ASSESSMENT OF A MODELING APPROACH FOR THE ESTIMATION OF AGRICULTURAL IRRIGATION WATER USE IN MICHIGAN

By

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ABSTRACT

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Monitoring the use of critical natural resources such as water is an important component of effective resource management. In Michigan, water use data are collected for four sectors; industrial, municipal, electrical power generation plants, and agriculture. In terms of agricultural use, Michigan's water use reporting law requires water users who have the capacity to withdraw over 100,000 gallons per day averaged over any 30-day period during a year to report their water use to the Department of Environmental Quality. From 1993 to 1995, agricultural water use data were collected using a direct reporting method. The survey method was time-consuming and prone to errors and biases in reporting. With the availability of high-resolution precipitation data from the National Weather Service in 1996, a modeling approach based on remotely-sensed weather data, a state-wide soil database, and a soil water balance model was developed. The soil water balance method (SWBM) offers many potential benefits compared to the survey approach; non-invasive data collection, detailed estimates of water use over time and space during the course of a growing season, and a defensible and scientific methodology for estimating water use. The SWBM method is dependent on the availability of spatially and temporally accurate data inputs for soil and weather data. In this research, the potential for the use of simplified soil data inputs was examined using 30 year simulation runs that test for irrigation differences between soil map

units. Precipitation data from the NEXRAD radar system of the National Weather Service was compared to rain gauge observations as a partial validation of the NEXRAD data. Range-dependent biases were found in the NEXRAD data for all three years of the study (1996 – 1998). The correlation of weekly precipitation totals between rain gauge sites was calculated to assess the potential for the use of rain gauge data as a precipitation source for the model. Low spatial correlation was found between rain gauge sites. It was concluded that NEXRAD precipitation data is the best source for detailed estimates at the sub-county level, although a dense rain gauge network could potentially be used for precipitation inputs at a county or watershed level. Large discrepancies between NEXRAD estimated precipitation and ground measured (gauge) precipitation were found for some sites, with NEXRAD precipitation levels generally lower than gauge observations. Further research must be conducted to more accurately assess the reliability and validity of the NEXRAD precipitation estimates. This research describes the successful integration of a biophysical model in a geographic information system (GIS) environment to provide estimates of agricultural water use in an operational setting. With continued advancements in data accuracy and resolution in the future, the SWBM approach is expected to become a valuable tool for the effective monitoring, management, and analysis of water resources.

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LIST OF ABBREVIATIONS

cm.	Centimeters
GIS	Geographic Information System
km.	Kilometers
MDA	Michigan Department of Agriculture
MDEQ	Michigan Department of Environmental Quality
MI	Michigan
NEXRAD	Next Generation Radar
NRCS	Natural Resources Conservation Service
NWS	National Weather Service
STATSGO	State Soil Geographic Data Base
SWBM	Soil Water Balance Model
USDA	United States Department of Agriculture

CHAPTER I

INTRODUCTION

1.1 Introduction

The waters of the Great Lakes Basin are a resource of enormous ecological and economic value. A 1985 study conducted by the International Joint Commission projected significant increases in industrial, power generation, agricultural, public supply, and other water uses in the Basin beyond 2000 (IJC, 1985). During the past twenty years, several proposals have been made to divert Great Lakes water outside of the Great Lakes Basin to alleviate water shortages. The need to meet current and future water needs within the Great Lakes Basin and to oppose unwarranted water diversions to other regions of the country prompted the eight Great Lakes states and two Canadian provinces to adopt the Great Lakes Charter in 1985 (Great Lakes Governors Task Force, 1985). The Charter is a vital cooperative agreement intended to guide the protection and management of the water resources of the Great Lakes Basin. While the Charter serves as a basic framework for preserving Great Lakes waters for use within the basin, long-term and effective Great Lakes protection will require cooperative efforts by the states and provinces to manage this internationally significant resource.

