the channel system.

Groundwater quality is very important, and is emerging in the United States as an area of great concern. Much of the domestic water supply comes from groundwater sources. Preventing groundwater contamination is much easier than dealing with it after it occurs; the latter may be impossible and is certainly uneconomical.

Soil loss and water quality models that are operational and practical must be available. Data requirements must be reasonable if the model is to be used for such purposes as farm planning. The models must be user-friendly if they are to be used by a wide range of personnel. Results obtained with the models must be realistic or they will not be accepted by field personnel. These requirements, though essential for successful application in the United States, are even more important if the models are to be used in developing nations.

Climate and soils data are needed for the operation of all erosion and water quality models, from the USLE to the most complex. In the case of the USLE, the climate data consist of break-point precipitation data or an estimate of that data. Ideally, the period of record should be about 20 years or sufficiently long to sample the precipitation cycle. Procedures have been developed to estimate break-point data from hourly precipitation data (Istok et al., 1986).

With increasing frequency, physically based models use climate-generation techniques to develop data for operating their models. For example, the WEPP model operates on the output from a climate generator (Nicks et al., 1987). The climate generator requires about 20 years of observational data of daily precipitation and daily maximum/minimum temperature. From these data the model can be developed to disaggregate the daily precipitation estimates into hourly or shorter data estimates (Woolhiser et al., 1988), which can then be used as input to time-based infiltration technology. The climate-generation and precipitation-disaggregation technologies are still in an evolutionary phase. The large number of parameters involved in such schemes make parameter determination difficult and preclude widespread application in many locations.

V. Summary

Accelerated soil erosion has been a problem since early civilization and remains so today. Population and economic pressures are causing the cultivation of steeper and more easily damaged lands. Water quality has joined soil erosion as a major concern. Previously this was primarily a concern of industrialized nations; now it must be dealt with by all. Models exist and are being developed and improved continually to determine the effect of land management decisions. These models will assist planners and policy makers worldwide in setting and meeting erosion and water quality goals.

References

ASAE. 1985. Erosion and soil productivity, Proceedings of the National Symposium on Erosion and Soil Productivity, New Orleans, La. Dec. 10–11, 1984. St. Joseph, Mich.: American Society of Agricultural Engineers.

Beasley, D.B. 1977. ANSWERS: A mathematical model for simulating the effects of land use and management on water quality. Ph.D. thesis, Purdue University, West Lafayette, Ind.

Bennett, H.H. 1939. Soil conservation. New York and London: McGraw-Hill Book Co.

Caro, J.H. 1976. Pesticides in agricultural runoff. *In*: Stewart, B.A. (Coordinator). Control of Water Pollution from Cropland. Vol. II–An Overview. pp. 91–119. USDA-ARS. Report No. ARS-H-5-2.

Carsel, R.F., L.A. Mulkey, M.N. Lorber, and L.B. Baskin. 1985. The pesticide root zone model (PRZM): A procedure for evaluating pesticide leaching threats to ground water. Ecological Modeling 30:49–69.

Carsel, R.F., C.N. Smith, L.A. Mulkey, J.D. Dean, and P. Jowise. 1984. User's manual for the pesticide root zone model (PRZM):Release 1. EPA-600/3-84-109. Athens, Ga.: USEPA, Environmental Research Laboratory.

Crosson, P. 1984. New perspectives on soil conservation policy. Journal of Soil and Water Conservation 39(4):222-225.

David, W.P., and C.E. Beer. 1975. Simulation of soil erosion—Part I. Development of a mathematical erosion model. Transactions of the ASAE 18(1):126-129,133.

Donigan, A.S., and N.H. Crawford. 1976. Modeling non point source pollution from the land surface. EPA-600/3-76-083. U.S. Environmental Protection Agency.

Donigan, A.S., and H.H. Davis. 1978. User's Manual for Agricultural Runoff Management (ARM) Model. EPA-600/3-78-080. U.S. Environmental Protection Agency.

Fleming, G., and K.M. Leytham. 1976. The hydrologic and sediment processes in natural watershed areas. *In*: Proc. of the Third Federal Inter-Agency Sedimentation Conference. Water Resources Council, Washington, D.C. 1:232-246.

Follett, R.F., and B.A. Stewart (eds.). 1985. Soil erosion and crop productivity. Madison, Wisc.: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.

Foster, G.R. 1982. Modeling the erosion process. *In*: Haan, C.T., H.P. Johnson, and D.L. Brakensiek (eds.). Hydrologic Modeling of Small Watersheds. pp. 297-380. St. Joseph, Mich.: American Society of Agricultural Engineers.

Foster, G.R., and L.J. Lane. 1987: User requirements, USDA-water erosion prediction project (WEPP). NSERL Report No. 1. National Soil Erosion Research Laboratory, West Lafayette, Ind.

Foster, G.R., L.J. Lane, J.D. Nowlin, J.M. Laflen, and R.A. Young. 1980. A model to estimate sediment yield from field-sized areas: Development of model. *In*: Knisel, W.G. (ed.). CREAMS—A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. Volume I: Model Documentation. Chap. 3, pp. 36-64. USDA-Science and Education Administration, Conservation Research Report No. 26.

