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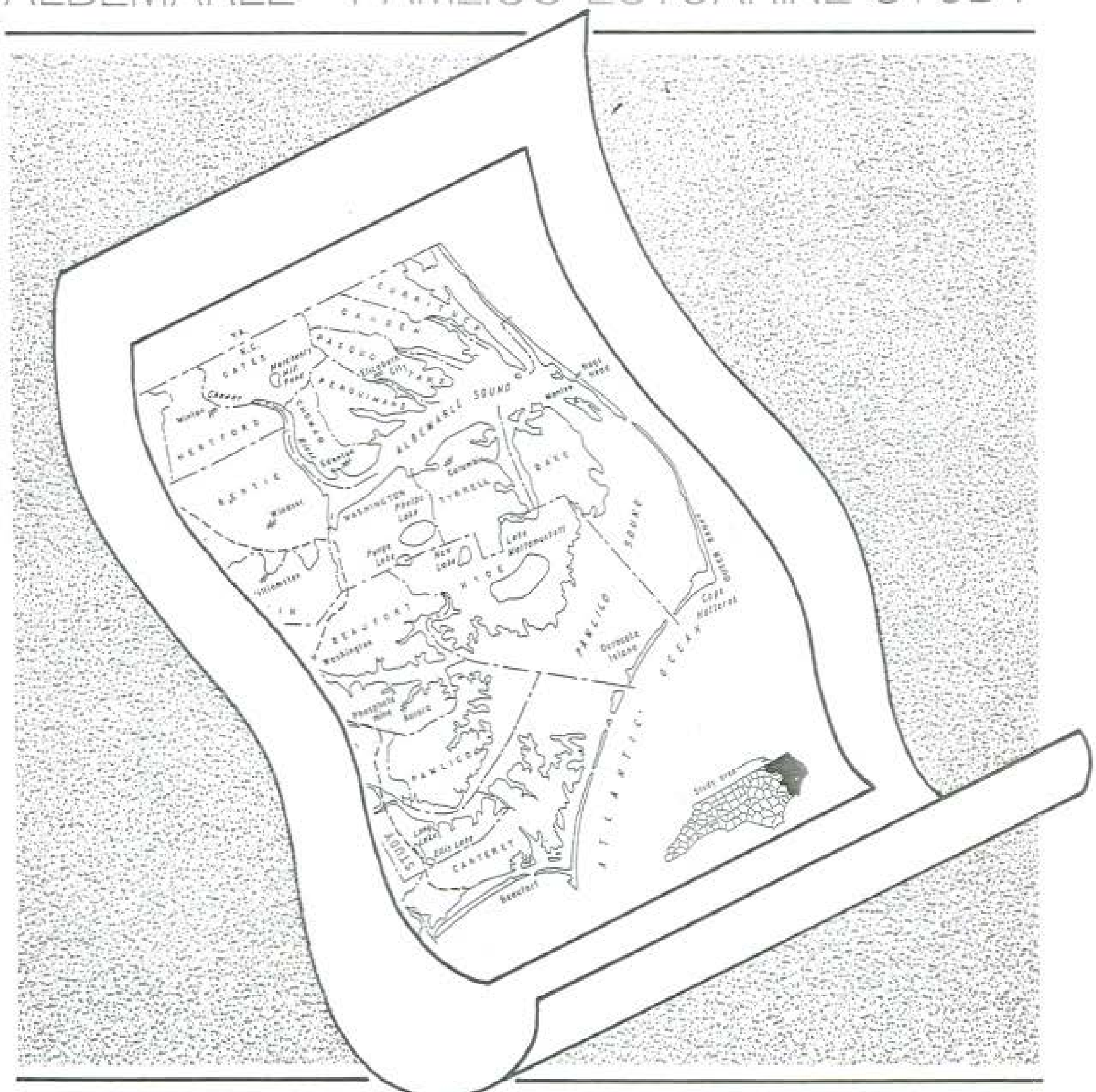
EFFECTS OF WATER MANAGEMENT AND LAND USE PRACTICES ON THE HYDROLOGY AND WATER QUALITY IN THE ALBEMARLE-PAMLICO REGION

ALBEMARLE - PAMLICO ESTUARINE STUDY



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ALBEMARLE-PAMLICO

EFFECTS OF WATER MANAGEMENT AND LAND USE PRACTICES ON THE HYDROLOGY AND WATER QUALITY IN THE ALBEMARLE - PAMLICO REGION

By

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ABSTRACT

This project was conducted to evaluate the effects of land use and water management practices on the hydrology and water quality for a large, poorly drained agricultural watershed in the Albemarle - Pamlico Estuarine Study area. A 5329 ha watershed representative of the region was selected for this modelling study. The hydrology of the agricultural fields was simulated using a version of DRAINMOD modified to account for lateral seepage losses from canals influenced by control structures. Average annual effluxes of nutrients (NO_3-N, TKN, and TP) from the fields were calculated using the drainage volumes predicted by DRAINMOD and nutrient concentration estimates determined from previous research. The total outflow of water and nutrients were predicted for the existing watershed and for a variety of other scenarios using alternate water management and land use practices. The medium scale watershed model, FLDNSTRM was used to determine the peak outflow rates from a 2126 ha section of the watershed under various water management practices. DRAINMOD simulations for the watershed predicted that the average annual total drainage under existing conditions would be 14.5 million m^3 of water (27 cm over the entire area). The simulations predicted that average annual effluxes of nutrients would be: 24 t/yr for NO_3-N, 23 t/yr for TKN, and 2.2 t/yr for TP. Control drainage practices on all of the agricultural land would reduce drainage from the watershed by 28 % and NO_3-N efflux from the watershed by 48 to 58 % when compared to the agricultural land with no control drainage practices. Control drainage practices would reduce TKN efflux from the agricultural lands by 23 to 29 %. Improved subsurface drainage would increase NO_3-N efflux by 138 to 249 % when compared to the existing unimproved subsurface drainage conditions. Improved subsurface drainage would decrease TKN efflux by 7 to 15 % and when used in combination with unimproved surface drainage would decrease TP efflux by 27 to 31 %. The volume of drainage water from the watershed was greater from the land developed for agriculture than from natural forest land, except when a high level of control was practiced on the agricultural land. The efflux of nutrients was greater from the agricultural land than from forest land particularly for NO_3-N on all soil types and for TP on deep organic soils. The FLDNSTRM simulations showed that peak flow rates at the outlet of a 2126 ha section of the watershed were reduced by 27 to 49 % when compared to the cumulative peak inflow rates from the individual fields. Improved subsurface drainage reduced peak outflow rates by 7 to 12 % compared to unimproved subsurface drainage. Control drainage increased peak outflow rates by less than 8 %. The total water and nutrient outflow predicted by the simulations should be considered conservative (ie. higher than measured) since total water outflow predicted by the simulations were generally lower than those observed in field experiments and since the simulations do not consider nutrient removal that occurs in the ditches and canals. Land use and water management practices affect the hydrology and water quality for large, poorly drained agricultural watersheds. These practices can be used to reduce the cumulative impacts of agricultural development in the A/P Study area.

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SUMMARY AND CONCLUSIONS

A 5329 ha watershed located in Camden and Currituck counties was selected as the site for this modelling study. The watershed area is made up of agricultural land (63 %) and forest land (37 %). Less than 1 % of the land is used for residential or commercial purposes. The watershed is drained by a network of canals to tributaries of the Albemarle Sound. The agricultural fields are drained by V - ditches spaced 80 m apart. Surface drainage is good with the surface sloped toward the ditches and only a small amount of depressional storage. Numerous water control structures are located on the watershed affecting the canal water levels on 57 % of the agricultural area. Soils on the watershed ranged from mineral to deep organics and were representative of those found in the A/P study area.

The hydrology of the agricultural fields was simulated using a version of DRAINMOD modified to account for lateral seepage losses from canals influenced by control structures. The DRAINMOD simulations predicted average annual surface and subsurface drainage volumes from fields for a variety of field drainage designs, canal control practices, soil types and land uses. Average annual effluxes of nutrients (NO_3-N, TKN, and TP) from the fields were calculated using the drainage volumes predicted by DRAINMOD and nutrient concentration estimates determined from previous research. Total outflows of water and nutrients from the watershed were determined by summing the predicted field scale values for each combination of conditions weighted by the area influenced by the combination. The total outflow of water and nutrients were predicted for the existing watershed and for a variety of other scenarios using alternate water management and land use practices. Transformations and losses of nutrients as the drainage water moved through the canal network to the outlet were not considered. That is, values predicted at the field edge were accumulated conservatively and projected to the outlet. This results in an overestimation of the pollutant load to the receiving waters, but should not significantly influence the relative effects of alternative water management practices and land uses.

The medium scale watershed model, FLDNSTRM was used to determine the peak outflow rates from a 2126 ha section of the watershed. FLDNSTRM predicted an outflow hydrograph from the watershed by simulating the hydrology of the fields and routing the drainage water through the canal network. Simulations were conducted to determine the effects of controlled drainage and improved subsurface drainage on peak outflow rates.

The hydrology of agricultural fields was significantly affected by water management methods. Changes in hydrology resulting from water management also affected the quality of the water leaving the agricultural field. Using control structures to hold drainage water in the canals decreased the total water outflow, as well as nitrate-nitrogen (NO_3-N) and total Kjeldahl nitrogen (TKN) efflux. Improving subsurface drainage increased total water outflow and NO_3-N efflux while decreasing total phosphorus (TP) and TKN efflux. Different crop rotations only slightly affected total water outflow and nutrient flux; however, water and nutrient outflows for agricultural crops were higher than predicted for forested conditions. The soil type on the fields affected water and nutrient outflows as well as effectiveness of the water management practices on the fields.

DRAINMOD simulations for the watershed predicted that the average annual total drainage under existing conditions would be 14.5 million m^3 of water (27 cm over the entire area). The simulations predicted that average annual effluxes of nutrients would be: 24 t/yr for NO_3-N, 23 t/yr for TKN, and 2.2 t/yr for TP.

Results of DRAINMOD simulations showed that alternative water management scenarios would affect water and nutrient outflows from the watershed. Control drainage practices would significantly reduce total outflow of water, NO_3-N, and TKN. Control drainage practices on all of the agricultural land would reduce NO_3-N efflux from the watershed by 48 to 58 % when compared to the agricultural land with no control drainage practices. Control drainage practices would reduce TKN efflux from the agricultural lands by 23 to 29 %. Improved subsurface drainage would increase NO_3-N efflux by 138 to 249 % when compared to the existing unimproved subsurface drainage conditions. Improved subsurface drainage would decrease TKN efflux by 7 to 15 % and when used in combination with unimproved surface drainage would decrease TP efflux by 27 to 31 %.

Land use greatly affected the outflow of water and nutrients from the watershed. The total volume of drainage water from the watershed was greater from the land developed for agriculture than from natural forest land, except when a high level of control was practiced on the agricultural land. The efflux of nutrients was greater from the agricultural land than from forest land particularly for NO_3-N. The distribution of land use on soil types significantly affected the efflux of TP from the watershed. Nearly all of the forest land on the existing watershed was located on organic and deep organic soils. Converting this land to agricultural land would increase TP efflux 7 to 18 times greater than under existing conditions.

The FLDNSTRM simulations showed that it is important to consider watershed scale channel systems when determining effects of land use and water management practices on outflow hydrographs. Peak flow rates at the outlet of a 2126 ha section of the watershed were reduced by 27 to 49 % when compared to the cumulative peak inflow rates from the individual fields. Improved subsurface drainage reduced peak outflow rates by 7 to 12 % compared to unimproved subsurface drainage. Control drainage increased peak outflow rates by less than 8 %.

The total water and nutrient outflow predicted by the simulations should be considered conservative (ie. higher than would actually occur), particularly for control drainage.

One reason is that the total water outflow predicted by the simulations were generally lower than those observed in field experiments for control drainage. More study is needed to more accurately quantify the water loss due to increased evapotranspiration and to seepage from ditches and canals influenced by control structures. Another reason that the predictions are conservative is that the simulations do not consider nutrient removal that occurs in the ditches and canals. Extensive monitoring in previous studies by the authors indicates that nutrient concentrations in major canals are usually lower than those measured in field ditches, which were used as a basis of the predictions in this study. Research is needed to quantify the nutrient removal that takes place in ditches and canals due to biological transformations and settling of soil particles.

RECOMMENDATIONS

Land use and water management practices affect the hydrology and water quality of large agricultural watersheds. A combination of practices can be selected to reduce the cumulative impacts of agriculture on the amount, rate and quality of water entering the streams and estuaries in the A/P Study area.

Control drainage practices are very effective at reducing outflow of drainage water, nitrate nitrogen (NO_3-N), and total Kjeldahl nitrogen. The effectiveness of control drainage increases as weir elevations and the time that the weirs are in place increase. We recommend that control drainage be used to reduce nonpoint pollutant loading to nutrient sensitive receiving waters. The expertise and assistance of the N. C. Extension Service and USDA-SCS personnel should be used in both design and management of controlled drainage systems. This will ensure proper installation and management strategies to most effectively control nutrient outflow while maintaining crop yields.

Improved subsurface drainage is effective at reducing peak outflow rates of drainage water and at reducing outflow of total phosphorus (TP) from most soils. Improved subsurface drainage will facilitate higher levels of control drainage management for some soil conditions. Improved subsurface drainage should be considered as a water management option particularly when receiving waters are sensitive to high freshwater flowrates; however, the fact that improved drainage increases outflow of NO_3-N should be weighed in these decisions.

The effect of land use changes on nutrient outflow is very dependent on soil type. The TP efflux from cropland on deep organic soils is high compared to forest land and to cropland on other soil types. Soil type should be considered when planning land use changes.

The many factors affecting hydrology and nutrient loading from coastal watersheds are complex. The evaluation of these complex systems requires the use of models and methods capable of quantifying the interactions of the systems' various components. The models and associated methods applied in this study can be used to evaluate the effects of land use and water management practices on the hydrology and water quality of large agricultural watersheds in the A/P region. Continued research in the following areas will improve the predictive capabilities of these models and methods.

1. Determine the rates of nutrient removal in ditches and canals, and develop methods for quantifying this nutrient removal in existing simulation models.

2. Develop methods for more accurately determining evapotranspiration in agricultural hydrologic models.

3. Develop methods for more accurately quantifying seepage losses from ditches and canals affected by control structures for a variety of site configurations.

INTRODUCTION

Over two million acres of land have been drained and developed for agriculture and silviculture along the North Carolina coast. As much as one-half of this area drains directly or through tributaries to the Albemarle - Pamlico Estuarine system. Aquatic biologists and fishermen generally believe that increased nutrient loads and peak flow rates of freshwater from conventional agricultural development has been detrimental to the productivity of estuarine nursery areas (Jones and Sholar, 1981, Kirby-Smith and Barber, 1979; Governor's Coastal Water Management Task Force, 1982) There is also considerable concern for water quality in the rivers which feed the estuarine system.

The conventional method for draining land for agriculture in the low lying coastal areas has been land forming the soil surface to reduce surface storage and to slope the land surface toward 1.2 to 1.5 m deep field ditches spaced 80 to 100 m apart. This method provides good surface drainage and increases surface runoff; however some subsurface drainage to the field ditches occurs. The field ditches drain to a network of canals and eventually to a receiving stream which eventually empties to the sounds.

Several alternate field designs and management options for controlling the drainage networks have been developed. One field design option is to improve subsurface drainage by installing drain tubes at spacings closer than field ditch spacings. This is often necessary for soils with low lateral hydraulic conductivities to reduce stresses on crops due to excessive wet conditions. Surface runoff can be reduced by reducing land forming and smoothing thus increasing surface storage.

In recent years water table management by the use of control drainage has gained popularity. With this method, flashboard riser structures are installed in canals that facilitate easy placement and removal of weirs to control the elevation of the water in the canal. Water in the canal is maintained at high levels during the growing season to reduce the threat of drought stress. The water in the canals is then released for planting and harvesting. Numerous field studies (Gilliam et al., 1978; Doty et al. 1986; and Evans et al. 1987) have shown that control drainage significantly reduces pollutant outflow from agricultural fields when properly designed and managed. This research has provided the technical background for acceptance of controlled drainage as a 'best management practice' for artificially drained soils. Therefore controlled drainage qualifies for cost share assistance under the North Carolina Agricultural Cost Share Program.

The hydrology and runoff water quality of agricultural fields in the region are significantly affected by land use and water management practices. Research over the past 15 years has documented the effects of drainage practices (Gambrell et al. 1974, 1975; Gilliam et al. 1978; and Evans et al. 1989) and land use changes (Daniel, 1981; and Skaggs et al. 1978) on water quality and hydrology of the poorly drained soils of the region. Most of this research has been at the field scale level and has not attempted to quantify the cumulative effects of multiple soil types, water management practices and land uses that would occur over a large watershed.

The purpose of this project was to use existing models and results of previous studies to evaluate the effects of land use and water management practices on the hydrology and water quality for a large, poorly drained watershed in the Albemarle - Pamlico Estuarine Study area. The specific objectives of this project were to:

1. Select a well-defined watershed of 4000 to 8000 hectare in the Albemarle-Pamlico Region. Document and map land uses, soils, and drainage system facilities on the watershed.

2. Use existing water management models to evaluate effects of alternative land uses and water management practices on the total outflow and peak drainage rates from the watershed.