Following formal adoption of the Great Lakes Charter, the seven Great Lakes states passed laws requiring water use reporting. In Michigan, Public Acts 326 and 327 of 1990 were enacted (now Part 327, Great Lakes Preservation, Michigan Natural Resources and Environmental Protection Act, 1994 PA 451, as amended) to authorize the Michigan Water Use Reporting Program. The overall goal of the program is to establish an inventory of major irrigation, industrial, power generation, and public water supply uses of water on a statewide basis. The program helps Michigan establish the strongest possible legal defense against Great Lakes water diversions to other areas of the country, while providing essential water use information for state and regional water resources planning and management.

Michigan's water use reporting law requires water users who have the capacity to withdraw over 100,000 gallons per day averaged over any 30-day period during a year to report their water use to the Department of Environmental Quality (MDEQ). The law includes a special provision for agricultural irrigation reporting that authorizes the Department of Environmental Quality and the Department of Agriculture (MDA) to work jointly with county soil conservation districts to collect water use information. Under the law, farmers are required to report their irrigated crops, acreage, and water sources on an annual basis.

From 1993 to 1995, data for the Water Use Reporting Program were collected using a direct reporting method. At the end of each growing season, a form was sent to irrigators for reporting crops grown, acreage, and water use estimates for the year. MDEQ project staff estimated that about 2/3 of the total irrigated crop acreage in the state was reported using the direct reporting method; many irrigators did not return the form. In addition, the process of data collection and verification was time consuming both from the standpoint of project staff and for irrigators filling out the lengthy form. Biases in water use estimates were also a concern of project administrators. It was felt that irrigators might tend to underestimate water use in anticipation of potential regulatory actions.

In 1996 the MDEQ contracted with the Department of Crop and Soil Sciences at Michigan State University to develop an alternative approach for estimating agricultural irrigation water use. The recently available precipitation data from the Next Generation Weather Radar System (NEXRAD) of the National Weather Service provided spatially referenced, hourly estimates of precipitation at a resolution of four kilometers. It was hypothesized that NEXRAD precipitation data, combined with other spatially referenced input data, could be used to run a physically-based soil water balance model (Ritchie, 1985) to simulate soil water conditions and irrigation requirements over the course of a growing season. Using the new method, irrigators would be required to report only the crops grown and the acreage of each crop for each year. Geographic Information System (GIS) and relational database technology would be used to integrate spatial and temporal data with the soil water balance model to provide simulated estimates of irrigation water requirements.

The soil water balance model (SWBM) method was developed during 1996 and 1997. This development involved the programming of a data entry application for acquiring and storing irrigator information, acquisition and conversion of soil and meteorological data layers, and conversion of the soil water balance model (Ritchie, 1985) to run in an integrated modeling environment (IME) designed for the Microsoft Windows operating environment. The IME was designed to incorporate the input data, model, and GIS data layers into a single application for efficient access, execution, and analysis. Results for the 1997 growing season were reported to MDA and MDEQ in October of 1998, using the irrigator records provided by MDA, which was a sample of the total population of irrigators. An advantage of the SWBM method is that data collection from irrigators is greatly simplified. Recent discussions at MDEQ and MDA have suggested use of the U.S. Department of Agriculture census data to identify irrigated acreage, which would eliminate the need for any direct data collection. In addition to county level reporting, the SWBM method also allows for results to be aggregated and analyzed on a watershed basis, consistent with the recent emphasis on watershed-based water quality management (Grant, 1997).

1.2 Problem Statement

The SWBM method provides the potential for a more efficient and more accurate reporting process for agricultural irrigation water use. The completion of the 1997 irrigation estimation demonstrated the ability of the SWBM method to simulate levels of irrigation water use in the range of expected values. Further analysis and validation is necessary before adoption and use on a wider scale is considered, however. The future adoption and use of the SWBM method by Michigan and other Great Lakes states could be negatively affected by the dependence of the SWBM on detailed input data requirements. Detailed precipitation data (both temporally and spatially) and detailed soil parameters are required by the SWBM. In addition, the location and acreage of irrigators must be known to a resolution of 4 km. in order to associate NEXRAD precipitation data with irrigated acreage. These data are often not readily available to government agencies in the format required for running the model. In some cases, the data may be obtainable, but the government agency may not have the technical expertise available or funding available to prepare and maintain data for use in the SWBM.

