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Optimal Operation of Large Agricultural Watersheds with Water Quality Restraints

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- Full Text

Improved technology is needed for use in properly managing large agricultural watersheds. Proper watershed management means selecting land uses that are appropriate for each subarea, using erosion control measures where necessary, and applying fertilizers at rates that maximize agricultural production without polluting the environment. Watershed runoff and industrial and municipal effluents pollute streams and reservoirs. Point source pollution (industries and municipalities) can be monitored. Nonpoint-source pollution (watersheds) is widely dispersed and not easily measured. Mathematical models are needed to predict nonpoint-source pollution as affected by watershed characteristics, land use, conservation practices, chemical fertilizers, and climatic variables. Routing models are needed to determine the quality of water as it flows from nonpoint sources through streams and valleys to rivers and large reservoirs. Models are also needed to determine optimal strategies for planning land use, conservation practices, and fertilizer application to maximize agricultural production subject to water quality constraints.

Three of the most important agricultural pollutants are suspended sediment, phosphorus, and nitrogen. Robinson [1971] pointed out that sediment is the greatest pollutant of water in terms of volume. Sediment also transports other pollutants, like phosphorus and nitrogen. These two elements are principally involved in lake eutrophication. Frequently algae blooms develop in nutrient-laden water and cause it to have an off-taste and an unpleasant odor. The odor of decaying plants becomes offensive; fish are killed because of reduced dissolved oxygen in the water, and recreation is deterred.

The objective of this research was to develop models for use in managing large agricultural watersheds to obtain maximum agricultural production and to maintain water quality standards. The models were designed to:

1. Simulate daily runoff, and sediment, phosphorus, and nitrogen yields from small watersheds (areas < 40 km2) and determine frequency relationships.
2. Route various frequency hydrography and sediment, phosphorus, and nitrogen yields from subwatersheds through streams and valleys of large agricultural watersheds (areas < 2500 km2) to obtain frequency relationships at the entrance of a river or reservoir.
3. Determine strategies that are acceptable to the decision makers (land owners and operators) for planning land use, fertilizer application, and conservation practices on subwatersheds.
4. Determine the optimal strategy for each subwatershed to maximize agricultural production for the entire watershed subject to water quality constraints.

Generally, water-quality models are developed by adding chemical modeling components to existing runoff and sediment models because runoff and sediment provide transportation for chemicals. Several conceptual models for predicting chemical yields from small watersheds have been presented [Crawford and Donigian, 1973; Donigian and Crawford, 1976; Frere, et al., 1975; Hagin and Amberger, 1974; Kling, 1974; Johnson and Straub, 1971]. However, these models are not applicable to large watersheds because they have no routing mechanism. For this reason, runoff, sediment, and nutrient models were refined and developed here for application to large watersheds.

Probably, the most widely used and accepted model for predicting runoff volume is the Soil Conservation Service (SCS) curve number system [U.S. Soil Conservation Service, 1972]. The SCS model was modified by adding a soil-moisture-index accounting procedure [Williams and Laseur, 1976]. The modified water yield model is considerably more accurate than the original SCS model. On a watershed near Riesel, Texas, the modified model explained 95% of the variation in monthly runoff as compared with 65% for the original model. The water-yield model was refined here by replacing the climatic index (lake evaporation) with daily consumptive water use for individual crops.

Besides predicting individual storm runoff volumes, it is also necessary to predict hydrographs and to perform flood routing for water quality modeling on large agricultural watersheds. HYMO, a problemoriented computer language for building hydrologic models [Williams and Hann, 1973] was selected to compute hydrographs and perform flood routings. Worldwide use has shown that HYMO is convenient and reliable for extremely varied hydrologic conditions. The Variable Travel Time (VTT) flood routing method [Williams, 1975a] used in HYMO is about as accurate as an implicit solution of the unsteady flow equations of continuity and motion and is free of convergence problems.

The USLE [Wischmeier and Smith, 1965] is the most widely used and accepted erosion model. It can be used to predict long-term average annual sediment yields for watersheds by applying a delivery ratio. However, the USLE was not designed for application to individual storms and is, therefore, not appropriate for individual storm water quality modeling. The USLE was modified [Williams, 1975c] by replacing the rainfall energy factor with a runoff factor. The modified universal soil loss equation (MUSLE) increased sediment-yield-prediction accuracy, eliminated the need for delivery ratios, and is applicable to individual storms. In tests with data from Riesel, Texas; Chickasha, Oklahoma; Oxford, Mississippi; Treynor, Iowa; Hastings, Nebraska; and Boise, Idaho, MUSLE generally explained 80% or more of the variation in individual storm sediment yield for each watershed. These tests included 60 watersheds with areas ranging from 0.01 to 234 km2 and slopes ranging from less than 1 to about 30%. The MUSLE was combined with the modified SCS water-yield model and HYMO to form a daily runoff-sediment prediction model [Williams and Berndt, 1976]. Satisfactory results were obtained when the runoff-sediment model was tested with data from 26 watersheds in Texas.