3. Estimate the effects of alternative land uses and water management practices on water quality and pollutant loading from the watershed using existing models and results of previous research.

WATERSHED DESCRIPTION

A. PROCEDURES

A. 1. Watershed Selection

A large agricultural watershed was selected to provide the input for the modeling study. The watershed was selected based on four criteria: size, boundary definition, land use, and soil types. Our objective was to select a watershed between 4000 and 8000 ha in area with a well defined boundary. The soil types on the selected watershed were to be typical of watersheds in the A/P study area with most common soil types being well represented. Land uses on the watershed were also to be typical of agricultural watersheds in the A/P region and uncomplicated so as to be within the constraints of the existing hydrologic models.

Three watersheds were evaluated for possible study. The first watershed evaluated was located in Beaufort County and drained to the Pamlico sound via Campbell Creek. This site was of particular interest since it was being used in a field study by USGS for A/P. The watershed was evaluated with the assistance of the principle investigator of the USGS project. The second site was located in Beaufort County and drained to the Pamlico sound via Broad Creek. This watershed was evaluated with the assistance of the SCS in Washington, NC. The third site was located in Camden and Currituck Counties and drained to the Albemarle sound via the Pasquotank River and the North River. The SCS in Elizabeth City, NC assisted in the evaluation of this watershed.

The two watersheds in Beaufort County were lacking in at least one of the four criteria listed above. The USGS field sites were located in small watersheds (less than 100 ha). Unfortunately, the boundaries and outlets of the large watershed that include the USGS field sites were complicated and not well defined. The other Beaufort County watershed included significant areas with land uses that were not agricultural or forestry. These land uses could not be adequately treated with the hydrologic agricultural models and water quality methods available for use in this project. The watershed in Camden County was selected since it met all four criteria for selection.

A. 2. General Data Collection

The selected watershed is 5329 ha in area and consists of agricultural and forest land drained by a network of canals to two distinct outlets. One outlet is to the North River and the other is to the Pasquotank river. Both rivers flow into the Albemarle Sound.

Specific information on the watershed was collected during three field trips to the site. Air photos were obtained and maps were constructed detailing the canal network. The canal dimensions, control structures, and flow paths were determined and placed on the canal network maps. Land uses and cropping practices were mapped on the fields delineated by the canal network. Planting and harvesting dates, and crop rotations in the fields were determined from interviews with growers in the watershed area. The distribution of soils on the watershed was determined from soil maps of the area.

The watershed was divided into fields according to land use and the canal network. The area of each field was determined by digitizer as was the area of each soil in each field. Each field was classified as to its cropping practice, field drainage design, soil type, and influence by canal control structures. The total area in the watershed affected by a particular cropping practice, field drainage system, soil type, or canal control was easily determined by summing the areas of fields in that particular category.

A. 3. Soil Data Collection

A field trip was conducted to determine the soil properties necessary for model input. For this study, the twelve soil series found on the watershed were divided into five groups: deep organic soils, organic soils, mineral organic soils, mineral sandy loam soils, and mineral silt loam soils. Soil property data were collected in the field for four of the groups. Soil properties for the fifth group (deep organic soils) were taken from previous research data. The saturated hydraulic conductivity of the four soil groups was measured in the field using the auger hole method (Van Beers, 1970). Undisturbed soil core samples were collected for determining soil water characteristic curves and for determining organic matter content and particle size distribution. Soil water characteristic data were measured in the lab using the pressure plate method (Klute, 1965). Particle size distribution was determined using the hydrometer method (Day 1965). Organic matter content was determined by hydrogen peroxide decomposition as described by Kunze (1965).

The soil input data required for the water management models were values for the relationships between volume drained and water table depth, Green-Ampt infiltration parameters and water table depth, and upward flux and water table depth values. The values for the volume drained relationship were calculated from the soil water characteristic data assuming drained to equilibrium conditions. Soil water characteristic and saturated hydraulic conductivity data were used to calculate the unsaturated hydraulic conductivity curve (K(h)) using the procedure of Millington and Quirk (1961). The Green-Ampt parameters were determined using the K(h) relationship in the Mein and Larson (1973) definition for effective suction at the wetting front. Upward flux values were calculated using the K(h) relationship in a numerical solution of the Darcy - Buckingham equation (see Skaggs, 1980).

B. RESULTS

Nearly all of the land on the selected watershed is in agricultural production or in forest. Less than 1 % of the land is used for residential or commercial purposes. Forest land makes up 37 % of the watershed with the remaining 63 % in agricultural crops (Fig. 1). Two crop rotations are used on the agricultural lands: a two year rotation of corn - wheat - soybean, and a three year rotation of corn - wheat - soybean - potato. Normal planting and harvesting dates of these rotations are shown in Fig. 2.

The agricultural fields are predominately drained by V - ditches spaced 80 m apart. The ditches range in depth from 1.0 to 1.5 m. The field surfaces are relatively smooth and are sloped toward the ditches to facilitate surface runoff. The V - ditches drain to a network of collector canals and main canals. The canal system, watershed divide, and flow directions in the system are shown in Fig. 3. The outlet to the North River receives runoff from 2446 ha of land and the outlet to the Pasquotank River receives runoff from 2883 ha of land.

The locations of existing water control structures on the canals are also shown in Fig 3. The water control structures utilized on the site were flashboard riser structures which facilitate easy adjustment of weir elevation. The weirs were maintained at elevations 45 cm below the field surface when crops were growing in the field. Weirs were removed for planting and harvesting. Approximately 57 % of the agricultural land and 36 % of the entire watershed was influenced by water control structures. None of the forest land was influenced by water control structures.

The watershed was made up of twelve different soil series. Taxonomic description and percent watershed coverage of each soil series is shown in Table 1. The soils on the watershed represent the range of soil series usually found in the A/P region. The soils in the table are divided into the five groups mentioned in the methods section. Each group is well represented on the site.

The soil properties of the four soil groups analyzed in the field are shown in Table 2. The soil series of the mineral sandy loam, mineral silt loam, mineral organic, and organic soil groups analyzed in the field were Portsmouth, Hyde, Roper, and Ponzer respectively. The particle size analysis and organic matter content confirm that the soil samples are in their respective series.

Soil moisture contents were measured over a range of pressure head values likely to occur in the field. The shapes of the resulting soil water characteristic curves for the soils groups were similar to the soil water characteristic curves reported for respective soil groups in North Carolina (Skaggs and Tabrizi, 1986; Evans et al, 1989; and Konyha, 1989). The saturated moisture content values of the surface layers for the mineral soils are higher than the reported values (0.37 - 0.48) reflecting the high organic matter

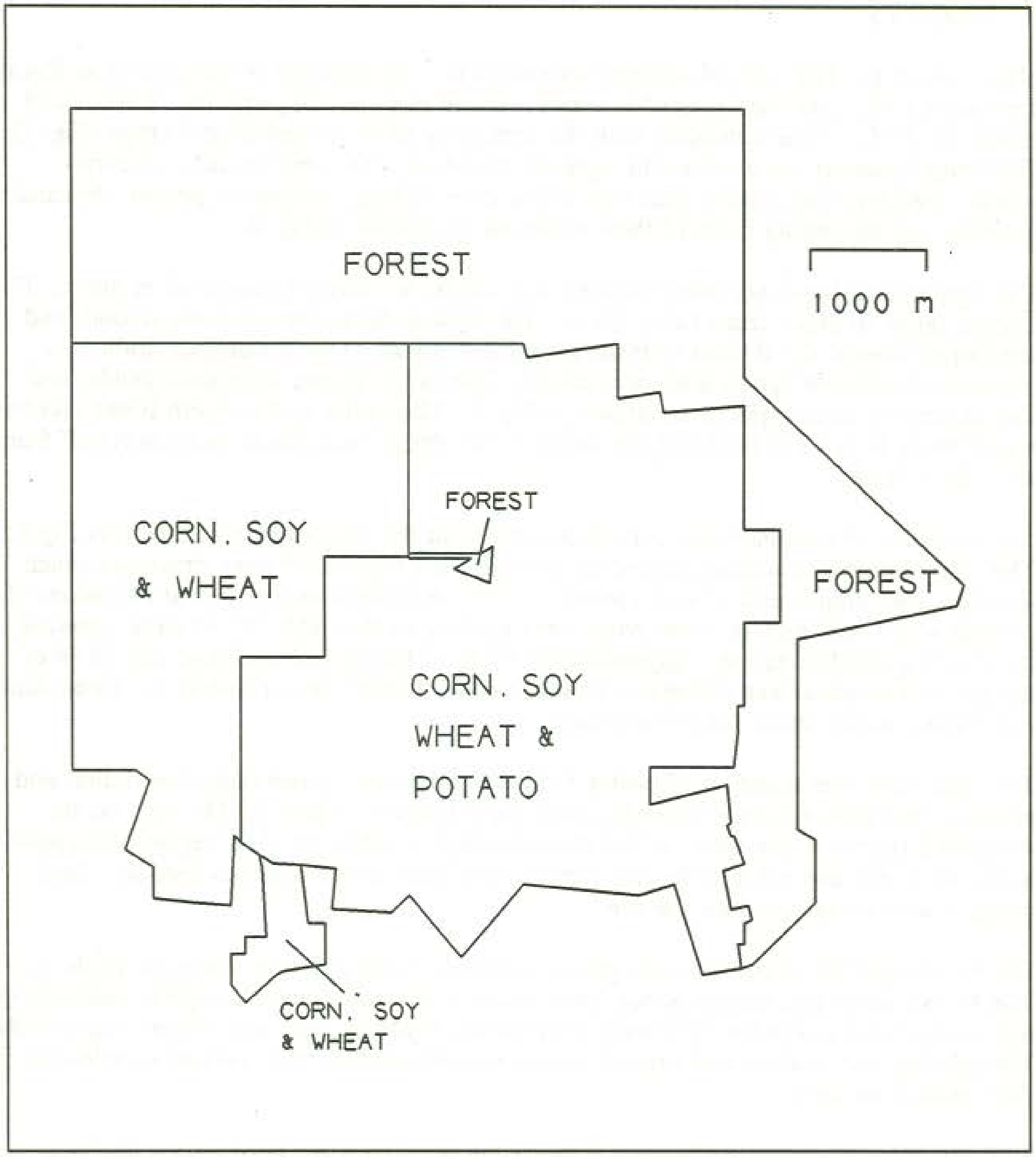

Figure 1. Distribution of crop rotations and forest on the watershed.

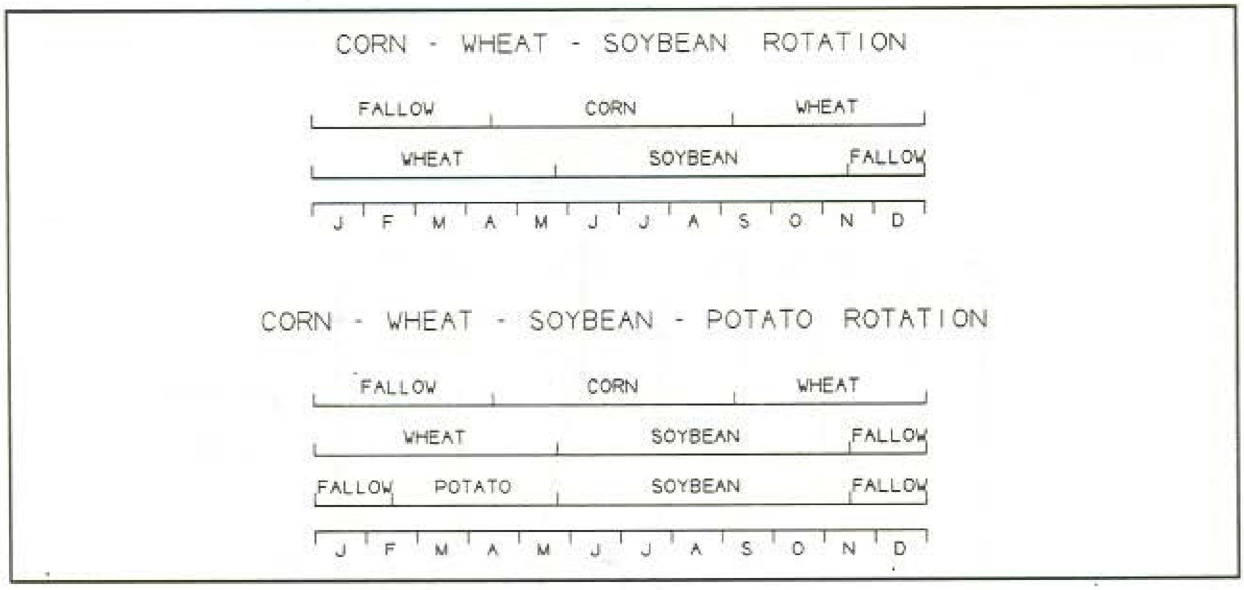

Figure 2. The two crop rotations used on the agricultural lands of the watershed.

content of these soils. Saturated moisture contents for the mineral organic and organic soils were within the ranges (0.59 - 0.76 for mineral organic soils, and 0.55 - 0.75 for organaic soils) reported for North Carolina.

Soil hydraulic conductivity values vary within the same soil group depending on soil texture, structure, depths of horizons, and macropores. The variations within the fields sampled on the study site are reflected in the coefficients of variation which ranged from 64 % for the mineral sandy loam and mineral organic soils to 110 % for the mineral silt loam soil. The mean hydraulic conductivity values for each soil group were within the respective ranges (1.5 - 5.1 cm/hr for the mineral sandy loam, 0.5 - 5.1 cm/hr for the mineral silt loam, and 0.5 to 15.2 cm/hr for the mineral organic and the organic soils) reported by USDA-SCS (1974).

Volume drained, upflux, and Green-Ampt parameter values calculated for various water table depths in the four soil groups are shown in Table 3. Also shown in the table are values for the deep organic soil group taken from Purisinsit (1982). The values in this table served as the input for the water management models.

More details about the distribution of soil groups, crops, field design, and canal control structures are given in Appendix A.

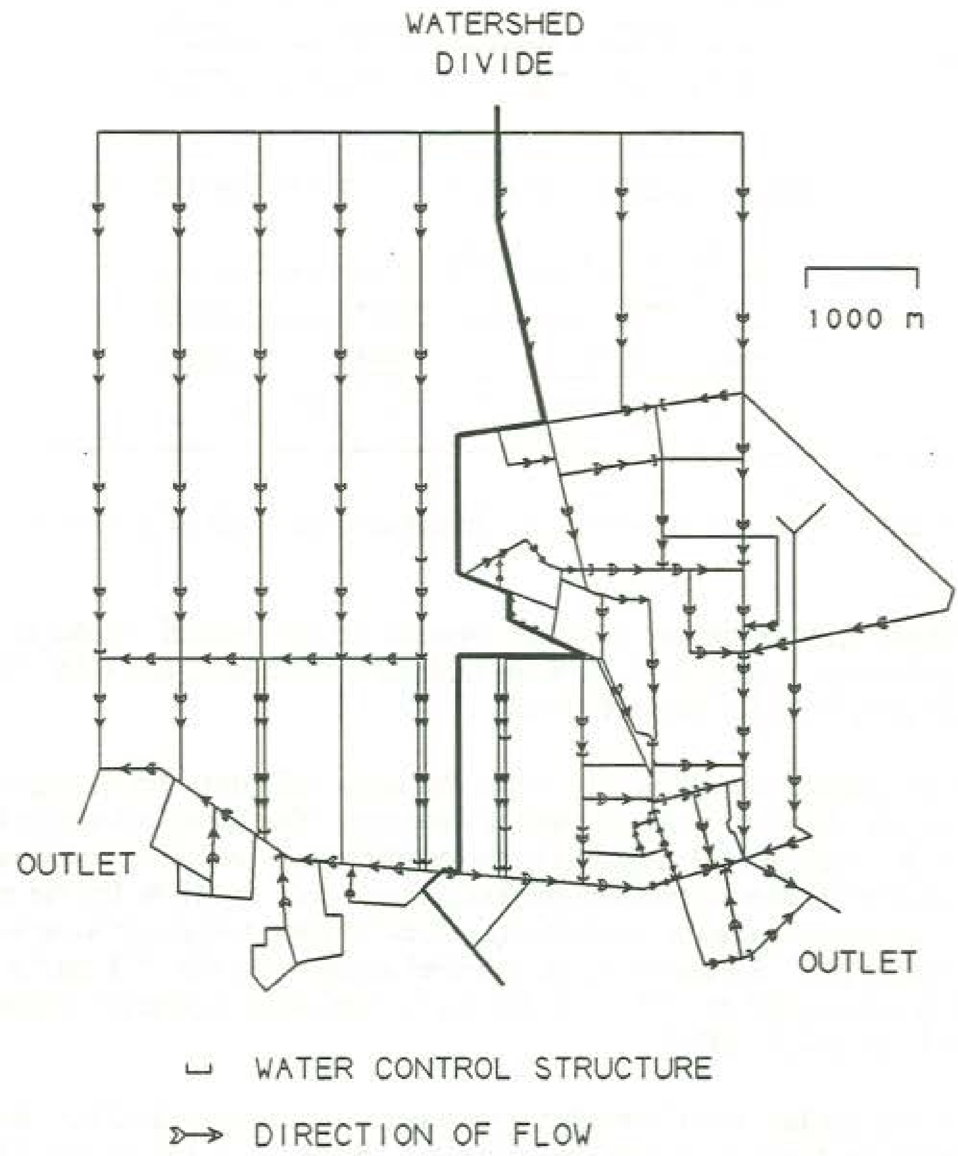

Figure 3. The network of canals on the watershed showing the flow directions and the location of canal control structures.