The SWBM currently uses hourly precipitation data during the course of the growing season at a spatial scale of 4 km. Most government agencies will have ready access only to daily estimates of precipitation at a larger spatial scale (county or larger area). The adaptation of the SWBM to use currently existing (but coarser resolution) soil and weather data would make implementation and adoption in other states and regions more likely. It is not known, however, if the use of coarser resolution input data would provide water use estimates within an acceptable level of precision and accuracy as compared to the use of fine-scale resolution input data. The accuracy of the NEXRAD precipitation data relative to rain gauge measured precipitation is also not known and is the subject of chapter V of this dissertation.

1.3 Objectives and Methodology

The overall goal of this research is to provide a thorough assessment of various factors affecting the use and accuracy of the SWBM method for the estimation of agricultural irrigation water use. The research focuses on the sensitivity of the irrigation estimates to soil data and precipitation data. The main objective of the analysis is to assess the potential for the use of coarse-scale input data and it's potential impact on the accuracy of results, as compared to the use of fine-scale data. A secondary, but no less important, objective is to compare NEXRAD precipitation estimates with precipitation levels reported from a network of rain gauges throughout the state.

For this project, the SWBM uses the STATSGO soil data (NRCS, 1994) to provide estimates of local soil parameters. The STATSGO database defines 190 soil map units for Michigan, each consisting of 2 to 21 soil series or soil phases. A more detailed description of the STATSGO database can be found in chapter III. The variability of irrigation requirements between different soil map units is not known. To determine the variability of irrigation requirements by soil map units a historical database of daily weather for central Michigan will be used to represent the range of climatic conditions expected. For each year simulated, climate will be assumed to be the same across the entire state, so the only difference in results will be due to differences in soil characteristics of the STATSGO soil map units. Simulations will be run for four crops for each map unit-year combination. For each soil map unit, the result of the simulations will be a record of total irrigation amount (cm.) applied for the year. A paired t-test will be used to determine if the difference in irrigation amount between any pair of soil map units was different than zero over the 30 year simulation period. Non-different soil map units will be grouped by crop type and the results analyzed. Results of this analysis will provide information on the potential to create major groups of soils from the 190 Map Units. The use of major soil groupings would greatly simplify the data inputs for soil, if the results show that this can be done without a loss in estimate accuracy.

Meteorological data inputs to the SWBM are precipitation, daily minimum temperature, maximum temperature, and daily solar radiation. Of these variables, precipitation plays a major role in determining the soil water balance, and is the most variable over space and time. For these reasons, the weather data analysis will focus on the NEXRAD precipitation data. Analysis of NEXRAD data will consist of the following:

1. Detection of outliers.
2. Detection/assessment of systematic bias.
3. Comparison and correlation with gauge measured weather station data.

Given the highly variable and somewhat random distribution of precipitation over space and time, it could be hypothesized that as the time period of analysis is increased, the values of cumulative precipitation for adjacent cells or cells in close proximity will converge to similar values. That is, distinct differences for adjacent cells are expected on a daily basis, but summed over the 4 month summer period, one would expect convergence to similar values for adjacent or nearby cells. Outlier cells, those that differ significantly from the regional mean, could be a result of consistent bias (ground clutter) or random errors in the radar estimation of precipitation. The relative occurrence and spatial and temporal variation of outlier cells for Michigan NEXRAD data is currently not known. Analysis to identify outliers will be performed for each of the three years of weather data. Outliers will be identified as those cells that have irrigation amounts greater than 1.96 standard deviations from the mean irrigation amount for the analysis period. Some researchers have shown changes in mean values for cells conditional upon distance from the radar site (Smith et. al., 1996). In this study, systematic range-dependent bias of the NEXRAD data will assessed by visual analysis of the monthly and seasonal precipitation values.

To determine the correlation between NEXRAD data and rain gauge measured data, daily precipitation data will be obtained from all reporting weather stations in the Michigan Agricultural Cooperative reporting network for the 3 year period 1996 – 1998. Linkage analysis of daily rainfall using the correlation coefficient will be performed to assess the degree of correlation (spatially and temporally) between the 64 stations. This information will be used to gain a better understanding of variation in rainfall over the state and potentially identify regions of strong correlation within the state. Significant differences, if any, between the NEXRAD precipitation data and the rain gauge data will be identified and discussed.

