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IMPACTS OF AGRICULTURAL DRAINAGE WELL CLOSURE ON CROP PRODUCTION: A WATERSHED CASE STUDY[1]

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ABSTRACT: Much of north-central Iowa is characterized by flat topography, shallow depressions, and poor natural surface drainage. Land drainage systems comprising of tile drains and agricultural drainage wells (ADWs) are used as outlets for subsurface drainage of cropland under corn and soybean production. Studies have shown that these drainage systems, mainly the ADWs, are potential routes for agricultural chemicals to underground aquifers. To protect the region's vital groundwater resource, researchers are evaluating alternative outlets ranging from complete closure of existing ADWs (and creation of wetlands) to continued use of ADWs and chemical management in a comprehensive policy framework.

This paper presents the results of a study designed to provide government jurisdictions, farmers, and land managers information for assessing the impact of closing ADWs on crop production. The study couples a geographic information systems database for a 471-hectare watershed in Humboldt County, Iowa, with a groundwater flow model (MODFLOW) and an empirical crop yield loss model to predict long-term effects of complete closure of ADWs on crop production. The cropland areas inundated and the relative crop yield loss due to ADW closure are determined as a function of long-term climatic data. The results indicate that elimination of drainage outlets in the watershed could result in ponding of low-lying areas and poorly drained soils, making them unsuitable for crop production. Such wetness also decreases the efficiency of production in the no-ponding areas by isolating fields, and the crop yield loss can be reduced by an annual average of about 18 percent.

(KEY TERMS: wetlands; hydrology; agricultural drainage well; geographic information systems; groundwater; modeling.)

INTRODUCTION

In parts of north-central Iowa, a unique hydrologic condition exists where poorly drained soils overlay shallow limestone formations (Musterman ***et al.,*** 1981; Kanwar ***et al.,*** 1983). Ponding on these soils severely limits farm operations. Farmers in the region recognized that the least-cost drainage system was to drill wells into the limestone aquifer to remove water from prairie potholes. In so doing, highly productive cropland areas were created out of the poorly drained soils. This land drainage system was found very efficient and effective (Soil Conservation Service, 1983; Wheaton, 1977). The value of the land increased, and the economy of the region was strongly impacted by drainage systems that were developed around subsurface drain tiles and agricultural drainage wells (ADWs).

Agricultural drainage wells are constructed as subsurface disposal systems to accelerate the drainage of agricultural runoff and subsurface flow. As shown in Figure 1a, an ADW consists of a buried collection of cistern, one or more drainage tiles entering the cistern, and a drilled or dug cased well (Baker and Austin, 1984; Glanville, 1985). ADWs receive field drainage via drainage tiles from precipitation, snowmelt, flood waters, irrigation return flow, and surface runoff from cropland, feedlots, and dairies. Normally ADWs are found in areas characterized by soil with low permeability, shallow water tables, and insufficient natural drainage. In Iowa, there are between 460 and 920 registered ADWs with the majority concentrated in the north-central portion of the state (Figure 1b). These land drainage systems are very efficient – they facilitate corn and soybean row-crop production, control flooding, and improve the

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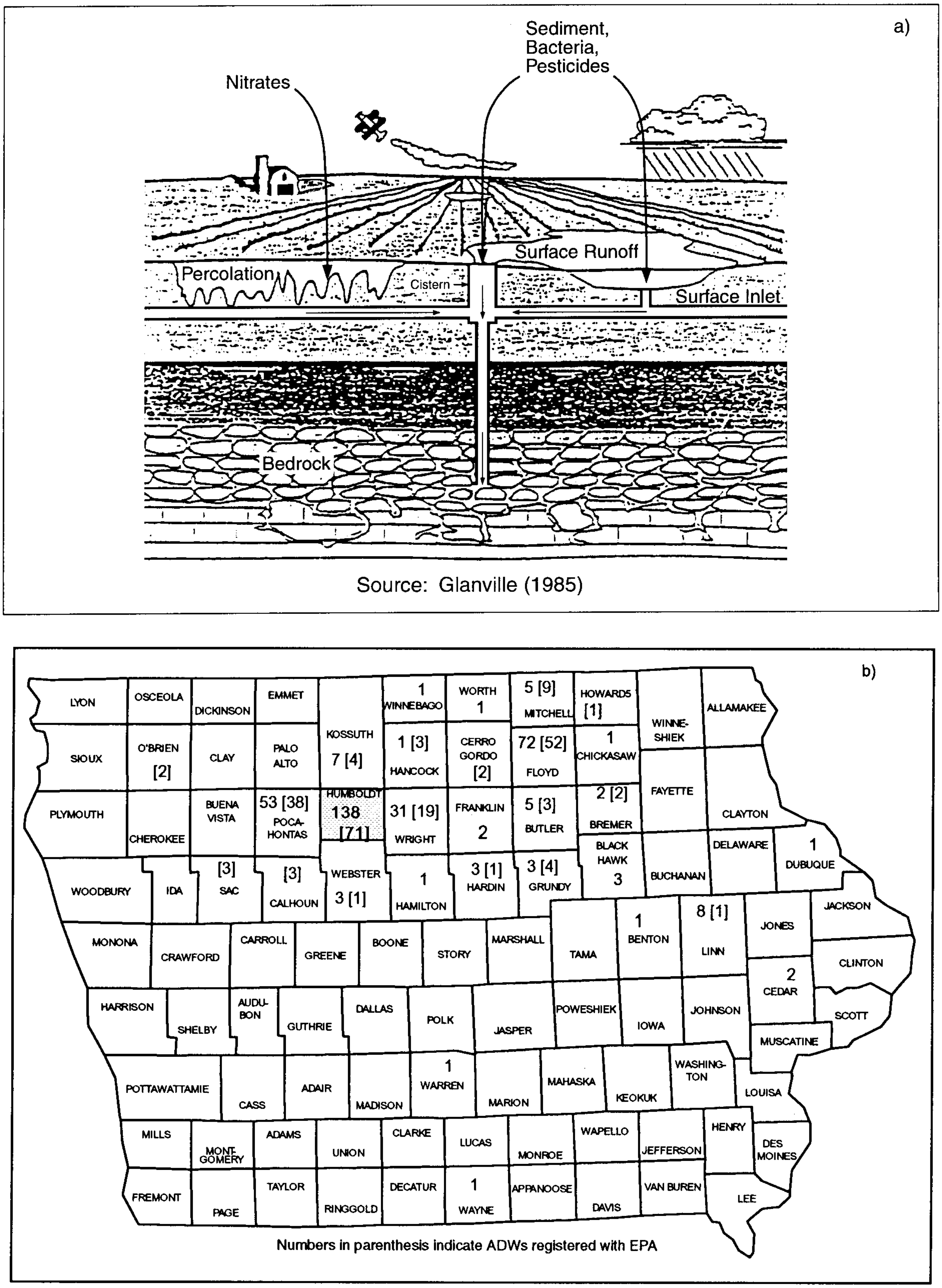


Figure 1. Agricultural Drainage Wells: (a) Cross-Sectional View of ADW Draining Agricultural Land; (b) Number of Registered ADWs in Iowa.

region's economy through enhanced crop profitability (Schult et al., 1981; DeBoer and Ritter, 1970; Kanwar et al., 1986). However, concerns have been raised about the potential movement of agricultural chemicals into the aquifers used as a major source of community water supply (Baker et al., 1985, Seitz *et al.*, 1977, Ludwig *et al.*, 1990).

In addressing the water quality problems associated with the use of ADWs, several alternative drainage initiatives, ranging from the continued use of ADWs (but with chemical management) to complete closure of the drainage systems (and converting the drained cropland to wetlands) have been proposed. Each initiative has associated economic and environmental implications. In Iowa, the land drainage initiatives are regulated by both the Underground Injection Control Program administered by the U.S. Environmental Protection Agency and Section 159.29(3) of the 1987 Iowa Ground Water Protection Act (IGWPA). Under IGWPA, the Iowa Department of Agriculture and Land Stewardship, according to Baker *et al.* (1992) is required to

> (a) "initiate a pilot demonstration and research project designed to identify the environmental, economic, and social problems presented by continued use or closure of ADWs and to monitor possible contamination caused by agricultural land management practices and agricultural chemical use relative to ADWs;
>
> (b) develop alternative management practices based upon the findings from the demonstration projects to reduce the infiltration of synthetic organic compounds into the ground water through ADWs; and
>
> (c) examine alternatives and the cost of implementation of alternatives to the use of ADWs and examine the legal, technical and hydrologic constraints for integrating alternative drainage systems into the existing drainage districts."

The elimination of drainage systems from the cropland without providing alternative and efficient water outlets could interfere with routine farming activities in the region. The total cropland areas inundated are dependent upon water-level fluctuations, which in turn are determined by site characteristics including climate, soils, land use and land cover, and topography.