Table 1. Soil series existing on watershed

Soil Series	Soil Family	Watershed Coverage
	--- Deep Organic Soils ----	
Dare Muck	Dysic, Thermic Typic Medaprists	12 %
Pungo Muck	Dysic, Thermic Typic Medaprists	6 %
	---- Organic Soils ----	
Ponzer	Loamy, Mixed, Dysic, Thermic Terric Medaprists	8 %
Belhaven	Loamy, Mixed, Dysic, Thermic Terric Medaprists	10 %
	--- Mineral-Organic Soils ----	
Wasda	Fine - Loamy, Mixed, Nonacid, Thermic Histic Humaquepts	10 %
Roper	Fine - Loamy, Mixed, Nonacid, Thermic Histic Humaquepts	22 %
	---- Mineral Silt Loam Soils ----	
Hyde Silt Loam	Fine - Silty, Mixed, Thermic Typic Umbraquults	12 %
Roanoke Silt Loam	Clayey, Mixed, Thermic Typic Ochraquults	4 %
Cape Fear Silt Loam	Clayey, Mixed, Thermic Typic Umbraquults	2 %
Perquimans Silt Loam	Fine - Silty, Mixed, Thermic Typic Umbraquults	1 %
	---- Mineral Sandy Loam Soils ----	
Portsmouth Sandy Loam	Fine - Loamy over Sand, Mixed, Thermic Typic Umbraquults	10 %
Tomotley Sandy Loam	Fine - Loamy, Mixed, Thermic Typic Ochraquults	2 %

Table 2. Properties of the soil samples collected in the field

	Mineral Sandy Loam		Mineral Silt Loam		Mineral Organic		Organic	
Depth	3 cm	30 cm	3 cm	30 cm	3 cm	50 cm	3 cm	70 cm
Pressure Head cm	---------- Moisture Content (cm/cm) * ----------							
0	.564	.370	.540	.496	.614	.477	.620	.480
2	.564	.361	.538	.494	.612	.477	.618	.480
10	.555	.352	.533	.489	.590	.468	.608	.480
30	.537	.340	.518	.475	.549	.465	.586	.480
60	.489	.329	.495	.462	.525	.459	.526	.467
100	.456	.317	.478	.451	.504	.451	.497	.456
200	.419	.290	.459	.436	.483	.434	.476	.438
400	.377	.271	.426	.418	.433	.399	.447	.400
600	.353	.257	.401	.406	.409	.379	.428	.377
735	.338	.251	.389	.400	.391	.370	.413	.364
900	.333	.248	.374	.397	.383	.361	.405	.354
% OM**	18	1	13	2	30	4	43	5
% Sand**	66	47	28	8	64	38	81	41
% Silt**	33	36	66	60	35	46	18	41
% Clay**	1	17	6	32	1	16	1	18
Hydraulic*** Conductivity (cm/hr)	4.2 ± 2.7		1.9 ± 2.1		3.9 ± 2.5		1.2 ± 1.0	

* Average of two replicates
** Single sample
*** Mean and standard deviation, N = 7 for mineral sandy loam
N = 8 for mineral silt loam
N = 9 for mineral organic
N = 5 for organic

Table 3. Volume drained, upflux, and Green-Ampt input values for water management models

Water Table Depth cm	Mineral[1] Sandy Loam Vol Drn cm	Mineral[1] Sandy Loam Upflux cm/hr	Mineral[1] Silt Loam Vol Drn cm	Mineral[1] Silt Loam Upflux cm/hr	Mineral[1] Organic Vol Drn cm	Mineral[1] Organic Upflux cm/hr	Organic[1] Vol Drn cm	Organic[1] Upflux cm/hr	Deep[2] Organic Vol Drn cm	Deep[2] Organic Upflux cm/hr
0	.00	.5000	.00	.5000	.00	.5000	.00	.5000	.00	.0079
10	.04	.3566	.04	.5000	.11	.4831	.06	.4778	.14	.0046
20	.17	.0672	.15	.4056	.45	.1800	.23	.1883	.29	.0030
30	.48	.0306	.33	.1837	1.00	.0912	.52	.0912	.58	.0023
40	.90	.0182	.59	.1087	1.69	.0550	.96	.0495	.99	.0020
50	1.47	.0126	.93	.0739	2.45	.0404	1.65	.0314	1.47	.0019
60	2.10	.0085	1.31	.0491	3.24	.0303	2.44	.0190	1.91	.0018
80	3.33	.0049	2.18	.0278	4.43	.0238	4.39	.0096	2.82	.0014
100	4.54	.0025	3.11	.0182	5.33	.0190	6.16	.0061	3.72	.0010
120	5.78	.0000	4.08	.0117	6.19	.0151	7.77	.0042	4.92	.0007
140	7.06	.0000	5.11	.0039	6.96	.0050	8.75	.0014	6.44	.0003
160	8.46	.0000	6.20	.0000	7.75	.0000	9.65	.0000	6.72	.0002
200	11.47	.0000	8.48	.0000	9.38	.0000	11.30	.0000	9.27	.0001
250	16.26	.0000	12.22	.0000	12.92	.0000	14.66	.0000	14.94	.0000
300	21.05	.0000	15.96	.0000	16.47	.0000	18.01	.0000	20.61	.0000
400	30.62	.0000	23.44	.0000	23.56	.0000	24.72	.0000	31.95	.0000
500	40.19	.0000	30.92	.0000	30.65	.0000	31.43	.0000	43.29	.0000

Water Table Depth cm	Green Ampt Parameters A	B	A	B	A	B	A	B	A	B
0	.00	2.00	.00	1.00	.00	1.70	.00	.50	.00	4.12
10	.35	2.00	.12	1.00	.25	1.70	.09	.50	.34	4.12
20	.70	2.00	.25	1.00	.48	1.70	.17	.50	.68	4.12
40	1.68	2.00	.51	1.00	.79	1.70	.39	.50	1.32	3.23
60	2.87	2.00	.75	1.00	.96	1.70	.66	.50	1.68	2.38
80	3.58	2.00	.92	1.00	1.08	1.70	.78	.50	1.67	1.92
100	4.16	2.00	1.05	1.00	1.20	1.70	.87	.50	1.40	1.60
150	13.69	2.00	4.48	1.00	3.48	1.70	2.23	.50	1.80	1.20
200	13.69	2.00	4.48	1.00	3.48	1.70	2.23	.50	1.60	1.20

1 Calculated from moisture content values in Table 2
2 Reported value from Purisinsit (1982)

FIELD SCALE SIMULATIONS

A. MODEL DESCRIPTION

The fields on the watershed were simulated using a modified version of the water management model, DRAINMOD. DRAINMOD performs water balances in the soil-water regime at the midpoint between two drains of equal elevation. The model is capable of calculating hourly values for water table depth, surface runoff, subsurface drainage, infiltration, and actual evapotranspiration over long periods of climatological data.

The reliability of DRAINMOD has been tested for a wide range of soil, crop, and climatological conditions. Results of tests in North Carolina (Skaggs, 1982), Ohio (Skaggs et al., 1981), Louisiana (Gayle et al., 1985; Fouss et al., 1987), Florida (Rogers, 1985), Michigan (Belcher and Merva, 1987) and Belgium (Susanto et al., 1987) indicate that the model can be used to reliably predict water table elevations and drain flow rates.

The water balances in DRAINMOD involve two basic equations. The first equation is a water balance in the soil profile:

$$\Delta V_a = D + ET + DS + LS - F \tag{1}$$

where ΔV_a is the change in air volume, D is the drainage from the profile, ET is the actual evapotranspiration from the profile, DS is the deep seepage from the profile, LS is lateral seepage from the profile, and F is infiltration into the profile. The second equation is a water balance at the soil surface,

$$\Delta S = P - F - RO \tag{2}$$

where ΔS is the change in water volume stored at the soil surface, P is precipitation, F is the infiltration volume, and RO is the surface runoff. Methods for evaluating equation variables are discussed in detail in Skaggs (1980).

For determining the volume of water that leaves the field and flows over the control structure, a water balance is also performed in the ditch and canal system upstream of the control structure.

$$WLOSS = D + RO - DV \tag{3}$$

where WLOSS is the water which flows over the weir, and DV is the change in water volume in the ditch.

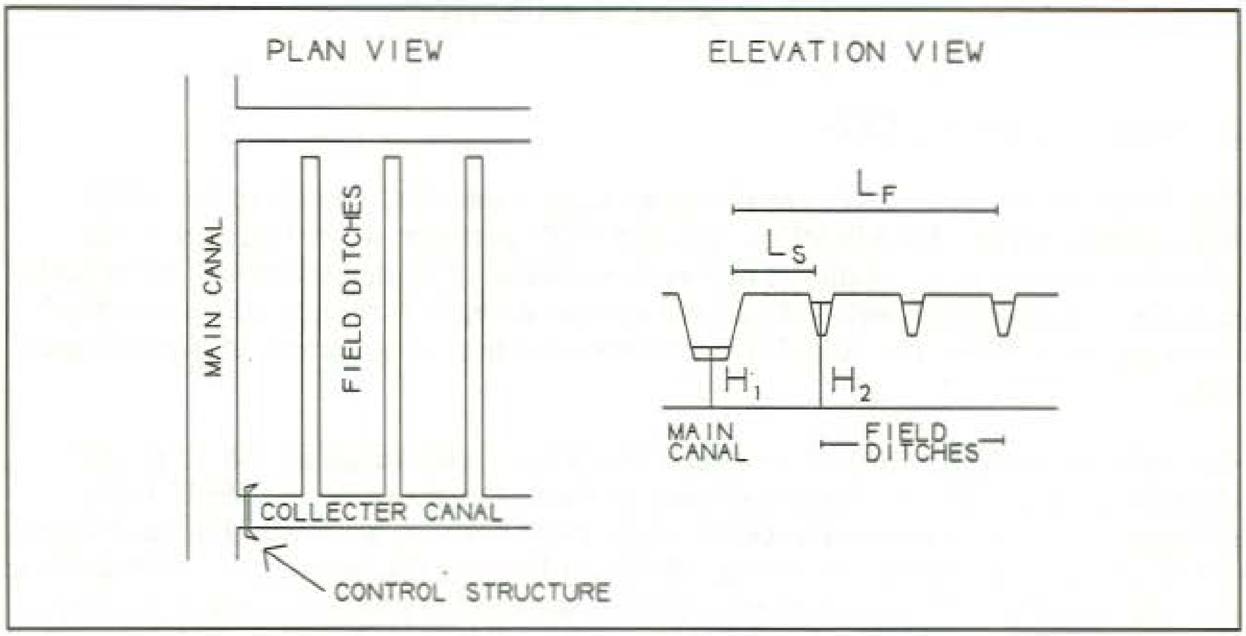

Figure 4. Schematic of canals and ditches on the fields of the watershed showing the variables used for calculating lateral seepage.

Past research has indicated that significant reductions in the total volume of water flowing from the field and ditch system occur when water levels in the ditches are maintained at high levels by control drainage. Evans et al. (1989) reported reductions in total outflow of between 17 and 56 % when comparing control drainage to no control drainage conditions. Gilliam et al. (1978) reported total outflow reductions of between 50 and 90 % due to control drainage practices. These large reductions could not be accounted for in the ditch water balance. An additional water loss occurs due to lateral seepage from the ditches and canals to field areas and canals where water is not controlled.

A method for quantifying this lateral seepage loss was incorporated into DRAINMOD for this study. The method assumes the ditch and canal situation occurring on the model watershed as shown in Fig 4. In this situation water is held in the collector canal and field ditches upstream of a control structure. The flowrate from the field ditch nearest the main canal to the main canal is calculated by the equation for steady flow between two parallel reservoirs

$$Q = \frac{K\,(H_2^2 - H_1^2)}{2\,L_S} \qquad (4)$$

Where Q is the flow rate in cm^3/cm of ditch length, and K is the soil hydraulic conductivity between the ditch and the main canal.

Since the water in the ditch nearest to the main canal is in connection with the canal and the rest of the field ditches in the affected field, the lateral seepage flux per unit surface area of the affected field is calculated as:

$$LS = \frac{Q}{L_F} \qquad (5)$$

Where L_F is the length of the affected field.

Lateral seepage in the modified model is a direct loss from the water in the ditch and canal system upstream of the control structure rather than a loss from the soil profile in the field. Therefore, LS is no longer a term in the water balance in the soil profile (Eq. 1), but is a term in the water balance in the ditch controlled by the water control structure:

$$WLOSS = D + RO - LS - DV \qquad (6)$$

The value for WLOSS represents the volume of water flowing over the weir and eventually to the receiving water. Nutrients in this water are derived from RO and D, each of which will have different nutrient concentrations. Since the concentration of nutrients in this water is a primary concern of this investigation, the modified model separates Eq. 6 into Eqs. 7 and 8.

$$WLOSS_{RO} = RO - LS_{RO} - DV_{RO} \qquad (7)$$

and

$$WLOSS_D = D - LS_D - DV_D \qquad (8)$$

where DV_{RO} and DV_D are RO and D components of DV, $WLOSS_{RO}$ and $WLOSS_D$ are RO and D components of WLOSS, and LS_{RO} and LS_D are RO and D components of LS. The modified version of DRAINMOD calculates these components according to theproportion of RO and D in the water stored in the ditch. These calculations are made assuming instantaneous mixing of the components in the ditch.

The $WLOSS_{RO}$ and $WLOSS_D$ values calculated in the modified version of DRAINMOD were used in a spreadsheet to determine nutrient loading at the outlet. The effluxes of nitrate nitrogen (NO_3-N), total Kjeldahl nitrogen (TKN), and total phosphorus (TP) were calculated as the products of the water loss volumes and estimated concentrations of the nutrients in the drain tubes and ditches.

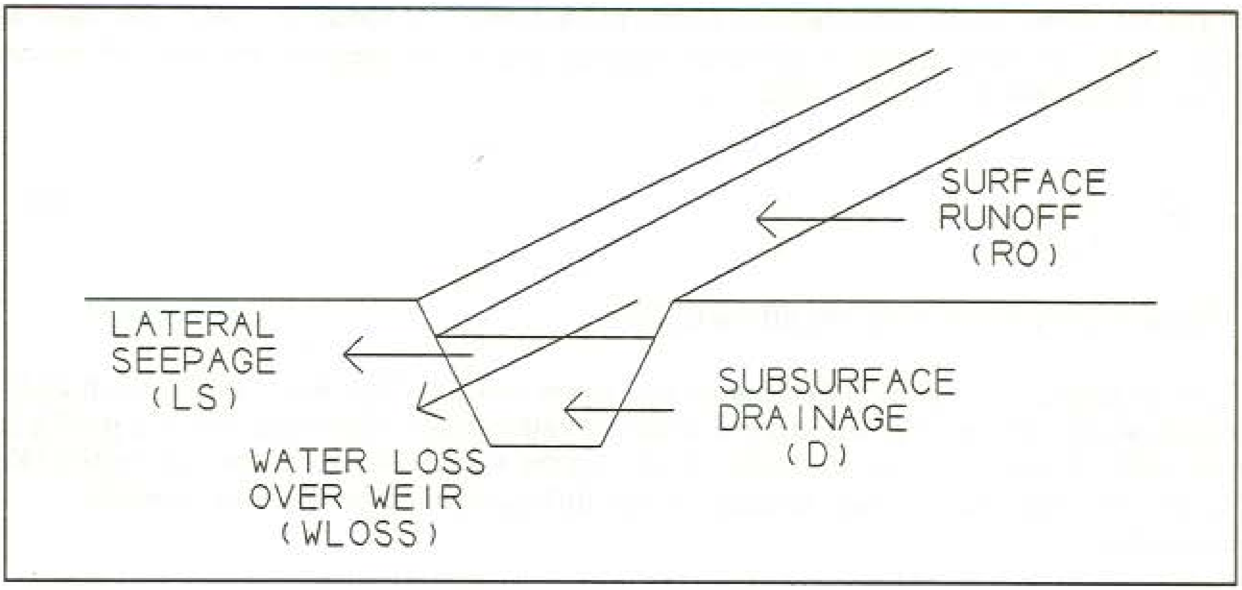

Figure 5. Schematic of variables in the water balance in the ditch (Eq 6).

$$EFF = (WLOSS_D)(C_D) + (WLOSS_{RO})(C_{RO}) \tag{9}$$

Where EFF is the efflux of the nutrient, C_D is the concentration of the nutrient in the subsurface drainage water, and C_{RO} is the concentration of the nutrient in the surface runoff water. Water lost by lateral seepage was assumed to move though anaerobic soils with sufficient mineral and organic soil components to remove nutrients by denitrification or adsorption. Losses of nutrients and sediment in the ditch and canal network due to settling or biological transformations were neglected. Significant losses of nutrients and sediments have been observed in canal networks (Gilliam and Skaggs, unpublished data); however, the rate at which these constituents are removed have not been quantified.