Results of the soil and precipitation analysis will be used to assess the potential for use of a coarse-resolution input data set consisting of aggregated soils and weather station data. The results will allow for an estimation of the magnitude of the difference in irrigation estimates obtained using fine-scale versus coarse-scale data. In addition to the soil and precipitation data analysis described above, the sensitivity of the SWBM to changes in management parameters will be assessed. There are two management parameters that can be manipulated by the operator of the SWBM that correspond to management decisions made by irrigators. The first management parameter is the decision of when to irrigate, as a function of soil moisture. The second management parameter is the amount of water to apply during each irrigation event. Simulations will be run to determine the sensitivity of model results to the range of reasonable and customary values for these two management parameters.

1.4 Research Assumptions and Limitations

A key assumption of this research is that irrigators use some logical method to determine when and how much to irrigate a crop, based on some desired objective. This method can be a computerized soil water budget, monitoring/measurement of actual soil water, observation of plant indicators, or some combination of these (Hill, 1991). It is assumed in this research that the desired objective is to maintain the soil water balance for optimal development of the crop. No constraints on water use, either physical or economic, are considered.

A limitation of this research is the lack of available data for which to validate the SWBM method results. Because of this, comparison of the SWBM method results to actual irrigator records will not be undertaken as part of this research. A partial validation of the SWBM method will be done by comparing SWBM results to those previously reported in other Michigan irrigation studies. Due to data, time and logistical constraints, it is not possible to comprehensively validate the SWBM method for all irrigated crops, all management strategies, and all possible climate and soil conditions that exist in Michigan.

The judgement of 'accuracy' is compounded by the differences in scale between the model and potential records used to validate the results. The finest resolution of the model is 4 km., while irrigator records pertain to the field level. Strict validation of the SWBM model over a wide range of climatic conditions and crops would require detailed data at the field level over many growing seasons and many crop types. Such validation will only be possible after the SWBM is implemented in an operational setting, with volunteered records used for validation on an on-going basis, as such data becomes available. Validation of the soil water balance model in a research setting is discussed in Chapter II.

The direct reporting method was conducted for the years 1993 to 1995, prior to the availability of NEXRAD precipitation data. The direct reporting method was suspended in 1996, with the SWBM method planned to be implemented in 1997. Because there is not a single year in which the Survey method and the SWBM method are used simultaneously, it is not possible to compare results of each method directly. Because of this, it will not be possible to analyze differences in water use estimates obtained using the two methods.

1.5 Water Resources in a Global Context

It is important to consider, in any research setting, the context of the research and it's objectives in relation to a global perspective. The basic goal of this research is to improve our ability to estimate and monitor agricultural irrigation water use. In this case, the monitoring function is performed by a government agency, the Michigan Department of Environmental Quality (MDEQ). MDEQ will use these results, in addition to information on water use by other sectors to analyze and monitor water use levels throughout the state.

While the results of this research will be directly used by MDEQ, there are a number of other potential beneficiaries. The water use reporting program is national in scope. If the SWBM method is shown to be reliable, accurate, and efficient, the potential exists for other states or regions to use this method in their water use reporting programs. Our understanding of irrigation water use impacts and potential for irrigation throughout the study area should be greatly enhanced. A by-product of the analysis will be the generation of model-simulated irrigation requirements that can be compared to actual water use by irrigators. Implementation of the SWBM at the field level could assist irrigators in determining optimal irrigation amounts. The efficient use of water in agriculture is critical. Deficiencies in water use result in failed or lowered crop yields, leading to inconsistent production levels and unstable economic returns for the irrigator. Over-use of water can result in excessive infiltration, and corresponding problems such as increased nitrogen leaching. Researchers, resource managers, and producers should all learn from this project.