The various issues and problems related to agricultural land drainage in the region require a framework for evaluating the impact of ADW closure on crop production. Such a framework can include long-term monitoring of water table fluctuations and crop yield losses. However, given the costs involved in long-term monitoring of farm fields, computer simulation modeling provides the only effective analytical framework. Models can be used to (a) assess past hydrologic conditions and their effects on cropland drainage, (b) analyze the effectiveness and impact of alternative cropland drainage options, and (c) assess the cumulative impacts (environmental and socio-economic) of alternative drainage strategies on crop production. The purpose of this study was to evaluate the effects of ADW closure on crop production in a watershed located in north-central Iowa. A simulation modeling approach based on geographic information system (GIS) was used to delineate cropland areas inundated by the closure of ADWs and the resulting crop yield loss, while taking into account spatially variable landscape characteristics and climate. The GIS was used to generate, manipulate, analyze, and spatially organize disparate data for modeling.

METHODS AND MATERIALS

Description of Study Area

The study area is a 471-ha agricultural watershed located in Humboldt County, Iowa, approximately 140 km north of Des Moines. The watershed, which is representative of north-central Iowa watersheds, is characterized by a relatively flat topography and is included in the region's organized drainage districts. Soils in the watershed are dominated by Wisconsin-age glacial till-derived soil associations developed under native vegetation of prairie grass. Predominant soils belong to the Clarion-Nicollet-Webster association with slopes ranging from nearly level to about 9 percent (Richlen *et al.*, 1961). Soils in this association occupy approximately 72 percent of the watershed area, and range from the poorly drained Webster soils to the well drained Clarion soils (Table 1). The remaining 28 percent of the watershed soils are either poorly to very poorly drained or well drained, as in the case of Storden soils. The majority of the ADWs are concentrated in watershed areas with somewhat poorly to very poorly drained soils.

Humboldt County lies within the area covered by the Des Moines Lobe of the late Wisconsin glaciation. The glacier originated in the Keewatin ice mass, west of the Hudson Bay in Canada. The topography is formed by a variety of depositional and erosional features in the glacial drift, which generally is 15 to 30 m thick except in end moraines and buried bedrock valleys. The major bedrock aquifers in the watershed consist of the Mississippian aquifer that ranges in thickness from 60 to 105 m and is composed primarily of limestone and dolomite of the Osage and Kinderhook series (Musterman *et al.*, 1981). The relatively

TABLE 1. Characteristics of the Humboldt Watershed Soils

Soil Name	**Soil Map Symbol**	**Area (ha)**	**Percent of Watershed**	**Drainage Class**	**Slope Class (percent)**
Canisteo Clay Loam	507	21.2	4.5	Poor	o-2
Clarion Loam	138B	139.9	29.7	Well	2-5
Clarion Loam	138B2	3.3	0.70	Well	2-5
Clarion Loam	138C2	8.9	1.90	Well	5-9
Delft Clay Loam	707	5.7	1.2	Poor	o-2
Garmore Loam	338	17.4	3.7	Moderately Well	o-2
Harps Clay Loam	95	21.2	4.5	Poor	o-2
Nicollet Loam	55	145.5	30.9	Somewhat Poor	1-3
Okoboji Mock	90	7.1	1.5	Very Poor	o-1
Okoboji Silt Clay Loam'	6	15.1	3.2	Very Poor	o-1
Rolfe Silt Loam	274	23.1	4.9	Very Poor	o-1
Springvalle Silt Clay	1743	7.5	1.6	Poor	o-2
Storden Loam	62C2	4.2	0.9	Well	5-9
Wacousta Silty Clay Loam	506	7.5	1.6	Very Poor	o-1
Webster Clay Loam	107	43.4	9.2	Poor	o-2
Total		471	100.0		

shallow depth of the Mississippian aquifer coupled with its high porosity makes it a prime candidate for ADWs.

Land use in the watershed is primarily row-cropping, which is typical of the Corn Belt. Corn and soybeans are the major crops, although oats, sorghum, and hay are also grown. The climate of Humboldt County is continental and typical of the mid-latitude region. Polar air masses that dominate the winter move across the county from northwest to southeast. During summer, maritime air masses from south and southwest are the primary weather makers. Under these climatic regimes, the long-term total annual rainfall and snowfall are 76 and 81 cm, respectively. Summer temperatures average 24°C with an average daily maximum temperature of 28"C, while the lowest winter temperature on record is –41°C. The average duration of the growing season is 148 days (May 15 to October 10), and the average growing season temperature and precipitation is 18°C and 56 cm, respectively (Richlen et al., 1961).

Watershed Hydrologic Processes

Analysis of the watershed hydrologic processes, the total cropland area inundated, and the crop yield loss necessitated two stages of investigation. The first stage involved identification of the pertinent hydrologic processes and simulation of the water table levels within the landscape. The second stage involved determination of the watershed area inundated (or flooded) due to closure of ADWs, the frequency of flooding, and the relative crop yield loss from stresses induced by the flooding. Figure 2 illustrates the modeling framework and the important hydrologic processes considered in the study, which include precipitation, evapotranspiration (ET), and surface and groundwater flow.

Precipitation is the primary input into a watershed ecosystem. It exhibits extreme spatial and temporal variations over relatively small areas during a given storm event. While the spatial variability in precipitation is usually recognized, the feasibility to accurately monitor rainfall at the landscape level is often a physical and economic limitation. Thus, we assumed that a single rain gage, located in close proximity to the watershed, would sufficiently provide the required precipitation data.

ET is a major route by which water leaves an agroecosystem, and often accounts for a large portion of the water loss. ET is a direct function of the microclimate (e.g., relative humidity, temperature, wind speed and wind direction, solar radiation), soil moisture status, and the density and type of vegetation (Swank and Douglass, 1974).

Knowledge of water inputs and losses at the soil atmosphere interface provides only limited hydrologic information. The surface (overland flow) and subsurface (interflow or base flow) components are more important hydrologic considerations. However, the contribution from overland flow in areas characterized by flat topography is usually small and can be neglected. On the basis of measured surface hydrologic data in the study area (Table 2), Baker and Austin (1984) reported that only 4 percent of the total precipitation goes out as surface runoff to potholes under continuous corn or corn-soybean production. Leach *et*

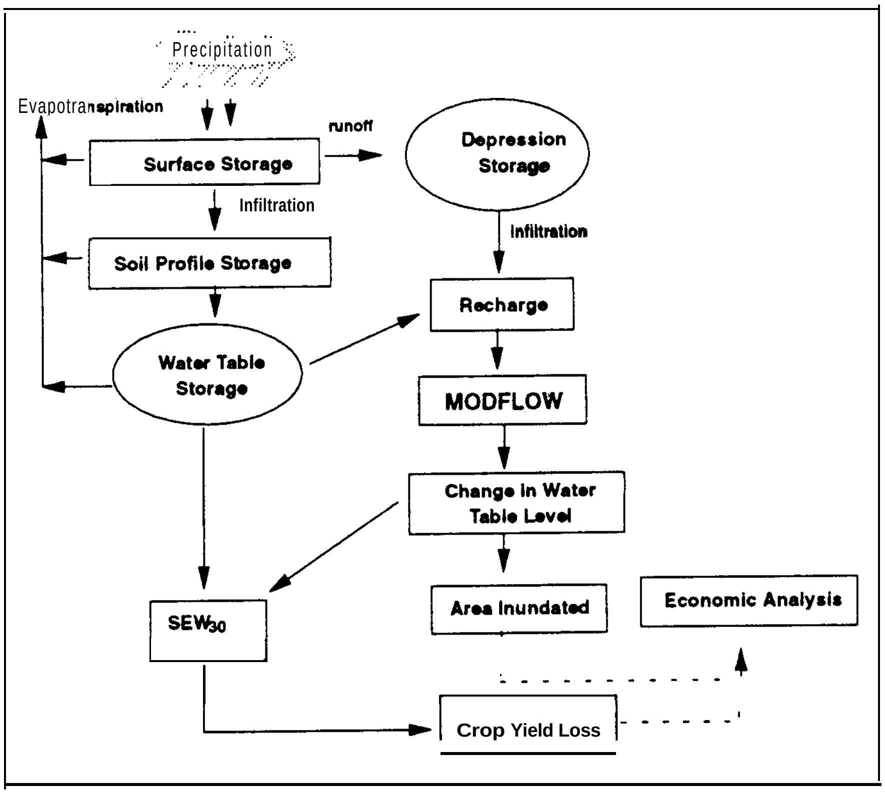


Figure 2. Conceptual Hydrologic Regime in the Undulated Terrain of the Agricultural Watershed Subject to the Closure of ADW(s).

TABLE 2. Observed Monthly Average Precipitation, Surface Runoff and Actual Evapotranspiration for the Study Area Under Continuous Corn Cropping (Baker and Austin, 1984).

Month	Precipitation (mm)	Runoff (mm)	Evapotranspiration (mm)
January	17.90	0.00 [0]	0.40
February	23.30	0.00 [0]	0.00
March	50.50	0.23 [0.5]	29.90
April	75.00	0.74 [0.99]	54.85
May	93.50	0.86 [0.92]	63.65
June	113.70	5.76 [5.1]	74.40
July	110.40	13.40 [12.1]	113.30
August	92.20	5.35 [5.8]	162.00
September	88.50	2.30 [2.6]	93.90
October	51.40	0.00 [0]	36.40
November	33.20	0.00 [0]	21.10
December	22.80	0.00 [0]	0.70
Annual **Total**	772.40	28.64 (3.7%)	650.65

(Note: Values in parenthesis denote percent of precipitation.)

al. **(1972)** and Parker (1974) found a small amount of (slow) overland flow because of the gentle slope and dense vegetation in their wetland studies in south Florida. It was assumed, on these bases, that the surface flow component would contribute a negligibly small percent of the surface water storage (ponding) because of the absence of well-defined surface channelization and flat topography of the study area.