Nutrient concentration estimates for the different combinations of soil type, field drainage design, and canal control management are shown in Table 4. Most of the estimates of nutrient concentration values for these calculations were made and reported by Deal et al. (1986). These estimates were based on data from various field studies of nutrient transport from agricultural fields in the North Carolina Coastal Plain (Gambrell et al., 1975; Gilliam et al., 1978; and Skaggs et al., 1980). NO_3-N concentration estimates for unimproved field drainage conditions were increased over the estimates of Deal et al. (1986) due to recent data from the watershed indicating higher subsurface drainage rates and NO_3-N concentrations from the conventional ditch drainage designs (Evans, 1989). The TP concentration estimates of Deal et al. (1986) for the organic soil type were reduced based on recent data collected on Ponzer soil series (Konyha, 1989). The nutrient concentration estimates used in this analysis are based on data and trends

Table 4. Estimates of nutrient concentrations for various combinations of soil types, field drainage designs, and canal control management.

Soil Group	Field Drainage Design	NO_3-N C_{RO}	NO_3-N C_D No Ctrl	NO_3-N C_D Ctrl	TKN C_{RO}	TKN C_D	TP C_{RO}	TP C_D
		mg/L			mg/L		mg/L	
Mineral Sandy Loam	IU	2.04	11.00	7.70	1.07	1.56	0.13	0.01
	II	2.04	11.55	8.08	1.14	1.56	0.13	0.01
	UI	2.04	6.00	4.00	1.43	1.56	0.13	0.01
	UU	0.11	0.11		0.82	0.82	0.05	0.01
Mineral Silt Loam	IU	2.04	11.00	7.70	1.07	1.56	0.13	0.01
	II	2.04	11.55	8.08	1.14	1.56	0.13	0.01
	UI	2.04	6.00	4.00	1.43	1.56	0.13	0.01
	UU	0.11	0.11		0.82	0.82	0.05	0.01
Mineral Organic	IU	0.50	9.00	6.30	1.93	1.56	0.26	0.02
	II	0.50	9.72	6.80	2.06	1.56	0.26	0.02
	UI	0.50	5.00	3.40	2.57	1.56	0.26	0.02
	UU	0.05	0.05		1.02	1.02	0.04	0.02
Organic	IU	0.14	7.00	4.90	1.67	1.56	0.35	0.07
	II	0.14	8.40	5.88	1.78	1.56	0.35	0.07
	UI	0.14	2.00	1.50	2.22	1.56	0.35	0.07
	UU	0.05	0.05		1.02	1.02	0.04	0.04
Deep Organic	IU	0.10	5.00	3.50	1.18	1.76	4.60	10.00
	II	0.10	6.20	4.34	1.26	1.76	4.60	12.40
	UI	0.10	0.32	0.22	1.58	1.76	4.60	7.00
	UU	0.03	0.03		1.15	1.15	0.06	0.06

IU -- Improved subsurface drainage Unimproved surface drainage Crop land
II -- Improved subsurface drainage Improved surface drainage Crop land
UI -- Unimproved subsurface drainage Improved surface drainage Crop land
UU -- Unimproved subsurface drainage Unimproved surface drainage Forest land
C_{RO} -- Concentration of nutrient in surface runoff water
C_D -- Concentration of nutrient in subsurface drainage water
Ctr -- Controlled drainage

observed in the above referenced field experiments and on the current understanding of nutrient transformations in the soil - water regime. The values in Table 4 are our best estimates given our current knowledge and experience; however, the data base for nutrient concentrations in drainage water is currently not large enough to statistically validate these estimates.

The NO_3-N concentration estimates varied with soil type, field drainage design, and canal management. NO_3-N concentrations were higher for subsurface drainage water than for surface drainage water since NO_3-N is soluble in water and readily moves with the water through the soil profile. Higher NO_3-N concentrations occur in drainage water from improved subsurface drainage conditions since less denitrification occurs in the more aerobic conditions and NO_3-N spends less time in the soil profile. Drainage water from control drainage conditions has lower NO_3-N concentrations since high water level in the ditches reduces drainage rates and provides more anaerobic conditions for increased denitrification. Increasing organic matter in the soils increases the denitrification and decreases the NO_3-N concentration of the drainage water.

Surface runoff can transport organic N and N associated with eroded sediment; therefore, TKN concentration estimates increased with increased potential for erosion due to field drainage design. Estimates of TKN concentrations in subsurface drainage water were not affected by drainage design.

The concentration estimates for TP in the surface runoff were higher than in the subsurface drainage water because phosphorus moving through the soil profile is readily absorbed onto mineral soil particles. Estimates of TP concentrations in the organic soils increased with the percent organic matter and as the percent of the TP absorbing mineral soil particles decreased. TP concentration for the deep organic soil were very high assuming very low percentages of mineral soil particles. Concentration estimates for TP did not vary with drainage design except in the deep organic soil where concentrations in subsurface drainage water increased with poor soil drainage conditions.

B. MODEL APPLICATION

The hydrology of various management scenarios were simulated using the modified version of DRAINMOD. The simulations were conducted for the time period from 1955 to 1979 using the climatological record from Elizabeth City, NC. The years 1968, 1970, 1971, 1973, and 1979 were omitted from the analysis due to inaccurate rainfall records.

Three levels of controlled drainage were considered: (NC) the use of no control structures, (LC) a low level of management with weir elevations maintained at 60 cm below the field surface only when the crop is in the field, and (HC) a high level of management with weir elevations maintained at 45 cm below the field surface at all times except for planting and harvesting. The two crop rotations considered were the corn - wheat - soybean (CWS) rotation and the corn - wheat - soybean - potato (CWSP) rotation currently used on the watershed. Elevations of the weirs with respect to time for each level of canal control are shown in Table 5 along with the rooting depths of the crop rotations. The forest lands were simulated with a constant rooting depth of 45 cm and with the NC level of canal control.

The field drainage designs considered were unimproved subsurface drainage with improved surface drainage (UI), improved subsurface drainage with improved surface drainage (II), improved subsurface drainage with unimproved surface drainage (IU), and unimproved subsurface drainage with unimproved surface drainage (UU). The UU design represents the forest land situation and was not considered for the crop rotations. The drain spacings and surface storage values for each design on each soil are summarized in Table 6. The drain spacings for the improved subsurface drainage designs represent optimum practical installation of drain tubes between the existing 80 m spaced ditches. This limited possible spacings to whole number divisions of the 80 m spacing (ie. 40 m, 26.7 m, 20 m, 16.7 m, etc.). The spacings were optimized for average annual net profit from the agricultural crops over 25 years.

The DRAINMOD simulations predicted the average annual surface runoff and subsurface drainage volume per unit area for each combination of soil, field drainage design, cropping practice, and canal control practice. The nutrient efflux per unit area from fields of each combination was calculated by Eq. 10 using the nutrient concentration values from previous field experiments (see Table 4). Total hydraulic and nutrient efflux (EFF_t) from the watershed was calculated by summing the unit area efflux values (E_i) weighted by the area (A_i) influenced by each combination (i).

$$EFF_t = \sum_{i=1}^{n} A_i E_i \qquad (10)$$

Table 5. Rooting depths and the three canal control management strategies for the annual cropping scenarios.

Corn - Wheat Year

Root Depth (cm)

Month	1	4	4	4	5	6	9	9	9	10	10	11	12
Day	1	10	20	30	31	22	2	12	27	7	27	26	31
Depth	3	3	6	15	25	30	30	10	3	3	10	15	15

Weir Control (cm below soil surface)

Month	1	2	3	4	5	6	7	8	9	10	11	12
Day	1	1	8	15	1	1	1	1	12	20	1	1
NC	120	120	120	120	120	120	120	120	120	120	120	120
LC	120	120	120	60	60	60	60	60	120	60	60	60
HC	45	45	120	45	45	45	45	45	120	45	45	45

Wheat - Soybean Year

Root Depth (cm)

Month	1	2	3	4	5	5	6	6	7	7	8	10	11	11	12
Day	1	9	1	1	25	26	5	16	4	20	3	27	16	21	31
Depth	15	15	20	25	25	3	3	7	20	25	30	30	10	3	3

Weir Control (cm below soil surface)

Month	1	2	3	4	5	6	7	8	9	10	11	12
Day	1	1	1	1	15	15	1	1	1	1	10	10
NC	120	120	120	120	120	120	120	120	120	120	120	120
LC	60	60	60	60	120	60	60	60	60	60	120	120
HC	45	45	45	45	120	45	45	45	45	45	120	45

Potato - Soybean Year

Root Depth (cm)

Month	1	2	3	3	3	5	6	6	7	7	8	10	11	11	12
Day	1	15	1	15	30	10	5	19	4	20	3	27	16	21	31
Depth	3	3	7	20	25	30	3	7	20	25	30	30	10	3	3

Weir Control (cm below soil surface)

Month	1	2	3	4	5	6	7	8	9	10	11	12
Day	1	6	15	1	15	15	1	1	1	1	10	10
NC	120	120	120	120	120	120	120	120	120	120	120	120
LC	120	120	60	60	120	60	60	60	60	60	120	120
HC	45	120	45	45	120	45	45	45	45	45	120	45

Canal Control Levels -- NC = No Control, LC = Low Control, HC = High Control
Crop Rotations -- CWS = Corn Wheat Year & Wheat Soybean Year
CWSP = Corn Wheat Year & Wheat Soybean Year & Potato Soybean Year (see Fig. 2)

Table 6. Field drainage designs for different soil types and canal control practices on the watershed

	Mineral Sandy Loam	Mineral Silt Loam	Mineral Organic	Organic	Deep Organic
Unimproved Subsurface - Improved Surface (UI)					
No Control					
Drain Spacing (m)	80.0	80.0	80.0	80.0	80.0
Surface Storage (cm)*	0.25	0.25	0.25	0.25	0.25
Control					
Drain Spacing (m)	80.0	80.0	80.0	80.0	80.0
Surface Storage (cm)*	0.25	0.25	0.25	0.25	0.25
Improved Subsurface - Improved Surface (II)					
No Control					
Drain Spacing (m)	40.0	26.7	40.0	40.0	16.0
Surface Storage (cm)*	0.25	0.25	0.25	0.25	0.25
Control					
Drain Spacing (m)	40.0	26.7	40.0	26.7	16.0
Surface Storage (cm)*	0.25	0.25	0.25	0.25	0.25
Improved Subsurface - Unimproved Surface (IU)					
No Control					
Drain Spacing (m)	40.0	26.7	40.0	26.7	13.0
Surface Storage (cm)*	2.5	2.5	2.5	2.5	2.5
Control					
Drain Spacing (m)	40.0	20.0	40.0	26.7	13.0
Surface Storage (cm)*	2.5	2.5	2.5	2.5	2.5
Unimproved Subsurface - Unimproved Surface (UU)					
No Control					
Drain Spacing (m)	80.0	80.0	80.0	160.0	160.0
Surface Storage (cm)*	2.5	2.5	2.5	2.5	2.5

* cm = cm^3 per cm^2 of surface area

Table 7. Summary of land areas for each combination of crop rotation, canal control, and soil type currently existing on the watershed.

Soil Type	No Control			Low Control		
	CWS ha	CWSP ha	FOR ha	CWS ha	CWSP ha	Total ha
Mineral Sandy Loam	78	72	33	75	367	624
Mineral Silt Loam	328	188	58	90	358	1022
Mineral Organic	626	78	217	74	738	1734
Organic	32	40	734	0	185	990
Deep Organic	0	4	933	0	21	959
Total	1064	382	1974	239	1669	5329

The mean hydraulic and nutrient efflux per unit area (EFF_a) from the watershed was calculated as the EFF_t divided by the total watershed area (A_t).

$$EFF_a = \frac{\sum_{i=1}^{n} A_i E_i}{A_t} \qquad (11)$$

Total hydraulic and nutrient effluxes from the watershed were calculated for the drainage design, canal control and, cropping practices currently existing on the watershed. The areas of the different combinations for the existing conditions are shown in Table 7.

The total effluxes were also calculated for a variety of water management and land use scenarios on the watershed. The first set of calculations pertained to the use of alternative water management methods on the cropland given the existing distribution of crop and forest land on the watershed. All nine combinations of the three canal control levels and the three field drainage designs were evaluated. A second set of calculations were conducted to evaluate total water and nutrient efflux if the entire watershed was developed for crop production or if the entire watershed was allowed to return to forest. The nine water management combinations were evaluated for the crop production scenarios. Only the combination of NC canal control and UU field design was considered for the all forest scenarios.

C. FIELD SIMULATION RESULTS

The hydrology of agricultural fields was significantly affected by water management methods. Changes in hydrology resulting from water management also affected the quality of the water leaving the agricultural field. Using control structures to hold drainage water in the canals decreased the total water outflow, as well as nitrate-nitrogen (NO_3-N) and total Kjeldahl nitrogen (TKN) efflux. Improving subsurface drainage increased total water outflow and NO_3-N efflux while decreasing total phosphorus (TP) and TKN efflux. Different crop rotations only slightly affected total water outflow and nutrient flux; however, water and nutrient outflows for agricultural crop rotations were higher than for forested conditions. The soil type affected water and nutrient outflows as well as effectiveness of the water management practices on the fields.

C. 1. Hydrology

The total volume of water leaving the field was significantly affected by canal control (Table 8). For all soil types and field drainage designs, total outflow decreased as the level of canal control increased. The low level of control (LC) decreased total outflow by between 15 to 20 % when compared to no control (NC). The high level of control (HC) decreased total outflow from 23 to 31 % when compared to no control. The reductions in total outflow due to canal control that were predicted by the simulations were lower than most reductions observed in field experiments; therefore, the reductions predicted by the simulations were considered conservative.

Total outflow was reduced by canal control because maintaining a higher water elevation in the ditch increased lateral seepage (Table 9) and because maintaining a lower depth to water table in the soil increased evapotranspiration (Table 10). The volume of surface runoff leaving the fields generally increased as canal control increased (Table 11). Exceptions to this observation occurred when the soil hydraulic conductivity was low and subsurface drainage was unimproved. For these cases enough of the surface runoff water stored in the ditch was lost to lateral seepage that the volume of surface runoff flowing over the weir was less than for the no control case. Subsurface drainage from the fields decreased with increasing levels of canal control (Table 12) due to decreased gradient from the water table in the field and the water level in the ditch.

The field drainage design had less of an effect on total outflow than did canal control. The improvement of subsurface drainage increased the total outflow by 3 to 9 % (Table 8). Improved subsurface drainage resulted in greater water table depths and less evapotranspiration (Table 10). Decreased evapotranspiration during the growing season would likely reduce yields; therefore, an intensity of subsurface drainage that would cause significant reduction of evapotranspiration would not be a desirable agronomic practice. Unimproved surface drainage decreased total outflow since more water infiltrated which decreased water table depth and increased evapotranspiration.

Table 8. Average volume or depth of water drained from fields by surface and subsurface drainage for each combination of field design, canal control, crop, and soil group.

Field Design	Canal Control	Crop	Mineral Sandy Loam	Mineral Silt Loam	Mineral Organic	Organic	Deep Organic
			cm/yr				
UI	NC	CWS	35.9	34.7	32.1	31.7	37.1
		CWSP	35.8	34.6	31.9	31.7	37.0
	LC	CWS	28.7	28.7	26.2	25.3	31.0
		CWSP	28.9	29.0	26.6	25.6	30.9
	HC	CWS	25.3	25.4	23.1	22.3	27.3
		CWSP	25.6	25.7	23.5	22.7	27.3
II	NC	CWS	37.4	36.4	34.7	32.7	38.8
		CWSP	37.2	36.3	34.7	32.6	38.6
	LC	CWS	30.4	30.5	28.0	26.6	32.4
		CWSP	30.9	31.0	28.5	27.0	32.8
	HC	CWS	26.7	27.0	24.3	23.4	29.5
		CWSP	27.2	27.5	25.0	23.8	29.8
IU	NC	CWS	37.2	35.9	34.4	32.8	38.5
		CWSP	37.1	35.8	34.4	32.8	38.4
	LC	CWS	30.0	30.0	27.6	26.4	31.8
		CWSP	30.5	30.5	28.2	26.9	32.3
	HC	CWS	26.2	26.3	23.8	23.0	28.9
		CWSP	26.8	26.9	24.5	23.6	29.3
UU	NC	FOR	27.6	27.5	26.6	24.3	25.8

Both improved subsurface drainage and unimproved surface drainage decreased surface runoff volumes (Table 11) and increased subsurface drainage volumes (Table 12).

The two agricultural crop rotations that were analyzed had a small effect on the hydrology of the fields. The water level in the canal was controlled for a longer period of time for the corn - wheat - soybean rotation (CWS) than for the corn - wheat - soybean - potato rotation (CWSP). Consequently, the CWS rotation resulted in higher

Table 9. Average lateral seepage from ditches for each combination of field design, canal control, crop, and soil group.