The MUSLE is useful in predicting sediment yield from small watersheds (area < 40 km2), but sediment routing is needed to maintain prediction accuracy on large watersheds with nonuniformly distributed sediment sources. A sediment routing model was developed for large agricultural watersheds [Williams, 1975b] and has had limited testing. The sediment routing model was refined here and combined with nutrient-loading functions to develop a sediment-phosphorus-nitrogen routing model.

Nitrogen and phosphorus loading functions [McElroy, et al., 1976] were developed for use on small agricultural watersheds. The loading functions were designed for predicting long-term average annual phosphorus and nitrogen yields based on predicted sediment yield, nutrient concentration in the soil, and enrichment ratios. However, there is no provision for predicting nitrate yield, since it is not attached to the sediment. There are no functions provided for determining nutrient concentrations in the soil as affected by fertilizer application. Also, relations were not developed for predicting enrichment ratios. Here the loading functions were adapted to individual storm prediction of phosphorus and nitrogen yields from small watersheds. A nitrate component was added and the enrichment ratios were related to particle-size distributions of the soil and the sediment.

Since water quality models are not well developed for large agricultural watersheds, little has been done to develop models to determine optimal watershed management strategies subject to water quality constraints. Onishi and Swanson [1974] used linear programming to determine crop systems and practices that are economically optimal on a 4.86-km2 watershed subject to sediment and nitrogen constraints. Wade, et al. [1974] described a model that uses linear programming to minimize national agricultural production costs subject to meeting agricultural production demands and sediment yield constraints. Miller and Gill [1976] used a linear programming model to maximize net revenue to farm firms constrained by acreage limits and soil loss limits. Heady [1976] developed a national model to minimize the cost of producing and transporting farm commodities subject to soil loss and other constraints.

None of these models are directly applicable to large agricultural watershed management, because only soil loss or nutrient losses are considered constraints. By including routing models, yields of sediment, phosphorus, and nitrogen can be determined and used as constraints. Considering yields to rivers or reservoirs provides more flexibility in management and higher potential agricultural production for the large watershed. Soil loss may not contribute to pollution because it may never reach a point to cause damage (permanent stream or reservoir). Yields of sediment, nitrogen, and phosphorus depend upon location of the source within a watershed, hydraulic efficiency of the channels, and the particle-size distribution as well as soil loss. If only soil loss is considered as a constraint, agricultural production cannot be truly maximized.

The model presented here uses linear programming to maximize agricultural utility subject to constraints of sediment, phosphorus, and nitrogen yields at the watershed outlet. Decision analysis, as described by Raiffa [1970], is used to determine strategies that are acceptable to the decision makers (landowners and land operators) and to calculate the utility of the strategies. A strategy specifies land use, fertilization rate, and conservation practice. Utility is described with a multiattribute utility function based on gross income, production cost, dependability, and disease, insect, and weed control. Utility theory expresses the decision makers' preferences on a scale from zero to one. This provides for easier and clearer decisions because attributes with various units can be compared and combined directly.

To apply decision analysis, each subwatershed is subdivided according to land capability classes. This simplifies the selection of strategies for the decision maker because different land classes have different production and pollution potentials. The number of possible strategies for operating each land capability class within a subwatershed approaches infinity, but the number can be reduced greatly by considering only strategies that are acceptable to the decision makers.

Generally, crop production records are not adequate to evaluate the attributes for all strategies. However, the analyst or modeler can evaluate the attributes through the use of subjective probability distributions. Raiffa [1970] suggested special techniques for developing subjective probability distributions by interviewing the decision makers. Each year as the crops are harvested, the probability distributions are revised using Bayes' Theorem [1763] to include the observed data.

Since there is usually more than one decision maker per subwatershed, most decisions concerning utility functions and probability distributions are group decisions. Raiffa [1970] suggested using Pareto-optimality in making group decisions. A joint action is Pareto-optimal if no alternative action exists that is at least as acceptable to all and definitely preferred by some. Decision analysis has been used very little in water-resources planning. McCuen [1973] used decision analysis to determine benefits from recreation facilities; Dean and Shih [1973] showed the advantages of subjective decision making for urban water resources development; and Russell [1974] applied decision theory to reservoir operation.

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