Thus, the surface water component was handled as part of unconfined groundwater flow. This simplification of the watershed surface hydrology facilitated the use of a groundwater flow model for the study.

Modeling Groundwater Flow

From the standpoint of developing a hydrologic flow model for examining the impacts of ADW closure, the watershed offers several modeling challenges. An adequately-scaled and physically-based model must first accommodate surface and subsurface hydrologic phenomena, flat topography, and the absence of a well-defined stream network. Also, landscape-related phenomena, including spatially variable land characteristics (e.g., soils, land use, etc.) and the temporal variability of major sources and sinks, must be addressed by the model. These issues are relevant to the use of the model as a landscape planning and management tool. Several existing hydrologic and groundwater flow models were evaluated for use in this study (Trescott *et al.*, 1976; Prickett, 1979; Arnold *et al., 1990).* The MODFLOW model (McDonald and Harbaugh, 1988) was selected and modified for this study.

MODFLOW is a modular three-dimensional finite difference model developed for analyzing both steady-state and transient groundwater flow. The physical system is idealized in the model as uniform or variable block-centered grids, each having homogenous properties. Development of the groundwater flow equation, in finite difference form, is based on the conservation of mass principle. The Darcy equation is used to predict the hydraulic head at each node within the discretized domain. In MODFLOW, both single and multilayered systems can be simulated as confined, unconfined, or a combination of confined and unconfined aquifer. The model can also simulate a heterogeneous or homogeneous, isotropic or anisotropic, and stratified aquifer. A detailed description of the model components can be found in McDonald and Harbaugh (1988).

As a brief overview, the MODFLOW model consists of the main program and several independent but linked subroutines or modules. Each module has been verified and validated against observed data (Scott Bair and Roadcap,l992). The model requires input data for some or all of the following major segments or "packages* depending on the aquifer, boundary conditions, and sources and sinks. These packages include: basic package; block-centered flow package; matrix solving package; ET package; river, well, and drain package; general head-type boundary package; and output control package (Walton, 1992). Output parameters from MODFLOW model include cell-by-cell head and drawdown information for each stress period (number of days of simulation) and time step. The grid discretization of the physical flow domain, including the cell-by-cell encoding of input and output data, facilitates the linkage of the model with a raster GIS.

To analyze the shallow water table fluctuations, we limited the number of layers to one. Note that flow and storage processes in unsaturated and saturated zones are not handled separately in MODFLOW since we considered one unconfined aquifer. Daily values of ET for each grid cell were calculated using a linear relationship based on a threshold water table depth for maximum ET, the actual water table depth, and an extinction depth which depends upon the rooting depth at different periods of the growing season. Thus, ET was calculated by linearly interpolating between maximum ET (for threshold water table depth) and minimum ET (for extinction water table depth) for the actual water table depth. Since surface runoff was considered to be an insignificant part of the watershed water balance (Table 2), daily values of rainfall minus ET were considered as the recharge to the shallow water table. A third-type (Cauchy or mixed) boundary condition was specified to limit the inward/outward flux across the watershed boundary. To achieve this, we assumed a series of cells of very low conductive material along the watershed boundary. The flux across this type of boundary is dependent on the difference between user-specified potential head values on one side of the boundary and the model-calculated potential head values on the other side.

Modeling Crop Yield Loss

Although crop yield in agroecosystems can be influenced by excess as well as lack of water, due to the nature of our investigation, the analysis was limited to the impact of excess water on yield. Crop yield loss, due to excess water, depends upon the fluctuation in the water table level above a reference level. The effects of excess water, which produces undue stresses on crops, were evaluated by using an empirical equation representing the stress-day index (SEW_{30}) (a quantitative measure of the degree and duration of the water table within 30 cm of the soil surface) for corn crop in Nicollet soil (Ahmad and Kanwar, 1989; Kanwar *et al.*, 1988). The stress-day index or "sum of excess water" concept can be computed from the equation originally proposed by Sieben (1964):

$$SEW_{30} = \sum_{i=1}^{n} (30 - x_i) \qquad (1)$$

where x_i (in cm) denotes the daily water table level below the ground surface (up to 30 cm) on day i, and n is the total number of days in a growing season (taken as 148 days). The constant 30 represents the threshold depth (30 cm) below the ground surface. The stress-day index (cumulative SEW_{30} for the whole growing season) was related to the relative crop yield (RY) through the following empirical relationship proposed by Kanwar et *al.* (1988):

$$RY = 0.91 - 0.00031\ SEW_{30} \qquad (2)$$

The study through which the above relationship was obtained assumed no crop yield loss when the water table level is at or below the 30 cm threshold depth. To accurately evaluate RY when SEW_{30} approaches zero, two regression equations that fit the original data of Kanwar et *al.* (1988) were developed. Thus the empirical relationships between SEW_{30} and RY used for the study are:

$$RY = 0.91 - 0.00031\ SEW_{30} \qquad SEW_{30} > 200 \qquad (3)$$

$$RY = 1 - 0.00076\ SEW_{30} \qquad SEW_{30} \leq 200 \qquad (4)$$

Using the above relationships, the relative crop yield loss (RL) was obtained for the growing season as:

$$RL = 1 - RY \qquad (5)$$

Although Equations (3) and (4) were developed originally for corn, for lack of similar field data on soybeans, we have used the same relationship for soybeans also under the present study condition. Furthermore, according to available farm records, the prevailing cropping patterns for the study area are continuous corn and corn/soybeans. Thus, for a given growing season, a given field within the study area will be under corn. This supports our use of the same empirical relationships between SEW_{30} and relative crop yield for corn and soybeans for the watershed in Humboldt County, Iowa.

Geographic Information System (GIS)

As indicated earlier, a GIS was used to spatially organize disparate data for both the MODFLOW model and the empirical crop yield loss model. GIS is an integrated system of computer hardware and software designed to manage, analyze, and display spatial data (Burrough, 1986). The advantage of the GIS lies in its ability to relate disparate data sets through a common denominator which is the spatial location. GIS also provides the tools for managing the modeling process, organizing model input parameters, analyzing the model results, and displaying both model input and output at user-defined scale.

In this study, ARC/INFO (ESRI, 1992) was used to generate, analyze, and organize spatial data for the MODFLOW model. Two classes of spatial data – locational (x, y coordinates) and attribute (or feature) characteristics (z-coordinates) – were organized in ARC/INFO. In the ARC/INFO system, information is stored as areas (POLYGONS), lines (ARCS), or points by using relational database tables that link attributes to features and store the information in hierarchical computer files called coverages. Each coverage, which constitutes a given hierarchical level of information, is organized within "workspaces" (a directory structure that facilitates interfacing between the ARC coverage and the INFO database). The recent addition of ArcGRID to ARC/INFO provides analytical functions and operators for raster-based modeling. Such a capability is important in environmental modeling, in general, and the present study in particular.

Integration of MODFLOW and GIS

The integration of physical models with GIS can be accomplished at several levels, depending on the nature of both the model and problem to be solved. Each level has associated procedures and limitations, some of which have been discussed earlier (Burrough, 1989; Tim and Jolly, 1994). Briefly, the first level of integration is an ad hoc approach where the GIS is used as a pre- and post-processor to simply generate model input data and display output. The second level involves efforts to integrate GIS with models into a tightly coupled but independent system, where the GIS and models interact through user interfaces. This level of integration, sometimes referred to as partial linkage, involves the development of special-purpose computer programs that provide both functionality and interface for the exchange of disparate data. The third level of integration, and probably the most sophisticated level, involves development of seamless links between model and GIS. Rather than loosely coupling the two technologies, the model is reprogrammed within the GIS. Access to the coupled system is through user interfaces, which also facilitate human-computer interaction.

In this study, a combination of the first and second levels of integration was adopted. Briefly, the procedure for linking MODFLOW and ARC/INFO GIS for analysis of watershed water table level involved the following basic steps:

1. Acquisition and assembly of data layers and coverages for soil, land use and land cover, topography, climate, and other groundwater-related information including transmissivity, hydraulic conductivity, long-term average seasonal water table elevation, and elevation of the base of unconfined aquifer.
2. The use of ARC/INFO GRID to generate and spatially organize data at the grid cell level for the MODFLOW block-centered scheme. The study adopted uniform grid cells of 1.4 ha resolution.
3. Preprocessing of the model input data and development of protocols and special purpose computer programs.
4. Interfacing of MODFLOW to the GIS by using the computer programs and protocols developed in Step 3.
5. MODFLOW model computation of hydraulic heads at each block-centered node.
6. Postprocessing of model output data and transfer of the data to ARC/INFO GIS for further analysis and display.

In the procedures outlined above, both the MODFLOW model and the GIS operate independently and are linked through shared data files and interfaces. We are currently examining an efficient approach to linking GIS and MODFLOW.