The earth's population continues to expand and requires more and more water for municipal, industrial, agricultural, environmental, recreational, and other needs (Bouwer, 1994). In addition to more direct consumption of water, more water will be needed for irrigation of crops to produce food for the expanding population. In water-scarce areas, competition for water will become increasingly intense, and regulation of water use will become greater. As an example of this, in 1980 the state of Arizona passed the Groundwater Management Act (Coupal and Wilson, 1990). Under this regulatory legislation, the Department of Water Resources is empowered to reduce farm-level water use by imposing higher irrigation efficiencies on farmers. In less developed countries, where much of the projected population expansion is expected (U.N. Population Fund, 1993), the problems of water quantity and quality are more acute. It is currently estimated that half of the population of the Third World does not have access to safe drinking water, that one billion get sick each year from water-borne diseases, and that 12 million die, 80% of which are children (Bouwer, 1994). Water resource management must be implemented on a local or regional scale, with different solutions to different problems in different areas. We should all be driven by a common goal however: promotion of the conservation, protection, and efficient use of water resources.

1.6 Summary

This chapter has discussed the historical development of this research project and the use of its results in a management setting. Objectives of the research have been discussed, and methodology introduced. The context of the research in a global setting has been discussed.

While this research is driven by an applied problem, in a more general sense it pertains to the application of advanced information technology for resource management. Most, if not all, resource management problems involve time and spatial components, encompassed and interrelated within a complex system. Better decisions can be made if one has timely access to pertinent information, and information technology can provide this information. This research offers the opportunity to bridge the gap between theory and practice that often exists between the research institution and managers of resources. This research will demonstrate that results of basic science (theory) can be used in a management setting (practice) to assist in our understanding and management of natural resources.

The remainder of this study is organized as follows. In Chapter II, a discussion of literature related to this research is presented. Chapter III discusses the soil water balance model, data conversions, and source of all data used in the research. Chapter IV presents and discusses the results of the soil data analysis. Chapter V presents and discusses the results of the precipitation data analysis. Chapter VI summarizes and discusses the results and provides recommendations for future research.

CHAPTER II

LITERATURE REVIEW

This chapter presents a review of literature related to this study. The literature review has been categorized according to the disciplines or fields of study represented in the study. Studies pertaining to soil water balance modeling are discussed in section 2.1, followed by a discussion of the use of Geographic Information Systems (GIS) for regional scale modeling in section 2.2. Studies on precipitation measurement using rain gauges and radar are discussed in sections 2.3 and 2.4. Section 2.5 presents issues relating to spatial scale and regional modeling. Section 2.6 summarizes the literature review.

2.1. Soil Water Balance Modeling

An understanding of the soil water storage profile is important for many hydrological problems, including irrigation management. Accordingly, factors affecting the soil water balance have been the focus of many researchers. In an agricultural setting, precipitation and irrigation provide the major water inputs to the hydrological system. Evaporation, transpiration, surface runoff, and drainage by percolation are the major water losses.

The Soil Water Balance Model (SWBM) used in this research is the current version of the Ritchie model as reported by Ritchie (1972), Richardson and Ritchie (1973), Ritchie (1985), and Ritchie (1998). Ritchie (1972) presented a model for calculating the daily evaporation rate from a crop surface. In this article, evaporation from the soil surface and evaporation from the plant surface are considered separately. Test of the model showed very good agreement between model estimated evaporation and measured evaporation using a weighing lysimeter for a 37 day period on a grain sorghum test plot.

Richardson and Ritchie (1973) evaluated the SWBM on a watershed basis. This work recognized the effect of soil water content on runoff, as discussed in Knisel and Baird (1969). In the 1973 study, Richardson and Ritchie used three years of data from a 20 acre watershed to test the model. Rainfall was measured with a rain gauge, and runoff measured at the watershed outlet. Effective rainfall was calculated as precipitation – runoff, and used as a model input. By removing an unknown from the equation (runoff) and replacing it with measured runoff, the SWBM predicted total soil water content with high accuracy (correlation coefficient = .99). The SWBM is a critical component of the CERES (Crop Estimation through Resource and Environmental Synthesis) family of crop-soil-atmosphere models, which are used in the Decision Support System for Agrotechnology Transfer (DSSAT), a product of the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT, 1986). Gerakis and Ritchie (1998) used the SWBM in the simulation of atrazine leaching and showed good agreement between simulated results and observed soil water content at three depths (13 cm., 26 cm., and 67 cm.).