Frere, M.H. 1976. Nutrient aspects of pollution from cropland. *In*: Stewart, B.A. (Coordinator). Control of Water Pollution from Cropland. Vol. II—An Overview. pp. 59-90. USDA-ARS. Report No. ARS-H-5-2.

Frere, M.H., C.A. Onstad, and H.N. Holtan. 1975. ACTMO, An Agricultural Chemical Transport Model. USDA-ARS-H-3, Washington, D.C.

Gilliam, J.W., D.K. Cassel, R.B. Daniels, and J.R. Stone. 1985. Interrelationships among soil erosion, landscape position and soil productivity in the North Carolina Piedmont. *In*: Erosion and Soil Productivity, Proceedings of the National Symposium on Erosion and Soil Productivity, New Orleans, LA. Dec. 10-11, 1984. pp. 75-82. St. Joseph, Mich.: American Society of Agricultural Engineers.

Istok, J.D., D.K. McCool, L.G. King, and L. Boersma. 1986. Effect of rainfall measurement interval on EI calculation. Transactions of the ASAE 29(3):730-734.

Johnson, L.C. 1987. Soil loss tolerance: Fact or myth. Journal of Soil and Water Conservation 42(3):155-160.

Knisel, W.G. (ed.). 1980. CREAMS—A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. USDA-Science and Education Administration, Conservation Research Report No. 26.

Leonard, R.A., W.G. Knisel, and D.A. Still. 1987. GLEAMS: Ground water loading effects of agricultural management systems. Transactions of the ASAE 30(5):1403-1418.

Li, R.M. 1977. Water and sediment routing from watersheds. *In*: Proc. of River Mechanics Institute, chap. 9. Ft. Collins: Colorado State University.

Meyer, L.D., F.E. Rhoton, and K.G. Renard. 1985. Soil erosion-soil productivity: A look to the future. *In*: Erosion and Soil Productivity, Proceedings of the National Symposium on Erosion and Soil Productivity, New Orleans, LA. Dec. 10–11, 1984. pp. 266–277. St. Joseph, Mich.: American Society of Agricultural Engineers.

Negev, M. 1967. A sediment model on a digital computer. Technical Report 76. Department of Civil Engineering, Stanford University, Stanford, Calif.

Nicks, A.D., D.A. Woolhiser, and C.W. Richardson. 1987. Generating climate data. ASAE Paper No. 87-2541. St. Joseph, Mich.: American Society of Agricultural Engineers.

Nofziger, D.L., and A.G. Hornsby. 1986. A microcomputer-based management tool for chemical movement in soil. Applied Agricultural Research 1:50–56.

Onstad, C.A., and G.R. Foster. 1975. Erosion modeling on a watershed. Transactions of the ASAE 18(2):288–292.

Sawyer, C.N. 1947. Fertilization of lakes by agricultural and urban drainage. New England Waterworks Assoc. 61:109–127.

Smith, R.E. 1977. Field test of a distributed watershed erosion/sedimentation model. *In*: Soil Erosion: Prediction and Control. pp. 201–209. Special Publication No. 21. Ankeny, Iowa: Soil Conservation Society of America.

Smith, R.E., and V.A. Ferreira. 1986. Effect of soil hydraulic properties on root zone transport processes. *In*: Proceedings of AGU Front Range Branch Hydrology Days. pp. 123–137. Ft. Collins: Hydrology Days Publications. Colorado State University.

Wadleigh, C.H. 1968. Wastes in relation to agriculture and forestry. USDA Miscellaneous Paper No. 1065, Washington, D.C.

Wagenet, R.L., and J.L. Hutson. 1987. Leaching estimation and chemistry model. Continuum Water Resources Institute. Vol. 2. Center for Environmental Research. Ithaca, N.Y.: Cornell University.

Williams, J.R. 1975. Sediment-yield prediction with universal equation using runoff energy factor. *In*: Present and Prospective Technology for Predicting Sediment Yields and Sources. pp. 244–252. USDA, ARS-S-40. Washington, D.C.: U.S. Government Printing Office.

Williams, J.R., R.R. Allmaras, K.G. Renard, L. Lyles, W.C. Moldenhauer, G.W. Langdale, L.D. Meyer, and W.J. Rawls. 1981. Soil erosion effects on soil productivity: A research perspective. Journal of Soil and Water Conservation 36(2):82–90.

Williams, J.R., and K.G. Renard. 1985. Assessment of soil erosion and crop productivity with process models (EPIC). *In*: Follett, R.F. and B.A. Stewart (eds.). Soil Erosion and Crop Productivity. pp. 67–103. Madison, Wisc.: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.

Wischmeier, W.H., and D.D. Smith. 1965. Predicting rainfall-erosion losses from cropland east of the Rocky Mountains, USDA, Agriculture Handbook 282. Washington, D.C.: U.S. Government Printing Office.