Field Design	Canal Control	Crop	Mineral Sandy Loam	Mineral Silt Loam	Mineral Organic	Organic	Deep Organic
			cm/yr				
UI	NC	CWS	0.0	0.0	0.0	0.0	0.0
		CWSP	0.0	0.0	0.0	0.0	0.0
	LC	CWS	5.3	4.3	4.9	4.7	4.8
		CWSP	4.7	3.8	4.3	4.3	4.3
	HC	CWS	7.7	6.7	7.3	7.0	7.3
		CWSP	7.2	6.2	6.7	6.5	6.8
II	NC	CWS	0.0	0.0	0.0	0.0	0.0
		CWSP	0.0	0.0	0.0	0.0	0.0
	LC	CWS	4.9	3.9	4.5	4.6	5.4
		CWSP	4.3	3.4	4.0	4.2	4.9
	HC	CWS	7.5	6.4	7.2	7.1	8.0
		CWSP	7.0	5.9	6.6	6.6	7.5
IU	NC	CWS	0.0	0.0	0.0	0.0	0.0
		CWSP	0.0	0.0	0.0	0.0	0.0
	LC	CWS	5.0	4.1	4.6	4.7	5.5
		CWSP	4.4	3.5	4.1	4.2	5.0
	HC	CWS	7.7	6.6	7.4	7.1	8.1
		CWSP	7.1	6.1	6.8	6.7	7.6
UU		FOR	0.0	0.0	0.0	0.0	0.0

lateral seepage, higher surface runoff, lower subsurface runoff, and lower total outflow from the fields in control drainage. The effect of crop rotation on the hydrology of fields with no control was insignificant.

The hydrology on forested fields was very different than on fields with agricultural crops. Evapotranspiration from the forested land was higher than from the crop land (Table 10) because of the constant deep rooting depths of the trees. Higher water loss to

Table 10. Average evapotranspiration from fields for each combination of field design, canal control, crop, and soil group.

Field Design	Canal Control	Crop	Mineral Sandy Loam	Mineral Silt Loam	Mineral Organic	Organic	Deep Organic
			cm/yr				
UI	NC	CWS	83.2	84.7	87.5	87.4	80.1
		CWSP	83.2	84.8	87.8	87.5	80.3
	LC	CWS	84.2	85.2	87.4	87.8	80.2
		CWSP	84.6	85.4	87.6	88.1	80.9
	HC	CWS	84.5	85.3	87.7	88.0	80.3
		CWSP	84.8	85.6	87.8	88.2	81.0
II	NC	CWS	81.8	83.3	84.9	86.5	78.8
		CWSP	81.9	83.4	85.0	86.6	79.0
	LC	CWS	83.1	84.4	86.3	87.3	79.4
		CWSP	83.3	84.5	86.3	87.3	79.6
	HC	CWS	83.6	84.8	86.8	87.6	79.5
		CWSP	83.7	84.8	86.7	87.6	79.7
IU	NC	CWS	82.0	83.7	85.3	86.5	79.2
		CWSP	82.1	83.8	85.3	86.5	79.4
	LC	CWS	83.3	84.7	86.5	87.4	79.8
		CWSP	83.4	84.8	86.5	87.5	80.0
	HC	CWS	83.9	85.2	87.1	87.8	79.9
		CWSP	83.9	85.2	87.0	87.8	80.1
UU	NC	FOR	91.4	91.7	92.9	94.4	91.5

evapotranspiration resulted in reduced total outflow from the forested lands. The total water outflows from the forested lands were 17 to 31 % less than for crop land with no control (Table 8); however, when compared to high level of control on crop land, the total outflows from the forested lands was very similar. High surface storage on the forested land resulted in lower surface runoff compared to crop land with unimproved subsurface drainage (Table 12).

Table 11. Surface runoff from fields for each combination of field design, canal control, crop, and soil group.

Field Design	Canal Control	Crop	Mineral Sandy Loam	Mineral Silt Loam	Mineral Organic	Organic	Deep Organic
			cm/yr				
UI	NC	CWS	17.2	25.8	14.7	22.7	25.6
		CWSP	17.2	25.8	14.6	22.6	25.6
	LC	CWS	18.2	23.6	15.8	20.1	23.3
		CWSP	17.7	23.6	15.5	20.0	23.0
	HC	CWS	18.9	22.4	16.7	19.2	21.9
		CWSP	18.5	22.4	16.3	19.1	21.7
II	NC	CWS	9.4	13.8	7.9	16.2	13.1
		CWSP	9.4	13.8	7.9	16.2	13.1
	LC	CWS	12.7	16.0	10.1	16.1	14.1
		CWSP	12.2	15.6	9.7	15.8	14.0
	HC	CWS	15.7	18.0	12.8	16.9	14.1
		CWSP	15.1	17.5	12.3	16.6	14.0
IU	NC	CWS	2.5	3.7	2.5	3.8	3.7
		CWSP	2.4	3.7	2.5	3.8	3.7
	LC	CWS	3.4	4.7	3.1	4.1	4.1
		CWSP	3.4	4.7	3.1	4.1	4.1
	HC	CWS	4.4	5.6	3.9	4.8	4.2
		CWSP	4.3	5.5	3.8	4.7	4.2
UU	NC	FOR	7.8	14.4	7.5	20.0	14.9

The field hydrology was dependent on soil type. Total water outflow from the mineral - organic and organic soils was lower than outflow from the mineral soils; however, the total outflow from the deep organic soil was the highest of all the soils. The high outflow rates from the deep organic soil was caused by low upflux values restricting evapotranspiration (Table 10). Evapotranspiration was higher from the mineral - organic and organic soils than from the mineral soils. Surface runoff was higher (Table 11) and subsurface drainage was lower (Table 12) from the soils with lower hydraulic conductivities. Improved subsurface drainage decreased surface runoff and subsurface drainage differences between the soil types.

Table 12. Subsurface drainage from fields for each combination of field design, canal control, crop, and soil group.

Field Design	Canal Control	Crop	Mineral Sandy Loam	Mineral Silt Loam	Mineral Organic	Organic	Deep Organic
			cm/yr				
UI	NC	CWS	18.7	8.8	17.4	9.1	11.5
		CWSP	18.6	8.8	17.3	9.1	11.4
	LC	CWS	10.4	5.1	10.4	5.2	7.7
		CWSP	11.1	5.5	11.1	5.6	7.9
	HC	CWS	6.4	3.0	6.4	3.1	5.3
		CWSP	7.1	3.3	7.2	3.6	5.6
II	NC	CWS	28.0	22.7	26.8	16.5	25.7
		CWSP	27.9	22.5	26.8	16.4	25.5
	LC	CWS	17.7	14.5	17.9	10.5	18.4
		CWSP	18.6	15.4	18.8	11.3	18.8
	HC	CWS	11.0	8.8	11.5	6.4	15.4
		CWSP	12.1	9.8	12.7	7.2	15.8
IU	NC	CWS	34.7	32.2	31.9	29.1	34.9
		CWSP	34.6	32.1	31.9	29.0	34.7
	LC	CWS	26.6	25.2	24.5	22.3	27.7
		CWSP	27.2	25.8	25.1	22.8	28.1
	HC	CWS	21.7	20.6	19.9	18.2	24.7
		CWSP	22.4	21.3	20.7	18.9	25.1
UU	NC	FOR	19.8	13.1	19.1	4.2	10.9

C. 2. Nutrient Efflux

Changes in hydrology caused by canal control practices caused significant changes in the efflux of nutrients from the fields. Canal control resulted in large reductions in NO_3-N efflux for all soil types and field drainage designs when compared to fields with no control (Table 13). NO_3-N reductions ranged from 25 to 41 % for low control and from 41 to 67 % for high control. These high levels of reduction reflect the cumulative effects of three compounding factors: 1) reduced total water outflow, 2) reduced concentration

Table 13. Nitrate nitrogen efflux from fields for each combination of field design, canal control, crop, and soil group.

Field Design	Canal Control	Crop	Mineral Sandy Loam	Mineral Silt Loam	Mineral Organic	Organic	Deep Organic
			----------------------------	----------------------------	kg/ha/yr	----------------------------	----------------------------
UI	NC	CWS	14.7	10.6	9.4	2.1	.6
		CWSP	14.7	10.5	9.4	2.1	.6
	LC	CWS	9.4	7.6	5.5	1.3	.5
		CWSP	9.8	7.9	6.0	1.4	.5
	HC	CWS	7.1	6.0	3.5	.8	.4
		CWSP	7.4	6.3	3.9	.9	.4
II	NC	CWS	34.2	29.0	26.5	14.1	16.1
		CWSP	34.1	28.8	26.4	14.0	16.0
	LC	CWS	21.0	18.3	16.1	8.3	10.0
		CWSP	22.4	19.6	17.3	9.1	10.5
	HC	CWS	13.8	12.0	9.9	4.7	7.6
		CWSP	15.2	13.2	11.2	5.5	8.0
IU	NC	CWS	38.7	36.2	28.9	20.4	17.5
		CWSP	38.6	36.1	28.8	20.4	17.4
	LC	CWS	26.0	24.7	19.3	13.6	11.8
		CWSP	27.1	25.8	20.2	14.3	12.2
	HC	CWS	19.8	18.8	14.4	10.2	9.6
		CWSP	20.9	19.8	15.4	10.9	9.9
UU	NC	FOR	0.5	0.5	0.3	0.2	0.2

of NO_3-N in the subsurface drainage water due to denitrification, and 3) reduced fraction of total outflow that was subsurface drainage.

Compared to fields with no control, efflux of TKN was reduced by 11 to 23% for low control cases and by 17 to 34 % for high control cases (Table 14). Since concentrations of TKN did not vary much between surface and subsurface drainage water, the TKN reductions primarily reflect the reduction in total water outflow.

Table 14. Total Kjeldahl nitrogen efflux from fields for each combination of field design, canal control, crop, and soil group.

Field Design	Canal Control	Crop	Mineral Sandy Loam	Mineral Silt Loam	Mineral Organic	Organic	Deep Organic
			kg/ha/yr				
UI	NC	CWS	5.4	5.1	6.5	6.5	6.1
		CWSP	5.4	5.1	6.4	6.4	6.1
	LC	CWS	4.2	4.2	5.7	5.3	5.0
		CWSP	4.3	4.2	5.7	5.3	5.0
	HC	CWS	3.7	3.7	5.3	4.8	4.4
		CWSP	3.8	3.7	5.3	4.8	4.4
II	NC	CWS	5.4	5.1	5.8	5.5	6.2
		CWSP	5.4	5.1	5.8	5.4	6.2
	LC	CWS	4.2	4.1	4.9	4.5	5.0
		CWSP	4.3	4.2	4.9	4.6	5.1
	HC	CWS	3.5	3.4	4.4	4.0	4.5
		CWSP	3.6	3.5	4.5	4.1	4.5
IU	NC	CWS	5.7	5.4	5.5	5.2	6.6
		CWSP	5.7	5.4	5.5	5.2	6.5
	LC	CWS	4.5	4.4	4.4	4.2	5.4
		CWSP	4.6	4.5	4.5	4.3	5.4
	HC	CWS	3.9	3.8	3.9	3.6	4.9
		CWSP	4.0	3.9	4.0	3.7	4.9
UU	NC	FOR	3.7	3.2	3.7	3.1	4.5

Changes in efflux of TP were variable in response to canal control management (Table 15). These changes in TP efflux with increasing canal control reflect the cumulative effects of the reduction of total water outflow and the increase in the fraction of total outflow that is surface runoff. While reduced total water outflow tended to decrease TP efflux, the increase of the surface runoff with its higher TP concentration tended to increase TP efflux. The cumulative effects of canal control were increased TP efflux in good subsurface drainage conditions on the mineral and mineral - organic soils, and reduced TP efflux in the organic and deep organic soils where TP concentrations were higher in subsurface drainage water.

Table 15. Total phosphorus efflux from fields for each combination of field design, canal control, crop, and soil group.

Field Design	Canal Control	Crop	Mineral Sandy Loam	Mineral Silt Loam	Mineral Organic	Organic	Deep Organic
			kg/ha/yr				
UI	NC	CWS	.24	.34	.42	.86	19.84
		CWSP	.24	.34	.41	.85	19.76
	LC	CWS	.25	.31	.43	.74	16.08
		CWSP	.24	.31	.42	.74	16.10
	HC	CWS	.25	.29	.45	.69	13.82
		CWSP	.25	.29	.44	.69	13.88
II	NC	CWS	.15	.20	.26	.68	37.91
		CWSP	.15	.20	.26	.68	37.69
	LC	CWS	.18	.22	.30	.64	29.23
		CWSP	.18	.22	.29	.63	29.73
	HC	CWS	.21	.24	.36	.64	25.52
		CWSP	.21	.24	.34	.63	25.99
IU	NC	CWS	.07	.08	.13	.34	36.55
		CWSP	.07	.08	.13	.33	36.37
	LC	CWS	.07	.09	.13	.30	29.62
		CWSP	.07	.09	.13	.30	30.02
	HC	CWS	.08	.09	.14	.29	26.66
		CWSP	.08	.09	.14	.30	27.03
UU	NC	FOR	.10	.16	.11	.24	.32

The nutrient effluxes predicted by the simulations for control drainage should be considered conservative for two reasons. By conservative we mean that the actual outflow to receiving streams will be less than predicted and reported herein. The first reason is that reductions in total water outflow resulting from control drainage were lower for the simulated results (15 - 31 %)than for those observed in field experiments (17 - 56 % reported by Evans et al. (1989), and 50 - 90 % reported by Gilliam et al. (1978)). This is probably due to underestimation of the increase in evapotranspiration or seepage due to control drainage. The second reason is that the simulations do not consider any nutrient removal that would occur in water held in the ditches and canals behind the control structure nor in the canal network as the water moves to the receiving stream. The mechanisms for this removal would be the settling of soil particles for TP and TKN removal, and denitrification for NO_3-N removal. Extensive sampling in major canals (Gilliam and Skaggs, unpublished data) have measured nutrient concentrations lower those measured in field ditches and used to calculate the predictions of these simulations. Thus these predictions best serve to show relative nutrient losses between various management alternatives and not the absolute contribution of nutrients to estuaries from land under a particular management option.

The nutrient efflux was greatly affected by improved subsurface drainage and increased surface storage. The cumulative effects of three factors compounded to increase NO_3-N efflux with improved subsurface drainage: 1) increased total water outflow, 2) increased concentration of NO_3-N in the subsurface drainage water, and 3) increased fraction of total outflow that was subsurface drainage. Increases in NO_3-N efflux that resulted from greater surface storage was mostly due to the increased fraction of total outflow occurring as subsurface drainage.

The change in TKN efflux in response to improved subsurface drainage was insignificant for the mineral soils and the deep organic soils. The increase in total water outflow caused by improved subsurface drainage was offset by a decrease in TKN concentration in the surface drainage water. TKN efflux decreased with improved subsurface drainage for the mineral organic and organic soils where TKN concentrations in subsurface drainage water were lower than for surface drainage water.

Improved subsurface drainage and increased surface storage reduced TP efflux for the mineral, mineral - organic and organic soils where TP concentrations were much higher in surface runoff waters. In the deep organic soil, TP concentrations of the subsurface drainage water were higher than in the surface runoff water; consequently, TP efflux from this soil increased as subsurface drainage was improved.

Differences in TP and TKN efflux between the CWS and CWSP crop rotations were insignificant. NO_3-N efflux from the CWSP rotation was 0 to 13% higher than from the CWS rotation. This increase was mostly due to less canal control for the CWSP rotation.

The nutrient efflux from the forested land was less than from the crop land. Predicted NO_3-N efflux from the forested land was 1 to 2 orders of magnitude less than from the cropland. This large difference was due to the combined effect of lower total water outflow from the forest land and lower NO_3-N concentrations in the forest land drainage water. Concentrations of NO_3-N in drainage water were much lower from the forest land than from the crop land since nitrogen fertilizer had not been applied to the forest lands. Differences between cropland and forest land in TP and TKN efflux were not as great since the TP and TKN concentrations of the forest land drainage water were more similar to those of the cropland.

Nutrient efflux was greatly affected by soil type in the fields. NO_3-N efflux decreased as the organic matter content of the soils increased. Increased organic matter provides a carbon source that is necessary for denitrification. TP efflux however increased as soil organic matter increased since the phosphorus absorbing mineral soil particles decreased. This increase was very large for the deep organic soil. TKN efflux was higher in the organic soils than in the mineral soils, but differences in efflux due to soil type were not as great for TKN as for TP or NO_3-N.

D. CUMULATIVE EFFECTS FOR WATERSHED

D. 1. Existing Watershed

The watershed in its existing condition is divided into cropland with no control, cropland with a low level of control and forest land. All of the cropland is drained by conventional ditch drainage with relatively smooth soil surfaces to promote surface runoff. The cumulative DRAINMOD simulations of the existing watershed predicted that the average annual total drainage from the watershed would be 14.5 million m^3 of water (27.2 cm over the entire area). The simulations predicted that 65 % of the drainage would be surface runoff and 35 % of the drainage would be subsurface drainage (Table 16). Drainage from the cropland managed with the high level of control (HC) was 9 cm/yr less than drainage from the cropland managed with no control (NC). Most of this decrease in total drainage caused by reduction in subsurface drainage. The total predicted drainage from the forest land was nearly the same as predicted from the controlled cropland.