Data Acquisition and Modeling

The acquisition and assembly of data to support MODFLOW modeling and the empirical crop yield loss model involve three principal disparate data types: spatial data, temporal data, and program execution control data. For the spatial data, primary map layers were created for land use and land cover, watershed boundary, soils, climate, and topography (elevation, slope, aspect, etc.). From these basic data layers, derived coverages at the grid cell level were obtained. Figure 3 shows some of the primary and derived data layers which include land cover or land use, soil permeability, soil drainage class, and depth to seasonal water table.

Hydraulic conductivity and storativity values for MODFLOW cells were based on the measured values from a nearby site of same soil types and aquifer characteristics. A total of 20 years (1972-1991) of daily precipitation data were used in the analysis. Daily values of ET, during the growing season, were calculated by combining the techniques in MODFLOW with the relationships proposed by Shaw ***et al.*** (1972). The maximum ET rate for each day and grid cell was specified on the basis of open pan evaporation multiplied by a pan coefficient for the predominant land use type in each cell. The maximum ET surface required in the MODFLOW model was specified for each grid cell on the basis of surface elevation and an imposed threshold water table level of 30 cm below ground surface, based on the SEW30 concept. An extinction depth was imposed to limit ET extraction when the water table level fell below the 2 m depth. It was assumed that the maximum ET surface and the extinction depth remain constant throughout the crop growing season. The daily rainfall amount and maximum ET rates were assembled at the grid cell level using ARC/INFO. The corresponding attribute data in the INFO database were converted to a format compatible with the MODFLOW model, using special-purpose computer programs developed for the study. For each year, ET, recharge, and block centered flow were simulated by MODFLOW for a total of 214 stress periods (April 1 to October 31 including growing season between May 15 and October 10). The resulting water table levels (referenced to the ground surface) were used in modeling relative crop yield loss. The computed water table levels and relative crop yield loss for each grid cell were analyzed and displayed using ArcGRID, a module of ARC/INFO software.

RESULTS AND DISCUSSION

Transient simulation was carried out by using the MODFLOW model for each year between April 1 to October 31 (214 days or stress periods) for 20 consecutive years (1972-1991). For 20 years considered, Figure 4 shows the distribution of total rainfall amount from April 1 to October 31 (214 days). The major output from the model consisted of water table head in each grid cell. Although we used four time steps for each stress period (one day), the primary interest was on the water table head values at the end of each stress period. Note that during the simulation, initial water level for day i was always taken to be equal to the final water table level for day i-l. For analysis purposes, the simulated water table head values were grouped into three different categories: above ground surface, between ground surface and 30 cm below ground surface, and greater than 30 cm below ground surface.

Figures 5, 6, and 7 show the results of model predictions for a normal year (1972 with total precipitation of 76.5 cm between April 1 and October 31), a wet

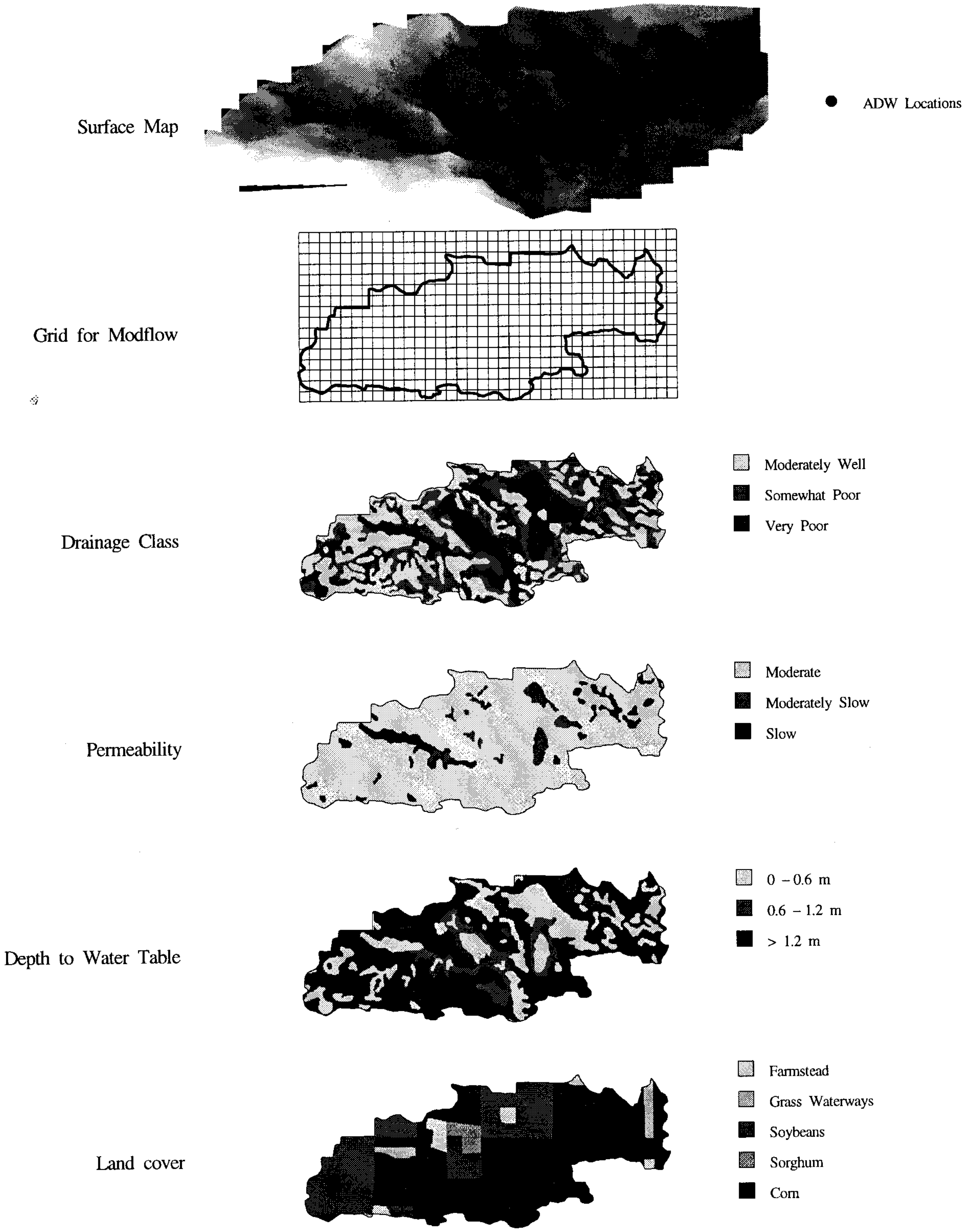


Figure 3. Some Basic Coverages Generated for Modeling Water Table Fluctuation and Crop Yield Loss in the Humboldt Watershed.