The soil water balance approach has been applied in a number of different research areas at different scales. Yates (1996) presented a water balance model (WatBal) that was used to assess the potential impact of climate change on a river basin. This study used the Priestly-Taylor (1972) method for estimating potential evapotranspiration. Two case studies were used to test the model, with historical data used to calibrate and validate the model for each. Hypothetical scenarios of climate change were then used to estimate the river basin discharge response to changes in temperature and precipitation levels. This study is an example of modeling at the watershed basin scale. Parameters for the water balance model such as catchment holding capacity (S_{max}) are given as basin-scale estimates. Changes to the soil water are also calculated at a basin scale. While this empirical approach is useful for understanding general rainfall/runoff/temperature relationships within a particular basin, it is necessary to calibrate the model for the basin being analyzed. The need to calibrate for specific locations renders the model less suitable for use in locales other than the study site.

To assess the impact of tillage practices on soil water, Shanhoultz and Younos (1994) also used a water balance model approach. Their model used an empirical formula to estimate evaporation that was derived from field measurements of pan evaporation, soil water content, precipitation, and runoff. In this formula, evaporation was estimated as a function of the plant available water in the top 30 cm. of soil, the average time since the soil was at field capacity, and an estimate of pan evaporation for the day. As in the Yates (1996) study, a number of parameters required calibration using the test data. These parameters included potential plant interception, an infiltration parameter, an evaporation recession constant, a stress factor, and potential depression storage. As in most reported studies, the simulated soil water content had reasonable agreement with the measured plant available soil water. Results were only reported for years for which the model was calibrated, there was no attempt to verify the model for other years.

Water balance calculations are often a critical sub-component of many agriculturally related studies. For example, studies that examine pesticide contamination of groundwater often use a soil water balance approach to estimate the amount of water percolating to groundwater. Peralta et al. (1994), as an example, present a simulation/optimization model for preventing pesticide contamination of groundwater while maximizing irrigated crop yield. A fundamental assumption of this model is that chemical moves only in the liquid phase in response to soil water movement. A similar study concerning the modeling of water transport and nitrogen dynamics is presented by Lafolie et al. (1997). In studies such as these, the accurate modeling of soil water content and soil water flow is a necessary condition for accurate model results.

Models such as those presented by Yates (1996) and Shanhoultz and Younos (1994) required calibration using test data sets. Interpretation of the results, therefore, should only be done within the context of the test sites and test years. Models that are more physically-based, such as that of Black et al. (1969) and Ritchie (1972) should be more adaptable to a GIS-based modeling environment. Physically-based models require less calibration for individual sites or regions, which is an important consideration for detailed modeling in a GIS environment. As detailed GIS data becomes available, the potential for incorporating physical models and analyzing larger spatial areas will become greater, but the models must use available and measurable independent variables in order to be easily integrated in a GIS environment.

The development and validation of soil water balance models has led to their use as sub-models in other modeling efforts. As an example Dierckx et. al (1988) used a soil water balance model (SWATRE) developed by Feddes et al. (1978) in conjunction with the SUCROS crop model (van Keulen et. al., 1982) to evaluate the ability of the combined models to estimate soil water levels (by depth) and crop yield under different irrigation strategies. Parameters for the model parameters were derived from published literature, including the work of Black et al. (1969) and Ritchie (1972). In this study, good agreement was obtained between simulated and measured soil water for fully irrigated and zero-irrigated corn. Predicted and measured grain yield under both conditions also showed good agreement. As suggested by the authors, these results indicate that such a modeling system might have the capability of predicting corn yield in response to a given irrigation sequence so that economic criteria can be used to schedule irrigation. In a similar study related to irrigation planning in India, Singh and Singh (1996) used simulation modeling to estimate the optimum irrigation schedule for cotton resulting in minimum percolation losses. They found the calibrated model to be an effective tool in evaluating the performance of different on-farm irrigation management scenarios.