Table 16. Hydrology and nutrient efflux from watershed with existing crop and water management conditions

	Subsurface Drainage	Surface Runoff	Total Drainage	NO_3-N	TKN	TP
			Outflow per unit area			
	cm/yr			kg/ha/yr		
Crop Control	5.82	18.60	24.42	4.91	4.51	.54
Crop No Control	14.02	19.34	33.36	9.98	5.86	.46
Forest	9.54	15.85	25.38	.19	3.01	.26
Weighted Mean	9.42	17.78	27.21	4.54	4.32	.41
			Total outflow			
	m^3/yr x 10^6			t/yr		
Crop Control	1.11	3.55	4.66	9.36	8.61	1.02
Crop No Control	2.03	2.80	4.82	14.43	8.47	.66
Forest	1.88	3.13	5.01	.38	5.94	.51
Total	5.02	9.47	14.49	24.17	23.02	2.19

Crop Control - 1907 ha, Crop No Control - 1445 ha, Forest - 1973 ha

Table 17. The effects of field design and canal control on the total water and nutrient effluxes from the 3350 ha of cropland currently existing on the watershed.

Field Design	Canal Control	Subsurface Drainage cm/yr	Surface Drainage cm/yr	Total Drainage cm/yr	NO_3 t/yr	TKN t/yr	TP t/yr
	NC	14.4	19.0	33.4	33.6	19.6	1.8
UI	LC	8.8	18.7	27.5	22.3	16.7	1.7
	HC	5.5	18.8	24.3	16.2	15.2	1.6
	NC	25.0	10.5	35.5	92.1	18.5	1.8
II	LC	16.9	12.5	29.3	59.3	15.2	1.7
	HC	10.9	14.8	25.7	38.6	13.4	1.7
	NC	32.3	2.9	35.2	107.0	18.3	1.3
IU	LC	25.3	3.7	28.9	74.2	15.0.	1.2
	HC	20.7	4.5	25.2	56.5	13.0	1.1

The simulations predicted that the average annual efflux of nutrients from the watershed was: 24.2 t/yr for NO_3-N, 23.0 t/yr for TKN, and 2.19 t/yr for TP. The efflux per ha of NO_3-N and TKN from cropland affected by control structure would be less (5.0 kg/ha/yr for NO_3-N and 1.3 kg/ha/yr for TKN) than from the cropland with no control. The efflux of TP from the cropland with control would be 0.1 kg/ha more than from the cropland with no control. The NO_3-N efflux from the forest land was much less than from the cropland. TKN and TP efflux per ha from the forest land was 50 - 60 % of that from cropland.

D. 2. Canal Control Scenarios

Results of the simulations showed that management of water control structures would greatly affect the hydrology and nutrient efflux from the existing 3350 ha of cropland on the watershed (Table 17). When compared to no control, the low level of control

Table 18. Total water and nutrient effluxes from the existing cropland for a wet year (1964) and a dry year (1977). Mean values for the 20 yr simulations are also shown.

Field Design	Canal Control	Subsurface Drainage cm/yr	Surface Drainage cm/yr	Total Drainage cm/yr	NO_3 t/yr	TKN t/yr	TP t/yr
	1977	11.4	10.2	21.6	24.1	12.3	1.1
NC	20 yr Mean	14.4	19.0	33.4	33.6	19.6	1.8
	1964	17.5	34.1	51.6	45.1	31.1	3.1
	1977	7.8	9.6	17.3	17.1	10.1	0.9
LC	20 yr Mean	8.8	18.7	27.5	22.3	16.7	1.7
	1964	10.7	34.7	45.5	31.9	28.3	3.0
	1977	4.9	9.2	14.1	11.2	8.4	0.8
HC	20 yr Mean	5.5	18.8	24.3	16.2	15.2	1.6
	1964	7.1	35.4	42.5	25.1	27.0	3.0

reduced total drainage by 18 % and the high level of control reduced total drainage by 27 %. Surface runoff did not change with canal control management; therefore, nearly all of the reductions in total drainage were reductions in subsurface drainage. The reductions in subsurface drainage resulted in reducing NO_3-N efflux by 34 % for low control management and by 52 % for high control management. Predicted efflux of TKN was reduced by 15 % for low control and by 22 % for high control. Reductions in TP due to control structure management were very small.

The effect of canal control on the hydrology and nutrient efflux of the watershed were compared for a wet year and a dry year (Table 18). The precipitation amount for the wet year (1964) was 136.2 cm and for the dry year (1977) was 111.8 cm. The average annual precipitation amount for the simulation period was 122.1 cm. The outflows of water and nutrients were generally two to three times greater for 1964 than for 1977.

Results of the simulations indicated that use of control structures would reduce total drainage, NO_3-N efflux, TKN efflux, and TP efflux for both wet years and dry years. The percent reduction was greatest for the dry year. The high level of control reduced total drainage volume by 7.5 cm for 1977 and by 9.1 cm for 1964. These volumes represent a 35 % reduction for 1977 and a 18 % reduction for 1964. The volume of surface runoff did not change significantly due to canal control for either the dry year or the wet year. Most of the reduction in drainage volume was in subsurface drainage. The high level of control reduced NO_3-N efflux by 13 t/yr (55 %) for the dry year and by 20 t/yr (44 %) for the wet year. For both 1964 and 1977 the simulations predicted a 4 t/yr reduction in TKN efflux due to the high level of canal control. This TKN reduction represented an 32 % decrease for 1977 and a 13 % decrease for 1964. Canal control reduced TP efflux reduced by 0.2 t/yr (22 %) for 1977 and 0.1 t/yr (3 %) for 1964.

D. 3. Field Design Scenarios

Improving the subsurface drainage on the fields also affected the hydrology and nutrient outflow of the watershed (see Table 17). Improved subsurface drainage only increased the total drainage volume from the agricultural land by 1 to 2 cm/yr, but the relative volumes of subsurface drainage and surface runoff changed significantly. The volume of subsurface drainage leaving the watershed increased by 5 to 10 cm/yr for smooth soil surface conditions and by 15 to 18 cm/yr for rough surface conditions. Consequently the surface runoff volume decreased by 4 to 9 cm/yr for smooth soil surface conditions and by 14 to 16 cm/yr for rough surface conditions.

The changes in the relative volumes of subsurface drainage and surface runoff would affect the nutrient efflux from the watershed. The increases in subsurface drainage volume resulted in two to three fold increases in NO_3-N efflux. Compared to the existing ditch drainage design, improved subsurface drainage with smooth soil surface (II) resulted in NO_3-N efflux increases ranging from 59 t/yr for no canal control to 22 t/yr for the high level of canal control. Improved subsurface drainage with rough soil surface (IU) resulted in NO_3-N efflux increases ranging from 73 t/yr for no control to 40 t/yr for the high level of control. The efflux of TKN decreased 6 to 14 % with improved subsurface drainage. TKN efflux decreases for the II field design ranged from 1.1 t/yr for no canal control to a 1.8 t/yr for the high level of canal control when compared to the existing ditch drainage design. The IU field design resulted in TKN efflux decreases ranging from 1.3 t/yr for no control to 2.2 t/yr for the high level of control. TP efflux from the agricultural lands with II field design did not differ from TP efflux from the agricultural lands with the existing UI field design. Improved subsurface drainage would be expected to reduce TP losses from the soils other than the deep organic soil by about a factor of 3 (see Table 15); however, the presence of the deep organic on the watershed increased TP losses and obscured the effect of improved drainage on TP losses from the other soils. TP efflux from the agricultural lands with IU field design was 0.5 t/yr less than from agricultural fields with II or UI field designs.

Canal control on the II and IU field designs reduced total drainage and nutrient efflux. Total drainage was reduced by 6 cm for low control and by 10 cm for high control when compared to no control. The NO_3-N efflux was decreased by 33 t/yr for low control and by 51 to 53 t/yr for high control. TKN efflux decreased by 3 t/yr for LC and by 5 t/yr for high control. TP decreased by 0.1 to 0.2 t/yr for low control and high control.

B. 4. Land Use Scenarios

Three possible distributions of land use are compared in Table 19. The land uses are all land in crop land, all land in forest and the land use that is presently existing on the watershed. The two land uses involving crop land are considered with combinations of the three canal control and three field designs.

The total drainage and nutrient efflux from the watershed increased as the amount of cropland increased. The only exception to this was for the high level of control where the total drainage was less than that from the forest land. The changes in the total drainage and TKN efflux reflect the simple changes in relative area of cropland and forest land. The changes in NO_3-N and TP efflux are affected by the distribution of the land uses on the soils as well as the relative areas of the land uses. In the existing land use the forest land is located on most of the organic soil and on nearly all of the deep organic soil. The efflux of NO_3-N and TP from the forest land on these soils is very low since no fertilizer is applied to the land. If this land was converted to cropland, the NO_3-N efflux would be much greater than from the forest land but not as great as from the cropland on the mineral soils. This is reflected by the 8 to 38 % increase in NO_3-N efflux for a 59 % increase in cropland area when comparing existing cropland to all cropland. The percent increases were less for the UI field design and for the HC canal control. The efflux of TP from the watershed would greatly increase if the forest land on the organic and deep organic soils was converted to cropland. The TP efflux from organic and deep organic soils is very high when developed for cropland; therefore, the TP efflux would be increased by 7 to 18 times if these soils were converted to cropland.

Table 19. Total water and nutrient effluxes from the watershed if all land was converted to corn - wheat - soybean rotation (All CWS), if the existing cropland was converted to corn - wheat - soybean rotation (Ext CWS), and if all land was converted to forest (All FOR). Each combination of field design and canal control are shown for the cropland.

Canal Control	Land Use	Subsurface Drainage cm/yr	Surface Drainage cm/yr	Total Drainage cm/yr	NO_3 t/yr	TKN t/yr	TP t/yr
		Unimproved Subsurface - Improved Surface on Cropland					
NC	All FOR	13.8	12.5	26.3	1.7	17.5	1.0
NC	Ext CWS	12.6	17.8	30.4	34.0	25.6	2.4
NC	All CWS	13.3	20.6	33.9	39.0	32.0	21.1
NC	All FOR	13.8	12.5	26.3	1.7	17.5	1.0
LC	Ext CWS	9.1	17.6	26.7	22.7	22.6	2.2
LC	All CWS	7.9	19.7	27.7	24.9	26.8	17.4
NC	All FOR	13.8	12.5	26.3	1.7	17.5	1.0
HC	Ext CWS	7.0	17.7	24.7	16.5	21.1	2.2
HC	All CWS	4.9	19.5	24.4	17.8	24.1	15.2
		Improved Subsurface - Improved Surface on Cropland					
NC	All FOR	13.8	12.5	26.3	1.7	17.5	1.0
NC	Ext CWS	19.3	12.5	31.8	92.5	24.4	2.3
NC	All CWS	24.0	11.7	35.7	126.2	30.0	37.8
NC	All FOR	13.8	12.5	26.3	1.7	17.5	1.0
LC	Ext CWS	14.1	13.7	27.9	59.7	21.2	2.2
LC	All CWS	15.9	13.3	29.3	77.5	24.5	29.5
NC	All FOR	13.8	12.5	26.3	1.7	17.5	1.0
HC	Ext CWS	10.4	15.2	25.6	39.0	19.3	2.2
HC	All CWS	10.7	15.1	25.8	49.9	21.6	26.1
		Improved Subsurface - Unimproved Surface on Cropland					
NC	All FOR	13.8	12.5	26.3	1.7	17.5	1.0
NC	Ext CWS	23.8	7.7	31.6	107.4	24.3	1.9
NC	All CWS	32.3	3.2	35.5	148.1	29.9	35.7
NC	All FOR	13.8	12.5	26.3	1.7	17.5	1.0
LC	Ext CWS	19.5	8.2	27.6	74.5	21.0	1.7
LC	All CWS	25.1	3.8	28.9	99.7	24.3	29.1
NC	All FOR	13.8	12.5	26.3	1.7	17.5	1.0
HC	Ext CWS	16.6	8.7	25.3	56.9	19.0	1.6
HC	ALL CWS	20.8	4.5	25.3	75.6	21.1	26.2

WATERSHED SCALE SIMULATIONS

A. MODEL DESCRIPTION

The medium scale watershed model, FLDNSTRM was used to simulate a large section of the watershed (Konyha, 1989). The model represented the canal system on the watershed as network of stream segments and junctions. The field areas within the network were divided into subcatchments. A field hydrology submodel was used to simulate the hydrology of each individual subcatchment. The outflow from the subcatchments predicted by the field submodel was routed through the network of channels using a channel routing submodel. The channel routing model predicted flow rates and depths at various locations along the channel network. Since water depth was an important variable for the field submodel, the process was iterated as needed until water depths predicted by both submodels converged.

The field hydrology submodel is a modified version of DRAINMOD. DRAINMOD was modified to route the surface runoff within the subcatchment overland to field ditches, and then route the surface runoff and subsurface drainage within the subcatch-ment through the ditches to the canals. The routing within the subcatchment is based on instantaneous unit hydrograph theory. The modified version of DRAINMOD simulates the hydrology of each subcatchment for a period of one day using the appropriate field parameters and conditions for that subcatchment and that day. At the end of the day the field submodel has predicted 24 hourly outflow values for each subcatchment.

The channel routing submodel is a one dimensional finite difference solution of the St. Venant equations (Amein, 1968). The hourly outflow values from the subcatchments become lateral inflow at the appropriate locations along the canals. The submodel is capable of simulating channel segments, midstream weirs, and branches in channels. The submodel considers known flow, known depth, and uniform flow downstream boundary conditions. The channel routing is simulated for every hour of the day pausing at the end of each day for iteration with the field model or for the next days input from the field model. Details of FLDNSTRM are discussed in Konyha (1989).

B. MODEL APPLICATION

The FLDNSTRM model was used to simulate outflow hydrographs from a 2126 ha section of the watershed. The watershed section consisted of 925 ha of forest land and 1201 ha of cropland (CWS rotation). The four possible combinations of two canal control levels (NC and HC) with two field designs (UI and II) were analyzed for both a winter wet period (February, 1961) and a summer wet period (July, 1959).

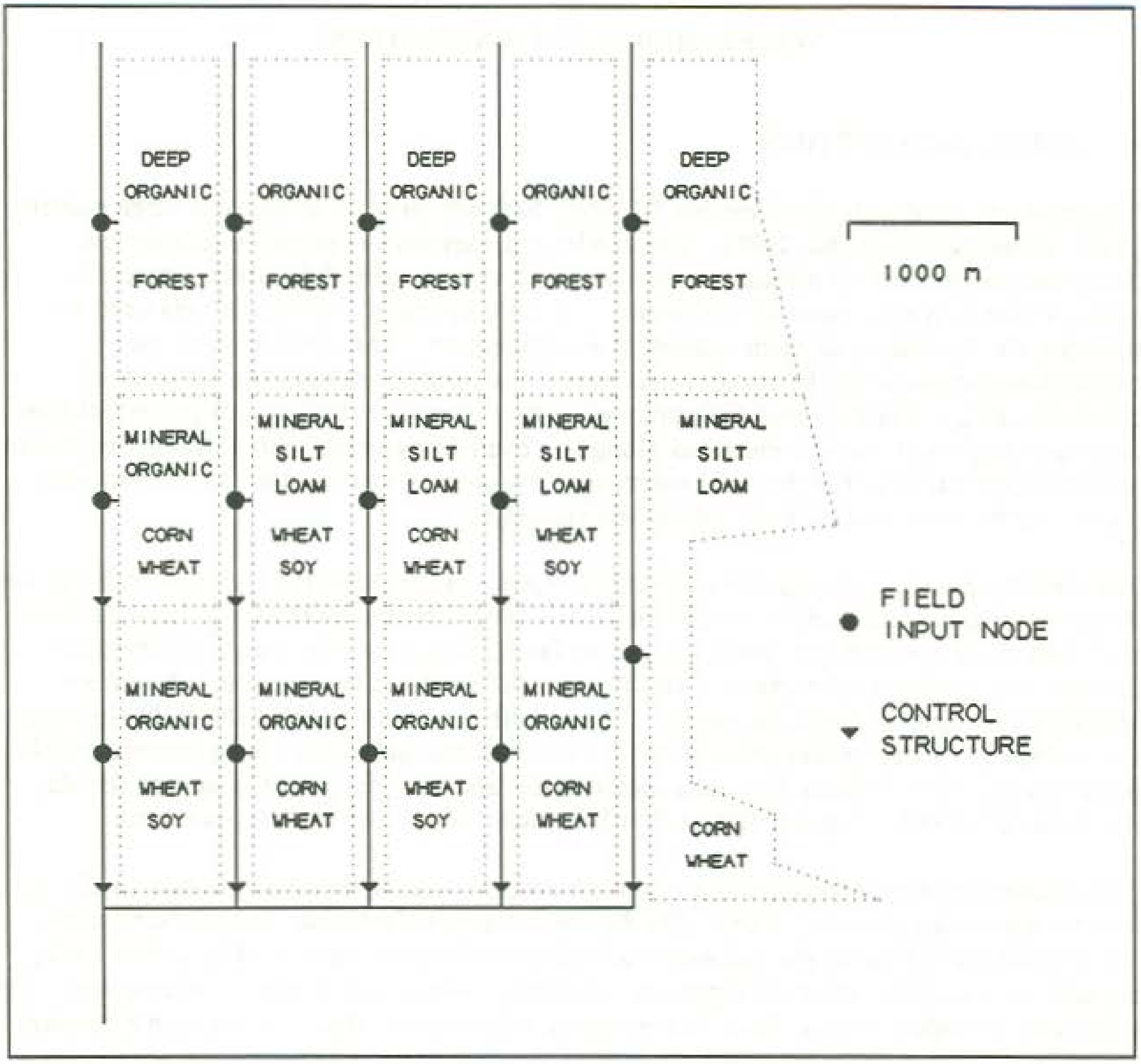

Figure 6. Discretization of watershed section used for the FLDNSTRM model.