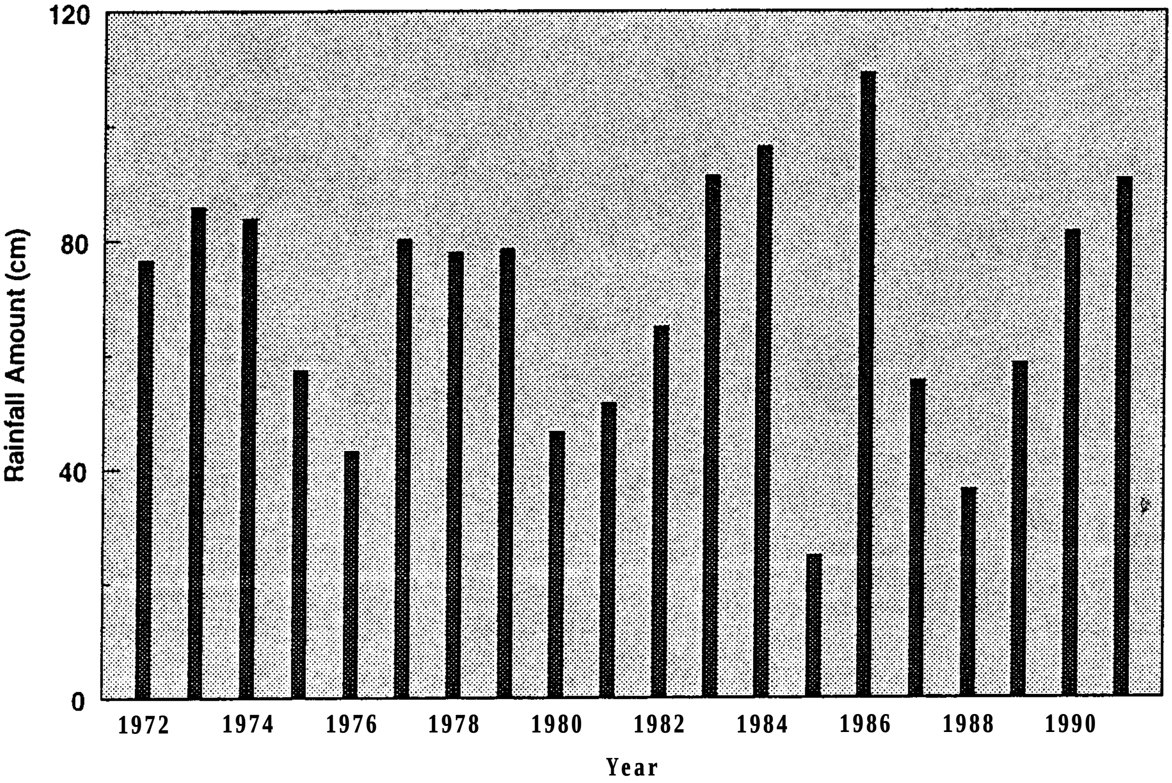
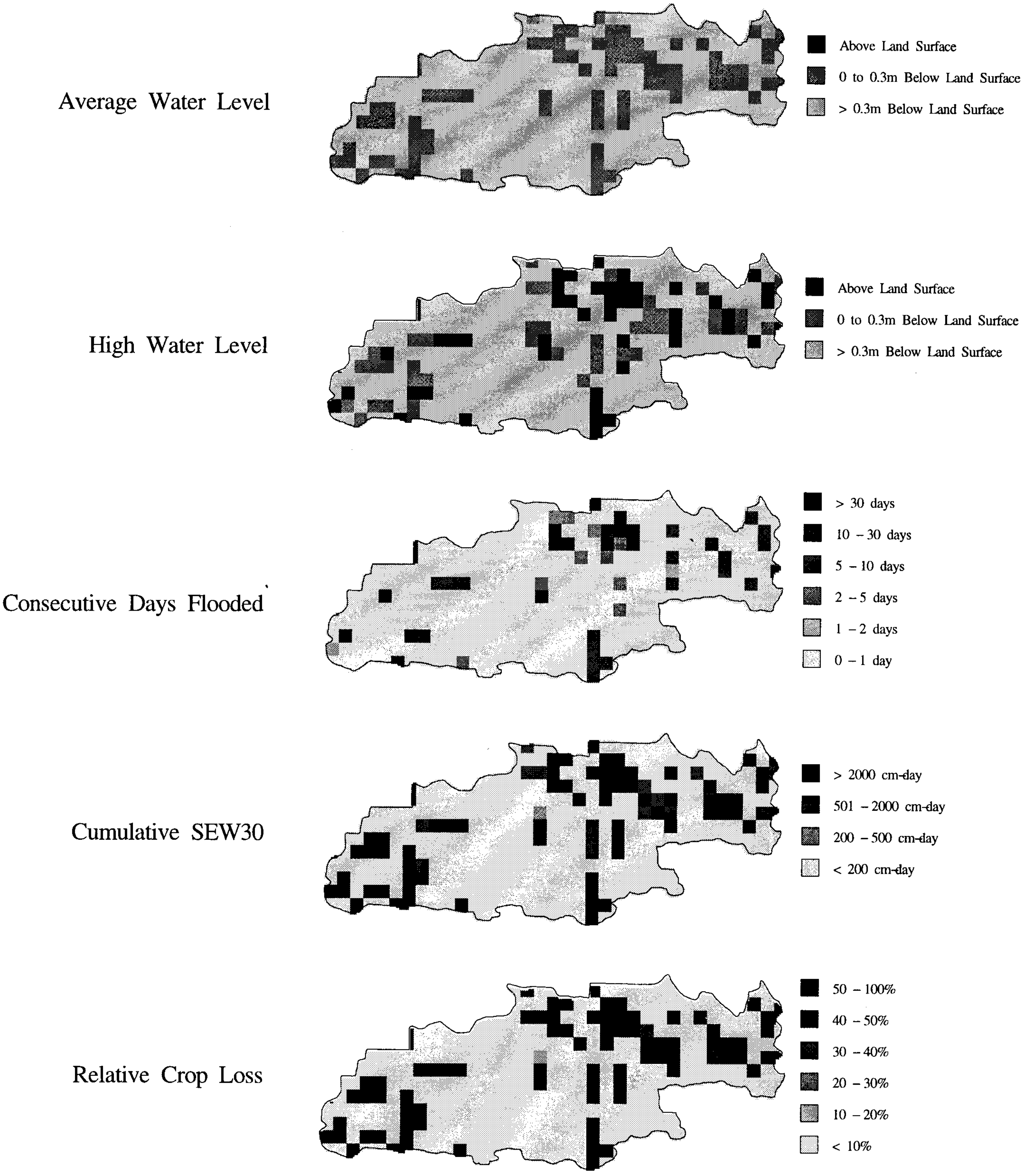


Figure 4. Total Rainfall Amount in the Humboldt Watershed for the Simulation Period (April 1 to October 31) for 1972 to 1991.

year (1986 with total precipitation of 109.2 cm between April 1 and October 31), and a dry year (1985 with total precipitation of 24.6 cm between April 1 and October 31), respectively. Each map shows the (a) average water level in each cell over the crop growing season, (b) maximum (high) water level in each cell over the crop growing season, (c) number of consecutive days (out of 214 days) in which a grid cell remains ponded during the simulation period, (d) cumulative SEW_{30} over the crop growing period, and (e) relative crop yield loss. These results indicate that the degree of ponding as well as the susceptibility of each grid cell to flooding during the crop growing season depends on rainfall recharge (intensity and seasonal pattern), ET, and initial water table conditions.

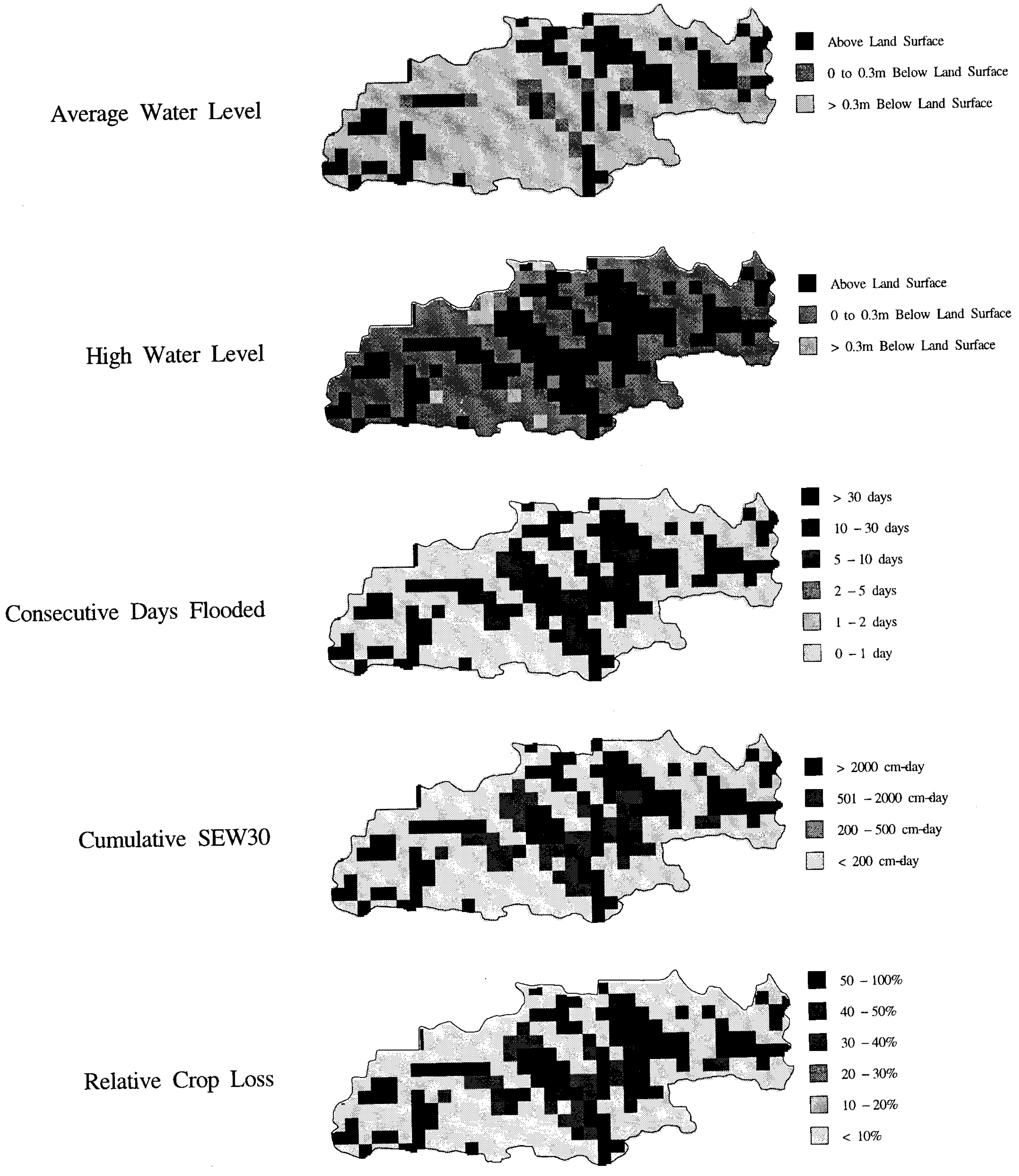
To elucidate the influence of the seasonal rainfall pattern on the water table elevation, two years, 1990 and 1989 with early spring rainfall and late fall rainfall, respectively, were examined. The results for the two years indicated a large difference in the water table elevation during the crop growing season. Further examination of the daily rainfall pattern for these years provides the reasons for the difference. The rainfall pattern showed that 1990 (total rainfall of 81.5 cm) was a relatively wet year, whereas 1989 (total rainfall of 58.4 cm) was a relatively dry year. Moreover, the heavy rainfall in early spring before crop maturity raised the water table in 1990. As the crop reaches maturity and full canopy, the water table drops gradually with more ET extraction. On the other hand, the low rainfall during the early part of crop growing season in 1989 lowered the water level due to ET extraction and gradually increased thereafter because of increased rainfall late in the growing season. However, the water table level could not reach the ground surface in 1989, resulting in a no-ponding condition.