Most, but not all, of the water balance models discussed in the literature run on a daily time-step. Victor et al. (1988) present the results of a study that used a simplified soil water balance model developed by Frere and Popov (1979), to estimate pearl millet yields in India. In this study, the soil water balance was computed on a weekly basis. A Water Requirement Satisfaction Index (WRSI) was used to indicate the extent to which the water requirements of the crop have been satisfied. Yield was found to be exponentially related to WRSI, with a high correlation ($R^2 = .88$) between estimated and observed yields. In this study the WRSI is a cumulative index, and is designed to be an easily calculated index value that can be used to estimate final yield during as the growing season progresses. Researchers have shown that moisture stress at a certain critical periods in crop development is more highly correlated with yields than stress at other times (Baier and Robertson, 1968, Mack and Ferguson, 1968). This work highlights the need for the dynamic and accurate modeling of soil water content in order to accurately estimate crop yields. Studies that involve the use of a water balance model to estimate other variables (such as crop yield, irrigation requirements, or runoff) are dependent upon accurate results of the soil water balance model.

The Dierckx et al. (1988) study is a good example of an integrated model, based partly on prior studies, used to reasonably estimate soil water and crop yield for a field test plot. Due to time and other constraints, such studies are often limited by space (one field) and time (one to five growing seasons). Further validation for many growing seasons, different soil types, and different irrigation strategies would be necessary before models such as these can be implemented in a management setting. As Lafolie et al. (1997) point out, it is essential to test models against various experimental conditions in order to improve them so that they can be applied to a broad range of soil and climatic conditions. Very few data sets are available for this purpose however. With the increased use of Geographic Information Systems (GIS) for modeling purposes, the potential to model over a broad range of soil and climatic conditions has increased. With this ability comes the enhanced ability to 'validate' models over a broader range of soil and climatic conditions, a necessary step in the integration of physical models in a GIS. In the next section, studies that have used GIS technology and data in a modeling context are discussed.

2.2 GIS and Regional Scale Studies

A number of studies have been conducted to map soil water balance or irrigation requirements on a regional or country scale. Madsen and Holst (1990) divided Denmark into four climatic zones and derived relationships between the root zone water holding capacities and the mean irrigation need for grass and barley in each zone. Maps for each crop showed the mean irrigation need for 36,000 soil profiles. These were further mapped as areas of low, medium, and high irrigation need for barley. These maps did not take into account current land use, they were based solely on soil properties. Kerkides et al. (1996) used measurements from 31 stations throughout Greece to define soil moisture deficit isolines for the country. Long term average monthly precipitation, evapotranspiraton, and combined soil and vegetation characteristics were used to estimate the soil water balance using the method of Thornthwaite and Mather (1955).

Knox et al. (1996) mapped the spatial irrigation water requirements for potatoes in England and Wales. In this study, an irrigation scheduler computer model was used to calculate the irrigation needs at 11 sites chosen to represent the typical range of climatic conditions experienced across England and Wales. A regression model within a GIS was then used to correlate the model results with existing soils, land use, and climate databases. A series of irrigation need maps at resolution of 5 km. were generated. This study was conducted in part to provide insights for potential policies for water conservation in England and Wales. In a follow-up study, Knox et al. (1997) mapped the total volumetric irrigation water requirements in England and Wales at a resolution of 2 km. using 1994 cropping data. In terms of output, these studies are similar to the outputs that are the objective of this study; irrigation water requirements on an annual basis for a region (State/Country). Knox et al., however, did not use actual precipitation when modeling and mapping irrigation water requirements, instead a 'design' dry year was used, based on simulations using 20 years of rainfall data. Comparison of the model estimates (adjusted for 1990 cropping patterns) to government reported results for 1990 showed no significant differences. As pointed out by the authors, a number of simplifying assumptions were made in these studies that are a potential source of error. These include the classification of soils into 3 categories, the assumption that all the crop is grown on the dominant soil within each 1 km pixel, and inaccuracies in the exact location of some farms due to the need for data confidentiality.