The simulated watershed (Fig. 6) was drained by five collector canals (5900 m long, 1.5 m deep, 4 m bottom width, and side slope of 0.9) that carried the drainage water south to a main canal (3200 m long, 2.1 m deep, 4.6 m bottom width, with a side slope of 0.9). All of the canals had bottom slopes of 0.02 % and Mannings roughness coefficients of 0.045. The canal outlet was simulated as a uniform flow boundary using Mannings equation for determining the depth - flow relationship. For the simulations with canal control, the weirs in the control structures (located as shown in Fig. 6) were set at an elevation 45 cm below the field surface.

The simulated watershed was divided into 14 fields of differing soil type and land use. The locations, relative areas, soil types, and land uses of the fields are shown in Fig 6. The FLDNSTRM input values for the fields were the same as those used in the DRAINMOD simulations discussed previously with the exception that the water level in the ditches was calculated by the routing submodel of FLDNSTRM. It should be noted that the DRAINMOD simulations used in the FLDNSTRM simulations do not account for lateral seepage loss as calculated by the modified version of DRAINMOD used in the previous field simulations. Consequently, the total outflow predicted by the FLDNSTRM will be somewhat higher than predicted by the modified version of DRAINMOD.

C. SIMULATION RESULTS

The FLDNSTRM simulations predicted that routing the surface and subsurface drainage from the fields attenuated the cumulative peak flow rate at the watershed outlet (Fig 7 - 14). The attenuation was more pronounced for the the larger more intense rainfall events. The reductions in peak outflow for the large runoff events ranged from 27 to 49 % resulting in decreases in flowrate of 5000 to 15000 m^3/hr (Table 20). This attenuation would be expected since the drainage enters the canals at various locations along the channel network. The attenuation was not as great for the small successive event occurring between day 194 and 197 during the summer wet period.

The FLDNSTRM simulations predicted that improved subsurface drainage would decrease both peak inflow rates and peak outflow rates. Improved subsurface drainage decreased peak inflow rates by 1900 to 7400 m^3/hr and peak outflow rates by 1100 to 2200 m^3/hr (Table 20). Improved subsurface drainage decreased the inflow rates by maintaining a lower water table and providing more storage in the soil profile. More water would infiltrate into the soil and leave the field as subsurface drainage. The higher subsurface drainage rate are evident in the higher flowrates late in the falling limb of the hydrograph.

The HC level of canal control increased outflow rates in most events, but the increases were less than 1100 m^3/hr. The HC control level would increase surface runoff by maintaining a higher water table elevation thus decreasing soil storage. The falling limb of the hydrographs for the large events fall abruptly to low flowrates indicating lower subsurface drainage rates for the HC cases.

The FLDNSTRM model in its present form does not consider lateral seepage losses from the ditches and canals. If lateral seepage was considered, storage in the canals would become available between events as the water seeps from the canals. This available storage would likely decrease peak outflow rates particularly for smaller events.

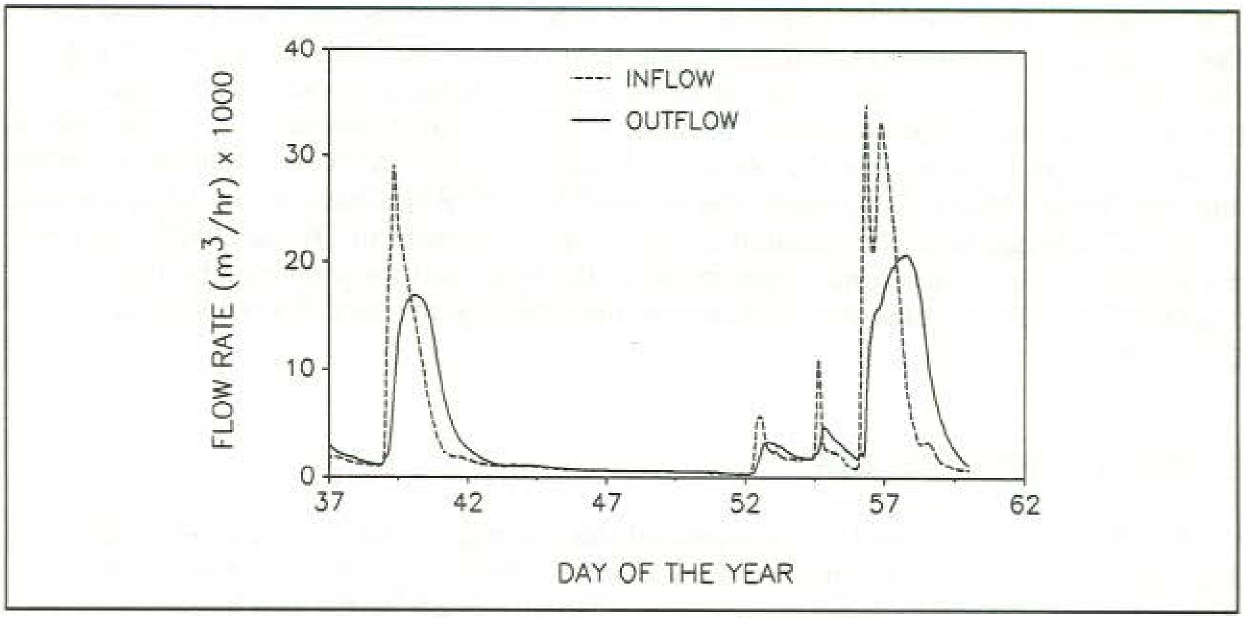

Figure 7. Inflow and outflow hydrograph for 2126 ha watershed section as predicted by FLDNSTRM. The UI field design and the NC canal control level were used on the agricultural fields in the watershed. The simulation was conducted during a wet period in the winter (February, 1961).

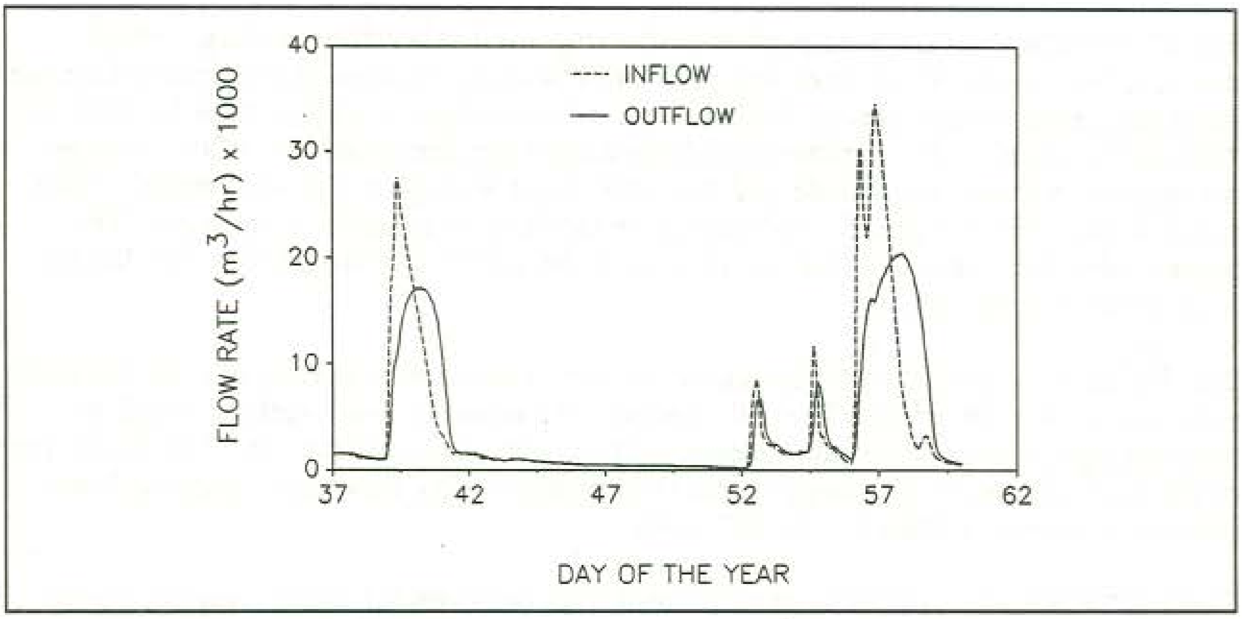

Figure 8. Inflow and outflow hydrograph for 2126 ha watershed section as predicted by FLDNSTRM. The UI field design and the HC canal control level were used on the agricultural fields in the watershed. The simulation was conducted during a wet period in the winter (February, 1961).

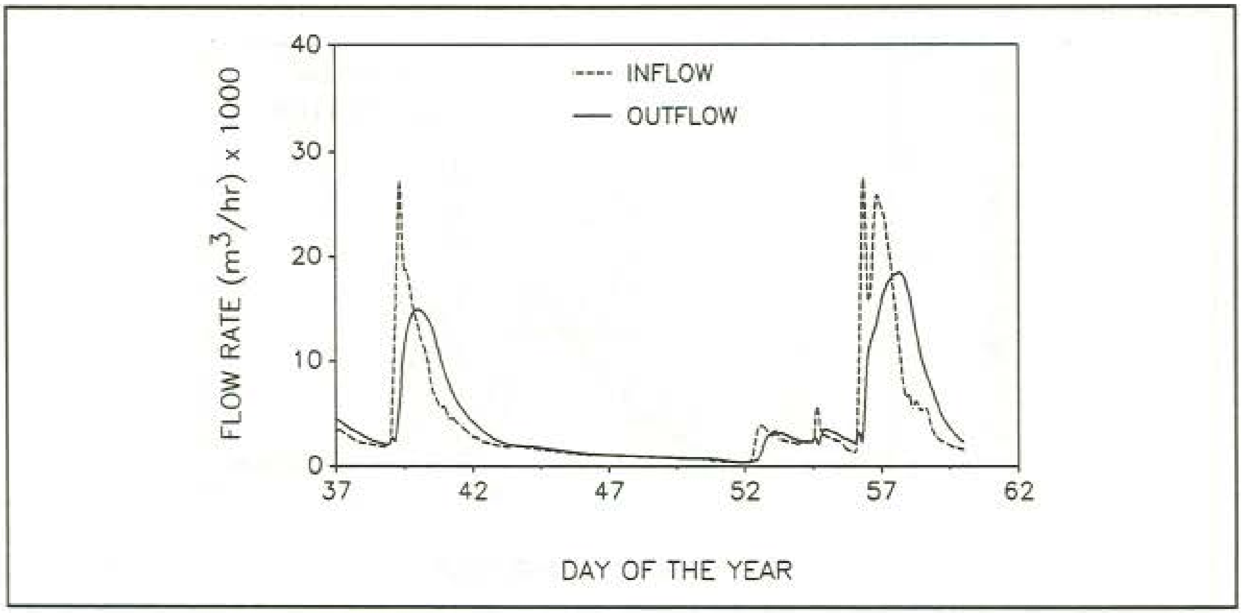

Figure 9. Inflow and outflow hydrograph for 2126 ha watershed section as predicted by FLDNSTRM. The II field design and the NC canal control level were used on the agricultural fields in the watershed. The simulation was conducted during a wet period in the winter (February, 1961).

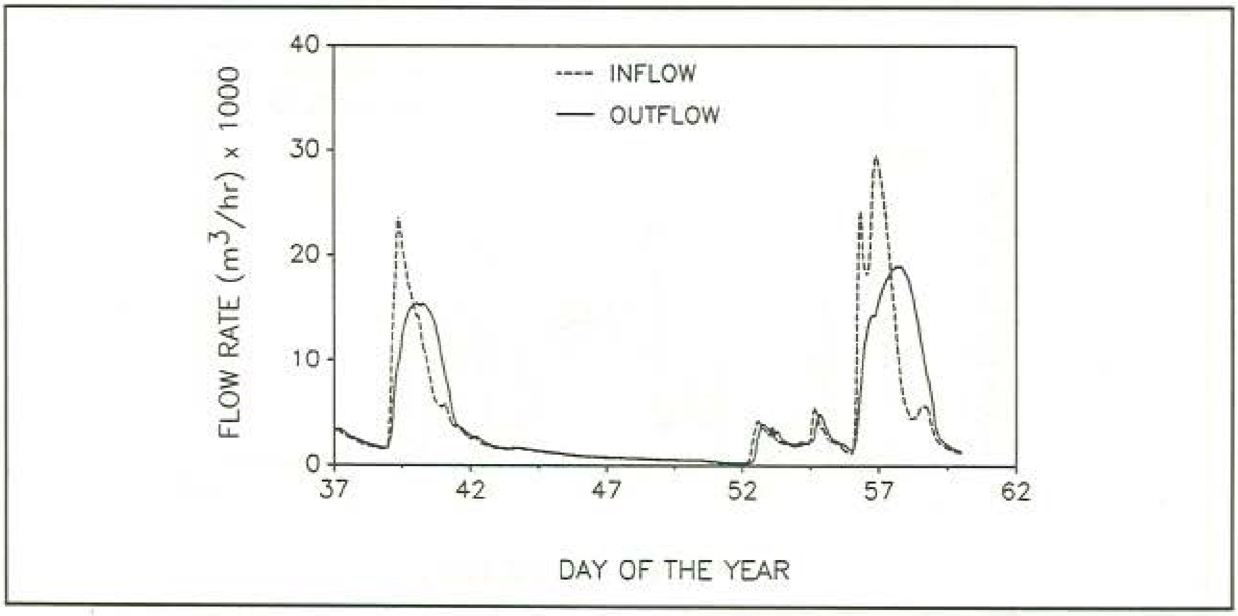

Figure 10. Inflow and outflow hydrograph for 2126 ha watershed section as predicted by FLDNSTRM. The II field design and the HC canal control level were used on the agricultural fields in the watershed. The simulation was conducted during a wet period in the winter (February, 1961).

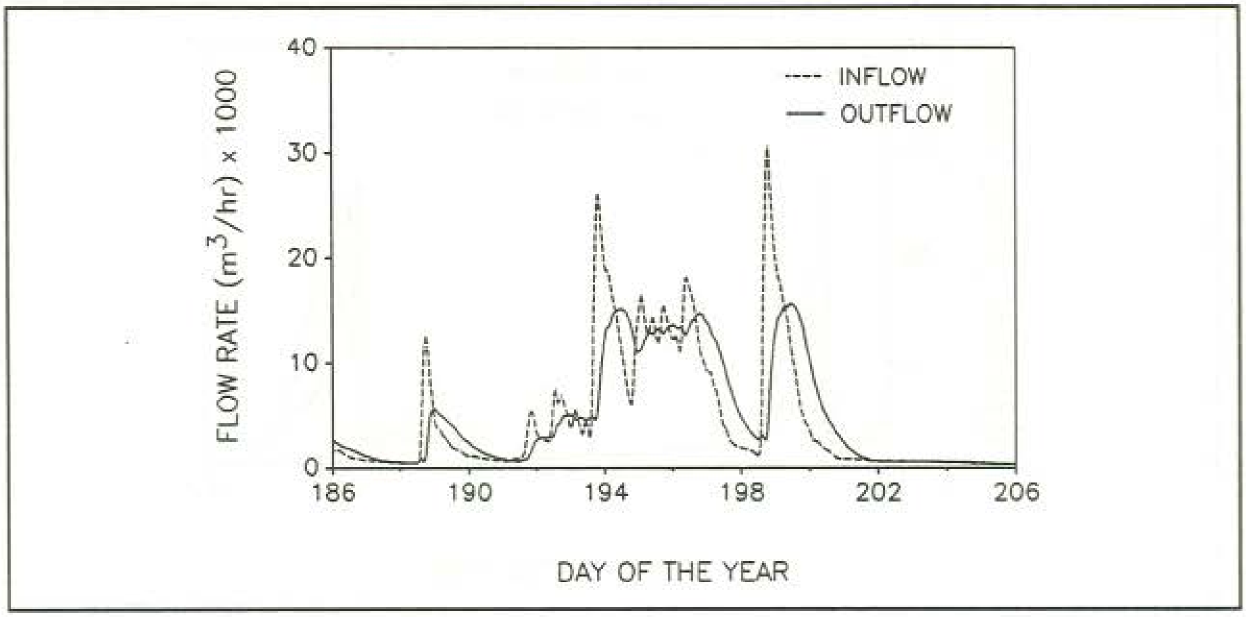

Figure 11. Inflow and outflow hydrograph for 2126 ha watershed section as predicted by FLDNSTRM. The UI field design and the NC canal control level were used on the agricultural fields in the watershed. The simulation was conducted during a wet period in the summer (July, 1959).