Figure 8 shows the total area of the watershed under different durations of continuous ponding or inundation. This graph is important from the standpoint that total crop loss can be expected if an area is ponded for more than two consecutive days (especially early in the growing season). Interestingly, for most of the years, a large portion of the watershed was not flooded (0 day ponding). However, for some of the ponded and nonponded watershed areas, farming operations would be severely impacted because of the formation of islands of potentially productive cropland. In general, the inundated areas of the watershed correlate very well with topography



1972 (Normal Rainfall Year)

Figure 5. Grid-Cell Level Display of Simulation Results for Year with Normal Rainfall (1972).



1986 (Wettest Rainfall Year)

Figure 6. Grid-Cell Level Display of Simulation Results for the Wettest Rainfall Year (1986).

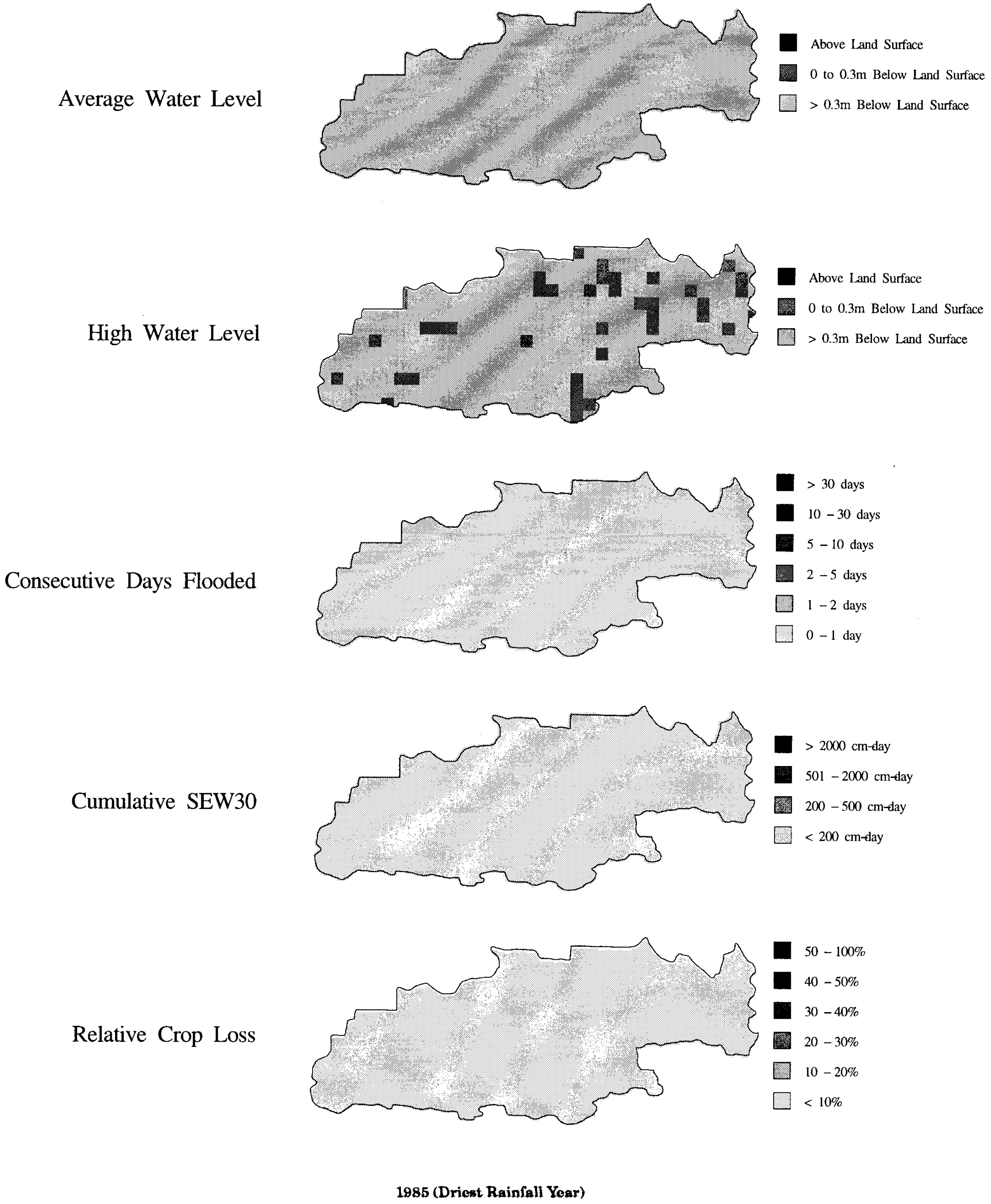


Figure 7. Grid-Cell Level Display of Simulation Results for the Driest Rainfall Year (1985).

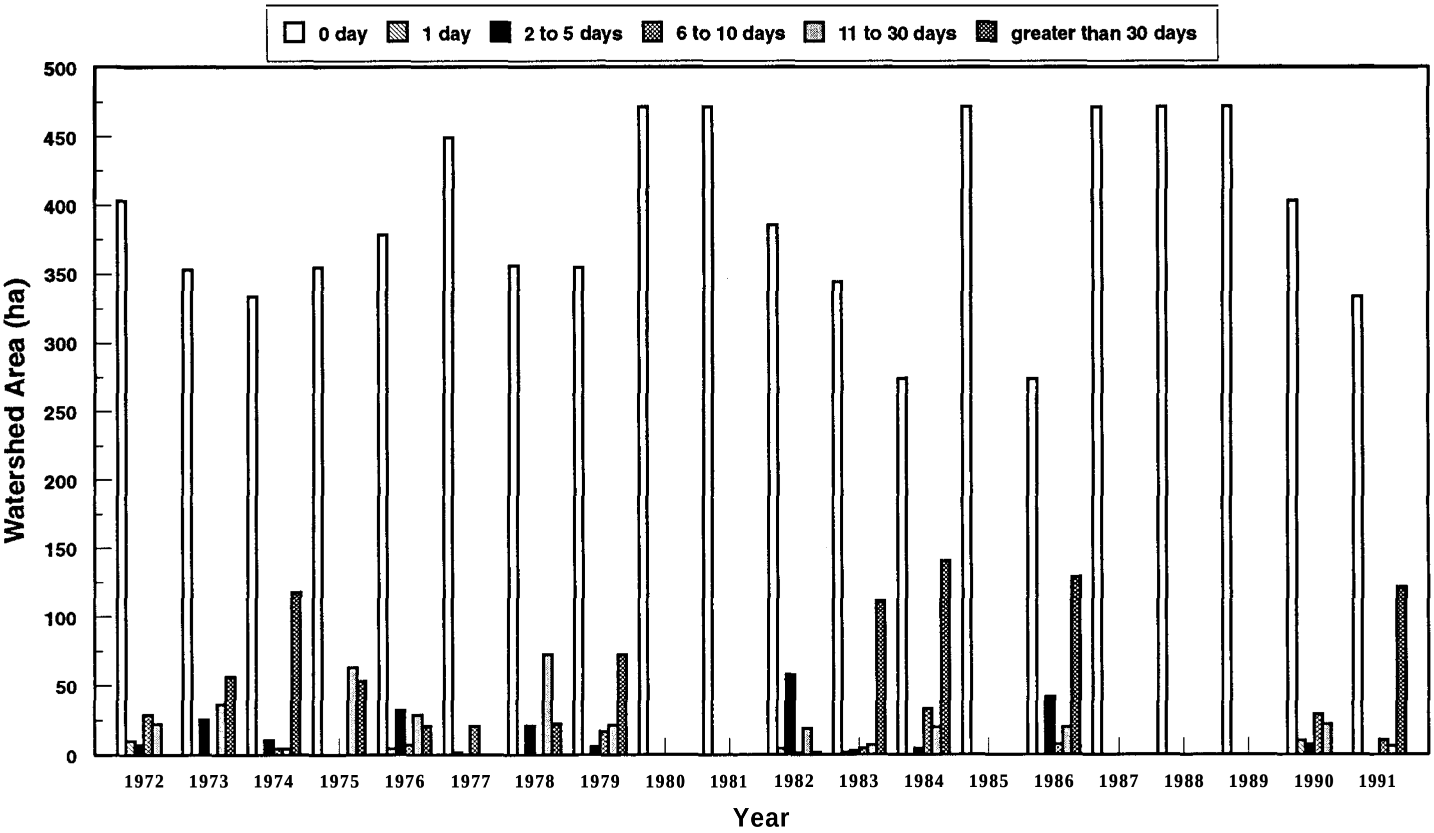


Figure 8. Watershed Area Under Different Number of Consecutive Days of Flooding from1972 to 1991.