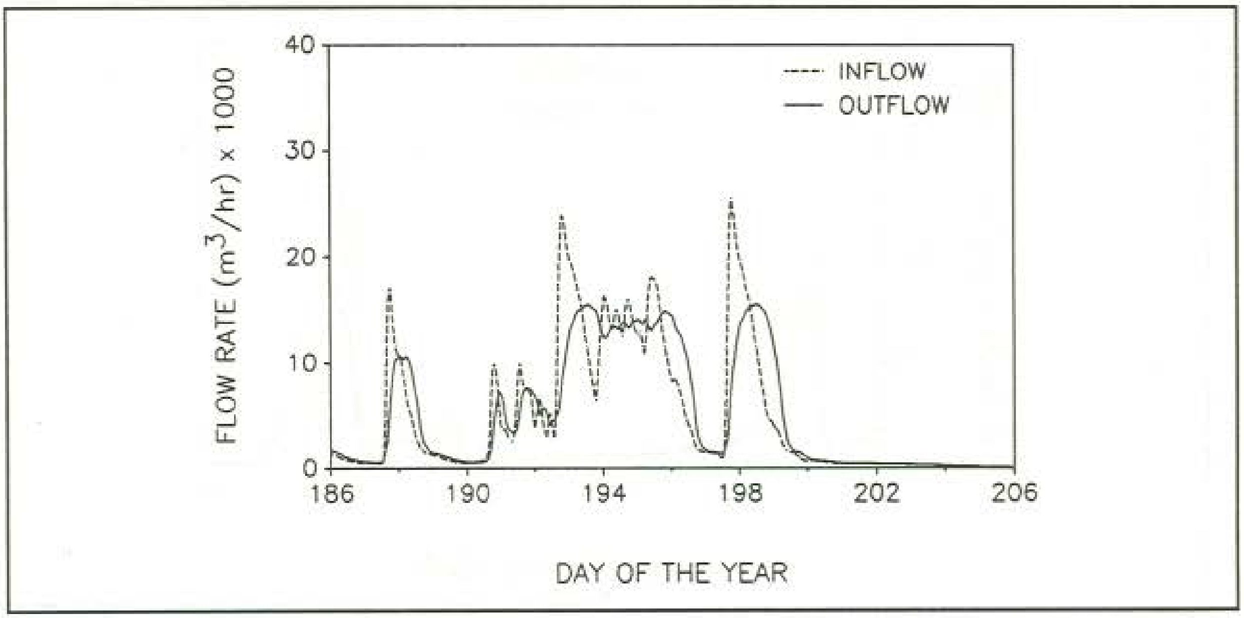

Figure 12. Inflow and outflow hydrograph for 2126 ha watershed section as predicted by FLDNSTRM. The UI field design and the HC canal control level were used on the agricultural fields in the watershed. The simulation was conducted during a wet period in the summer (July, 1959).

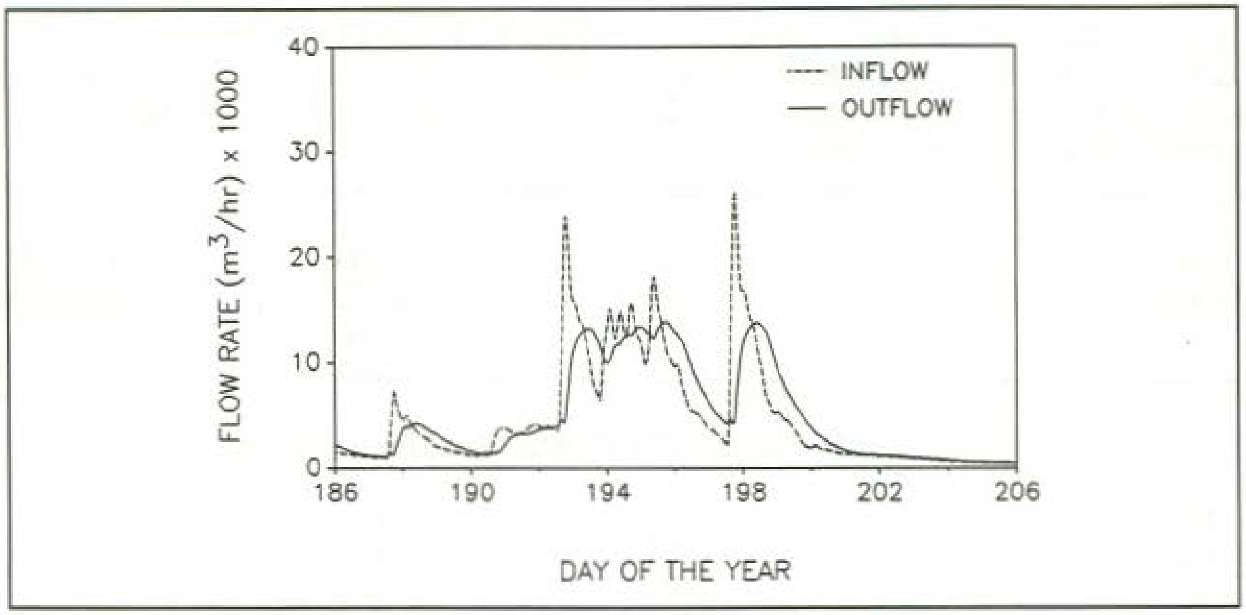

Figure 13. Inflow and outflow hydrograph for 2126 ha watershed section as predicted by FLDNSTRM. The II field design and the NC canal control level were used on the agricultural fields in the watershed. The simulation was conducted during a wet period in the summer (July, 1959).

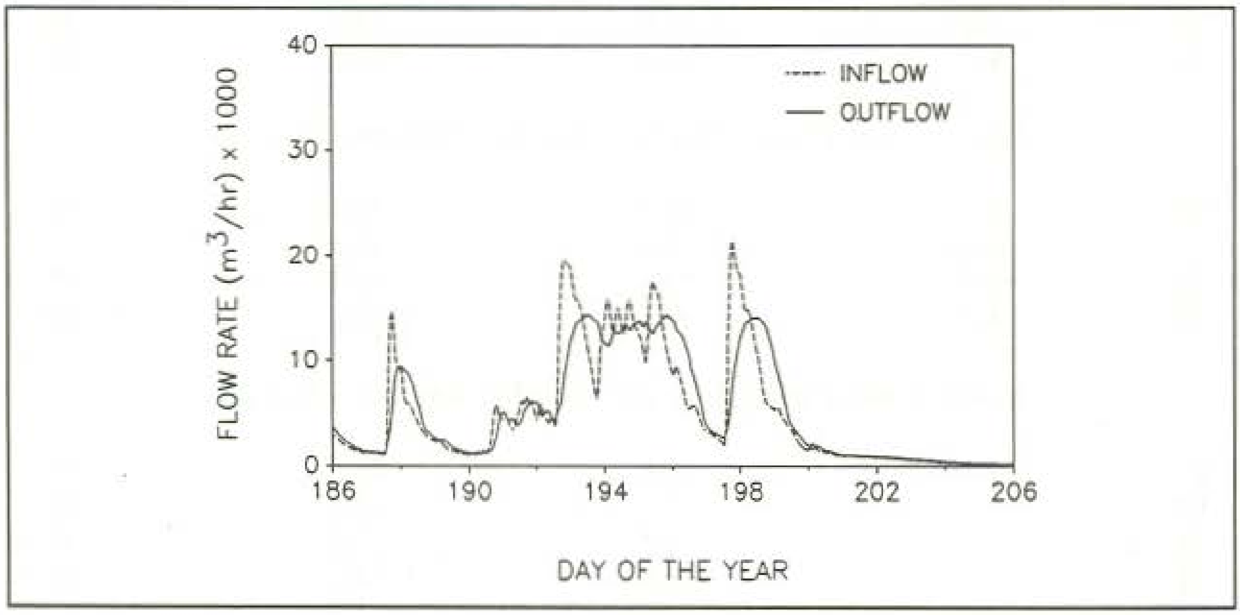

Figure 14. Inflow and outflow hydrograph for 2126 ha watershed section as predicted by FLDNSTRM. The II field design and the HC canal control level were used on the agricultural fields in the watershed. The simulation was conducted during a wet period in the summer (July, 1959).

Table 20. Summary of peak outflow rates predicted by FLDNSTRM simulations of a 2126 ha section of the watershed. Inflow and outflow rates are compared for the two largest runoff events during the winter wet period (February, 1961) and during the summer wet period (July, 1959).

Field Design	Canal Control	Peak Inflow m^3/hr x 1000	Peak Outflow m^3/hr x 1000	Percent Reduction
	Winter Wet Period, Day 39, Rainfall Amount - 38.6 mm			
UI	NC	29.1	17.0	42
UI	HC	27.5	17.1	38
II	NC	27.2	14.9	45
II	HC	23.6	15.5	34
	Winter Wet Period, Day 57, Rainfall Amount - 59.7 mm			
UI	NC	33.2	20.7	38
UI	HC	34.6	20.5	41
II	NC	25.8	18.5	28
II	HC	29.6	19.0	36
	Summer Wet Period, Day 193, Rainfall Amount - 28.2 mm			
UI	NC	26.0	15.1	42
UI	HC	23.9	15.4	36
II	NC	23.9	13.2	45
II	HC	19.5	14.3	27
	Summer Wet Period, Day 198, Rainfall Amount - 32.5 mm			
UI	NC	30.6	15.6	49
UI	HC	25.5	15.5	39
II	NC	26.2	13.8	47
II	HC	21.6	14.1	35

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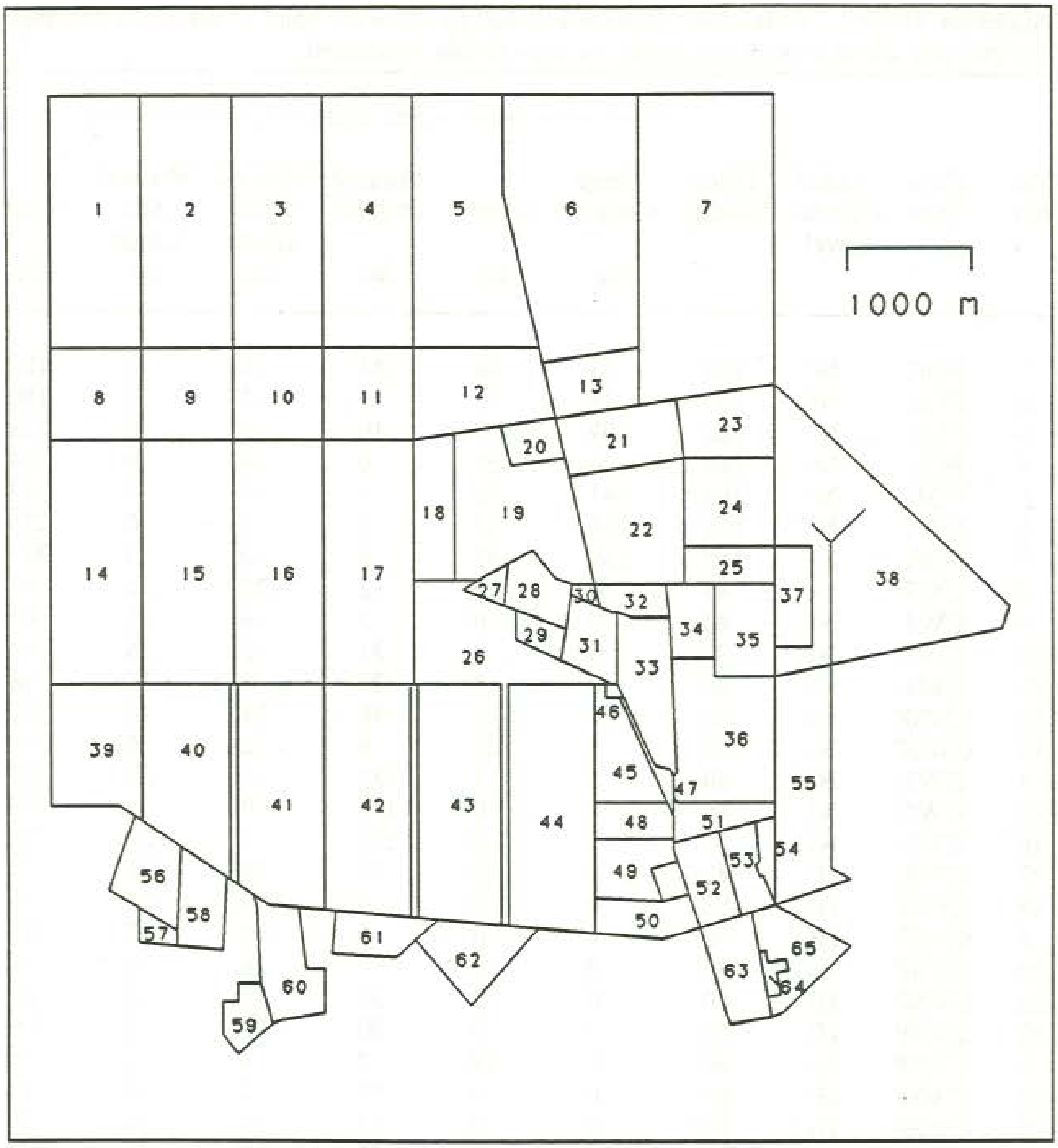

Appendix Figure 1. The watershed divided into fields for determining areas of cropping, field drainage, and canal control practices. The field numbers correspond to those in Appendix Table 1.

Appendix Table 1. Tabulation of areas covered by different soils, crops, field drainage designs, and canal control structures on the existing watershed.

Fld No	Crop Type	Canal Control Level	Ditch Spacing	Deep Organic	Organic	Mineral Organic	Mineral Sandy Loam	Mineral Silt Loam	Total
				-----	-----	Soil Type	-----	-----	
				ha	ha	ha	ha	ha	ha
1	FOR	NC	160	35	96	44	4	0	180
2	FOR	NC	160	78	73	29	0	0	180
3	FOR	NC	160	109	58	10	0	0	178
4	FOR	NC	160	124	50	0	0	0	174
5	FOR	NC	160	141	72	0	0	0	213
6	FOR	NC	160	168	87	0	0	0	255
7	FOR	NC	160	239	83	0	0	0	321
8	CWS	NC	80	0	10	12	22	21	64
9	CWS	NC	80	0	0	3	0	63	66
10	CWS	NC	80	0	9	31	0	26	66
11	CWS	NC	80	0	7	27	0	34	68
12	CWSP	NC	80	0	11	48	24	10	93
13	CWSP	NC	80	4	29	9	2	0	44
14	CWS	NC	80	0	2	134	4	32	172
15	CWS	NC	80	0	0	149	9	15	173
16	CWS	NC	80	0	0	110	8	52	170
17	CWS	HC	80	0	0	74	16	81	172
18	CWSP	HC	80	0	0	0	14	35	49
19	CWSP	HC	80	0	0	0	103	13	117
20	CWSP	HC	80	0	0	0	14	0	14
21	CWSP	HC	80	0	0	34	17	0	51
22	CWSP	HC	80	0	0	30	77	0	106
23	CWSP	HC	80	21	19	9	0	0	49
24	CWSP	HC	80	0	0	75	2	0	77
25	CWSP	HC	80	0	0	15	13	0	28
26	CWSP	HC	80	0	0	52	15	36	103
27	CWSP	NC	160	0	0	0	8	0	8
28	CWSP	HC	80	0	0	0	11	14	25
29	CWSP	NC	100	0	0	0	0	10	10
30	CWSP	HC	80	0	0	0	0	4	4
31	CWSP	NC	80	0	0	0	0	28	28
32	CWSP	HC	80	0	0	0	12	9	20
33	CWSP	HC	80	0	0	0	40	17	57

Table # continued

34	CWSP	HC	80	0	0	3	8	13	24
35	CWSP	HC	100	0	0	0	6	40	47
36	CWSP	NC	80	0	0	17	25	66	108
37	CWSP	HC	100	0	0	19	0	12	31
38	FOR	NC	160	38	156	92	0	6	293
39	CWS	NC	80	0	0	16	0	71	87
40	CWS	NC	80	0	5	111	0	0	117
41	CWSP	HC	80	0	50	95	0	0	145
42	CWSP	HC	80	0	51	106	0	0	156
43	CWSP	HC	80	0	53	113	0	5	170
44	CWSP	HC	80	0	6	130	0	25	161
45	CWSP	HC	80	0	0	8	19	20	47
46	CWSP	HC	80	0	0	0	0	2	2
47	CWSP	HC	80	0	0	0	6	0	6
48	CWSP	HC	80	0	0	19	0	6	26
49	CWSP	HC	80	0	6	21	0	11	37
50	CWSP	HC	80	0	0	6	0	26	32
51	FOR	NC	160	0	0	13	9	0	22
52	CWSP	HC	100	0	0	3	10	20	34
53	CWSP	NC	100	0	0	3	6	20	30
54	FOR	NC	160	0	0	10	4	0	15
55	FOR	NC	160	0	59	19	13	8	99
56	CWS	NC	80	0	0	21	13	7	41
57	CWS	NC	80	0	0	0	2	4	6
58	CWS	NC	80	0	0	11	19	4	34
59	CWS	HC	80	0	0	0	22	0	22
60	CWS	HC	80	0	0	0	37	9	45
61	CWSP	NC	100	0	0	1	6	17	24
62	CWSP	NC	80	0	0	0	0	38	38
63	CWSP	HC	100	0	0	0	0	41	41
64	CWSP	HC	80	0	0	0	0	9	9
65	FOR	NC	160	0	0	0	2	43	45
TOTAL AREA				959	990	1734	624	1022	5329
TOTAL % OF WATERSHED:				18	19	33	12	19	

Crop Type
CWS: Corn - Wheat - Soybean
CWSP: Corn - Wheat - Soybean - Potato
FOR: Forest

Canal Control
NC: No control
HC: High level of control