Figure 9 shows the watershed area under each category of maximum water table level for the simulation period (214 days). For each year, three categories of water table elevation were analyzed: (a) above ground surface, (b) from ground surface to 30 cm below ground surface (0 to - 30 cm), and (c) greater than 30 cm below ground surface (below -30 cm). Recall that the crop yield loss, due to excess water-induced stress, was calculated on the basis of a 30 cm threshold depth. An examination of Figure 9 reveals that, for a large proportion of the watershed, the water table was below or at the 30 cm depth. However, for most years, some areas of the watershed were inundated and consequently one can expect either partial or total crop yield loss in those areas.

The cumulative SEW_{30} expressed in cm-day was calculated for each year using Equation (1). The values obtained for a normal year (1972), a wet year (1986), and a dry year (1985) are shown in Figures 5, 6, and 7, respectively. On the basis of the cumulative SEW_{30} values for each grid cell and simulation year, the relative crop yield loss was computed by using the empirical relationships described earlier. Figure 10 shows the yearly variations in relative crop yield loss averaged over the 471-ha watershed. In Table 3, the percentages of total land areas subjected to different crop yield loss levels are also presented. The annual average relative crop yield loss (over the entire watershed) varied from a low value of zero in 1985 to a maximum of 35.4 percent in 1984. The long-term mean relative crop yield loss over the 20 years was 17.5 percent (Figure 10). In addition, of the 20 years simulated in this study, 13 years had relative crop yield loss exceeding the mean value of 17.5 percent. Therefore, in probability terms, it can be inferred that a 60 percent chance exists that the relative yield loss of corn and soybean crops in the watershed will equal or exceed 17.5 percent. Figure 10 (inset) also shows the cumulative frequency plot of the simulated relative crop yield loss levels. In addition to supporting the above conclusion, the cumulative frequency plot can provide the framework for decision-making relative to the impacts of ADW closure on crop production.

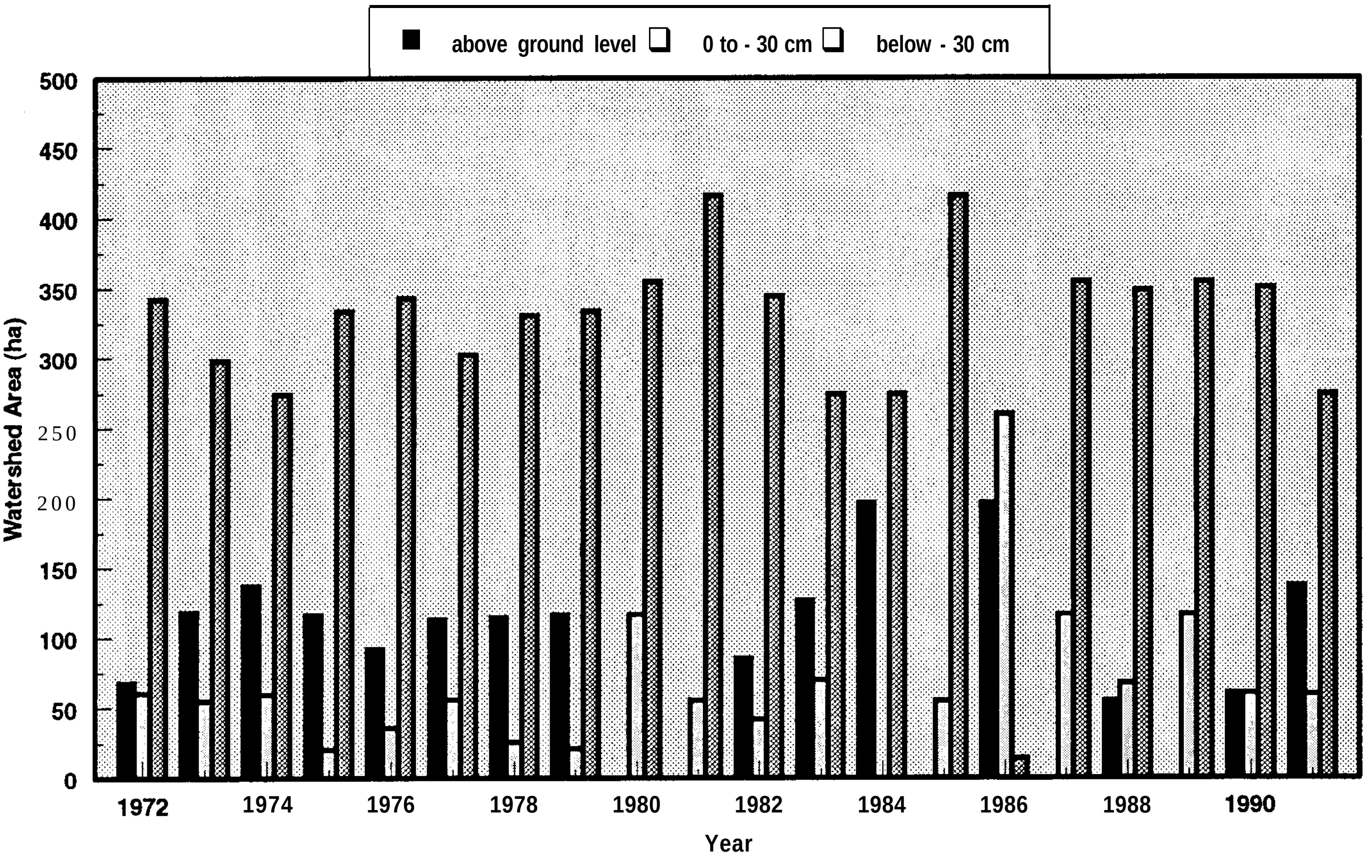


Figure 9. Watershed Area Under Different Maximum Water Table Levels from 1972 to 1991.

SUMMARY

The hydrologic analysis of impact of ADW closure in the Humboldt County, Iowa, watershed was presented. Simulation results indicate that closure of ADWs could lead to ponding of low-lying areas and total or partial crop failure for most years. In addition, there is a potential for decrease in the efficiency of crop production in the no-ponding areas. This is due, in part, to a situation in which small island of productive croplands are intermixed with potholes. Furthermore, there would be a higher probability of flooding in the low-lying areas of the watershed for years with early spring precipitation than for the years with late fall precipitation. The variable degrees of ponding of the watershed depend largely upon landscape characteristics including elevation, slope, soil type, and hydraulic properties. The results of the 20-year simulation indicate different probability levels for different levels of crop yield loss due to the closure of the ADWs. For example, there is a 60 percent chance that crop yield loss in the 471-ha watershed could exceed 17.5 percent for any year out of the 20 years considered in the study.

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LITERATURE CITED

Ahmad, N. and R. S. Kanwar, 1989. Crop Susceptibility Factors for Corn and their Effect on Stress-Day Index. Transactions of the ASAE 32:1979-1986.

Arnold, J. G., J. R. Williams, A. D. Nicks, and N. B. Sammons, 1990. SWRRB: A Basin-Scale Simulation Model for Soil and Water Resources Management. Texas A&M University Press, College Station, Texas.

Baker J. L. and T. A. Austin, 1984. Impact of Agricultural Drainage Wells on Groundwater. Completion Report, EPA Grant No. G007228010, U. S. Environmental Protection Agency, Washington, D C.

Baker, J. L., R. S. Kanwar, and T. A. Austin, 1985. Impact of Agricultural Drainage Wells on Groundwater. Journal of Soil and Water Conservation 40:517-520.

Baker, J. L., D. W. Lemke, and S. W. Melvin, 1992. Agricultural Drainage Wells: Research and Demonstration Project. Annual Report, Iowa Department of Agriculture and Land Stewardship, Des Moines, Iowa.

Burrough, P. A., 1986. Principles of Geographical Information Systems for Land Resources Assessment. Clarendon Press, Oxford, United Kingdom.

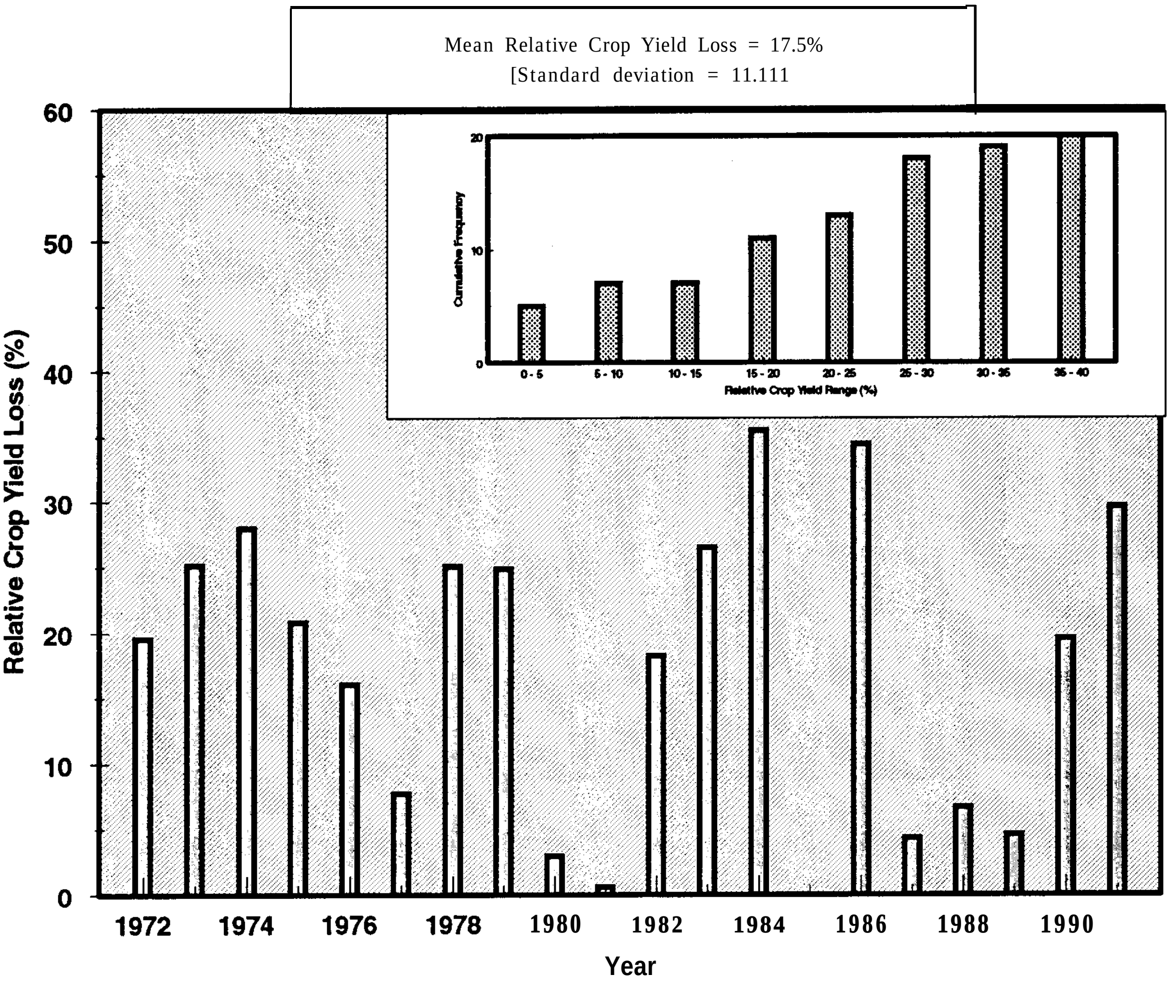

Figure 10. Simulated Average Annual Relative Crop Yield Loss for the Watershed (cumulative frequency plot shown as inset).

TABLE 3. Percent of Watershed Area (ha) Under Different Relative Crop Yield Loss Levels.

	Relative CropYield Loss Level (percent)						
Year	0	l-10	10-20	20-30	30-40	40-50	SO-100
1972	73.1	1.9	0.3	0.0	0.2	1.5	23.0
1973	63.3	7.6	3.2	0.6	0.2	0.3	24.8
1974	58.2	9.8	2.2	0.6	0.0	0.3	28.9
1975	70.9	0.6	2.5	0.9	0.3	0.0	24.8
1976	72.7	2.2	0.3	0.0	0.0	2.1	22.7
1977	71.6	3.4	0.8	11.7	9.0	3.5	0.0
1978	70.2	1.3	2.5	0.9	0.0	0.3	24.8
1979	70.9	0.9	2.2	0.9	0.0	0.3	24.8
1980	75.2	11.3	9.2	4.3	0.0	0.0	0.0
1981	89.6	7.1	3.3	0.0	0.0	0.0	0.0
1982	73.1	1.9	0.3	0.0	0.0	1.5	23.2
1983	58.2	12.0	0.6	0.6	2.2	0.3	26.1
1984	58.2	0.0	0.0	0.0	0.0	3.8	38.0
1985	100.0	0.0	0.0	0.0	0.0	0.0	0.0
1986	2.7	55.5	0.0	0.0	7.0	3.4	31.4
1987	76.4	5.8	9.8	3.7	3.2	1.1	0.0
1988	75.3	0.0	1.5	17.6	5.6	0.0	0.0
1989	76.0	4.9	10.4	4.4	2.5	1.8	0.0
1990	73.0	1.9	0.3	0.0	0.3	1.5	23.0
1991	58.4	3.8	7.2	1.5	0.0	0.0	29.1

Burrough, PA., 1989. Matching Spatial Databases and Quantitative Models in Land Resource Assessment. Soil Use and Management 5:3-8.

DeBoer, D. W. and W. F. Ritter, 1970. Flood Damage to Crops in Depressional Areas of Northcentral Iowa. Transactions of the ASAE 13:547-549.

ESRI, 1992. ARC/INFO User's Manual, Revision 6.1. Environmental Systems Research Institute, Redlands, California.

Glanville, T. D., 1985. Agricultural Drainage Wells in Iowa. Publication Pm. 1201, Iowa State University, Ames, Iowa.

Kanwar, R.S., J. L. Baker, and S. W. Melvin, 1986. Alternatives to the Use of Agricultural Drainage Wells. Water Resources Bulletin 22:573-579.

Kanwar, R. S., J. L. Baker, and S. Mukhtar, 1988. Excessive Soil Water Effects at Various Stages of Development on the Growth andYield of Corn. Transactions of the ASAE. 31:133-141.

Kanwar, R. S., H. P. Johnson, D. L. Schult, T. E. Fenton, and R. D. Hickman, 1983. Drainage Needs and Returns in Northcentral Iowa. Transactions of the ASAE 23:457-464.

Leach, S. D., H. Klein, and E. R. Hampton, 1972. Hydrologic Effects of Water Control and Management of South-Eastern Florida. Florida Bureau of Geology Report Investigation 6O,Tallahassee, Florida.

Ludwig, R. D., R. L. Drake, and D. A. Sternitzke, 1990. Agricultural Drainage Wells: Impact on Groundwater. EPA/600/8-90/054, Office of Research and Development, U. S. Environmental Protection Agency, Washington, D.C.

McDonald, M. G. and A. W. Harbaugh, 1988. A Modular Three-Dimensional Finite Difference Gmundwater Flow Model. Open-File Report 83 - 875, U.S. Geological Survey, Reston,Virginia.

Musterman, J. L., R. A. Fisher, and L. Drake, 1981. Underground Injection Control in Iowa. Pmject Completion Report, Department of Environmental Engineering, University of Iowa,Iowa City, Iowa.

Parker, G. G., 1974. Hydrology of Pre-Drainage System of the Everglades in Southern Florida. In: Environments of South Florida: Present and Past, P. J. Gleason (Editor). Miami Geological Society, Miami, Florida, pp. 18-27.

Prickett, T. A., 1979. Gmundwater Computer Models - State of the Art. Journal of Gmund Water 17:167-173.

Richlen, C. M., S. M. Smith, and D. F. Slusher, 1961. Soil Survey of Humboldt County, Iowa. U.S. Department of Agriculture, Washington, D. C.

Schult, D. L., T. E. Fenton, R. D. Hickman, H. P. Johnson, R. S. Kanwar, and J. F. Timmons, 1981. Present and Potential Agricultural Drainage Situation in the Upper Des Moines River Basin – Ten County Area. Special Report, Departments of Agricultural Engineering, Agronomy, and Economics, Iowa State University, Ames, IA.

Scott Bair, E. and G. S. Roadcap, 1992. Comparison of Flow Models Used to Delineate Capture Zones of Wells: 1. Leaky-Confined Fractured-Carbonate Aquifer. Journal of Ground Water 30:199-211.

Seitz, H. R., A. M. LaSala, and J. A. Moreland, 1977. Effects of Drainage Wells on the Groundwater Quality of the Western Snake Plain Aquifer, Idaho. Open File Report 76-673,U. S. Geological Survey, Reston, Virginia.

Shaw, R. H., R. E. Felch, and E. R. Duncan, 1972. Soil Moisture Available for Plant Growth in Iowa. Special Report No. 70, Iowa Agriculture and Home Economics Experiment Station, Iowa State University, Ames, Iowa.

Sieben, W. H., 1964. Het verban tussen ontwatering en opbrengst bi j de jonge zavelgronden inde Noordoostpolder. van Zee tot Land. 40, Tjeenk Willink V. Zwolle, The Netherlands. (as cited by Wesseling, 1974).

Soil Conservation Service, 1983. Des Moines River Basin Study – Drainage Report. Iowa Department of Agriculture and Land Stewardship, Des Moines, Iowa.

Swank W. T. and J. E. Douglass, 1974. Streamflow Greatly Reduced by Converting Deciduous Hardwood Stands to Pine. Science 185:857-859

Tim, U. S. and R. Jolly, 1994. Evaluating Agricultural Nonpoint Source Pollution Using Integrated Geographic Information Systems and Hydrologic/Water Quality Model. Journal of Environmental Quality 23:25-35.

Trescott, P. C., G. F. Pinder, and S. P. Larson, 1976. Finite Difference Model for Aquifer Simulation in Two-Dimensions with Results of Numerical Experiments. Techniques of Water Resources Investigations. Book 7, Chapter Cl, U.S. Geological Survey, Reston, Virginia.

Walton, W. C., 1992. Gmundwater Modeling Utilities. Lewis Publisher, Ann Arbor, Michigan.

Wheaton, R. Z., 1977. Drainage Needs of the Upper Midwest. Paper No 77-2086, American Society of Agricultural Engineers, St. Joseph, Michigan.