Thomas (1992) mapped the agricultural water balance for rice and maize in Yunnan Province, PR China using a monthly water balance model and GIS data for soils and elevation. The result of this study was a province-level map showing areas that are fully suitable, suitable, moderately suitable, and unsuitable for rice and maize. The use of 1:5 million scale soils maps and 600 M contour intervals in this study, however, leads to only generalized conclusions. Lal et al. (1993) reported on the use of crop simulation models and GIS for regional productivity analysis in a study that simulated bean cultivation in western Puerto Rico. Studies such as these are important in developing and demonstrating technological capabilities. However, higher resolution input data is often necessary before the results are useful for agricultural planners beyond a general sense.

The use of coarse-scale spatial data is currently necessary because, for many areas of the world, high-resolution digitized data sets are not yet available. Remote sensing of climatic data and soil characteristics should provide more detailed data in the future for many areas of the world, however. As an example, Stewart et al. (1999) report on the use of satellite data to estimate radiation and evaporation for northwest Mexico. This area has only a sparse network of instruments measuring climatic variables. Estimates of solar radiation from satellite data closely matched measured hourly solar radiation. The maximum spatial resolution of the satellite data was .8 km. The authors indicate that both radiation and rainfall data were available from the satellite, but only report on radiation estimates. Validation of rainfall estimates would require a much denser network of ground-based weather stations (only three were used in the study).

To summarize the current literature regarding the use of GIS and remotely-sensed data for detailed spatially explicit modeling, it is fair to say that this is a field of research and technology in early developmental stages. Current research is often hampered by the lack of high-resolution data. Because of this, assumptions must be made and results are general, based somewhat on the researcher's assumptions. In the case of remotely-sensed data, data may be available at high resolutions, but dense networks of ground-based data stations do not exist for the validation of the remotely-sensed data. In this study this is the situation for precipitation data. Rainfall is reported at a resolution of 4 km on an hourly basis to the nearest 1/100th mm. The network of weather stations, located many kilometers apart, report precipitation on a daily basis to the nearest 1/100th inch. The relatively sparse network of rain gauges makes comprehensive validation of the NEXRAD data a difficult task. Validation of the NEXRAD precipitation data used in this study, to the extent possible, is discussed in Chapter V.

2.3 Rain Gauge Measurement of Precipitation

Precipitation is an important variable affecting the soil water balance. Because of its affect on agriculture and other human activities, the measurement and spatial variation of precipitation (and other weather variables) is also a topic of importance to climate researchers. Many studies have been conducted concerning the accuracy of measurement. Other researchers are concerned with the optimum density of sensors (rain gauges) in a network with the goal of identifying the minimum network necessary to provide sufficient information on rainfall amounts for a given area. Other researchers focus on the spatial and temporal variability of precipitation and the movement of storms. Each of these areas of study are relevant to this research effort. It should be recognized that precipitation patterns are variable by region or smaller scales and therefore results of studies reported below are not in all cases directly applicable to Michigan.

As discussed by Neff (1977), early studies (late 1800's and early 1900's) of rain gauge accuracy demonstrated that wind influenced rain-gauge catch, and catch decreased as wind velocity increased with height. Neff (1977) conducted a study to determine the difference in rainfall measurement between standard U.S. Weather Bureau rain gauges normally exposed (1 M above ground) and rainfall measured in control gauges at the ground surface. The study was conducted at four locations; Pullman, Washington, Reynolds Creek, Idaho, Sidney, Montana, and Ekalaka, Montana. The average error for all locations combined was found to be –10%. That is, rain gauges 1 M above the ground caught 10% less rain than the control gauges. The range was 5 – 15%. As Neff points out, whether this difference is important depends upon the intended use of the rain gauge data. The difference may be important in a network whose purpose is to provide quantitative estimates of precipitation for detailed hydrological modeling. It is not possible to use a simple adjustment (10%) to correct rain gauge records because of the relationship of error to wind velocity. Errors were zero for storms with little or now wind, but as much as 75% for storms with high wind. Other factors besides wind velocity influence wind effects on rain gauge catch. The effect is related to drop size distribution and the relative timing of wind activity and rainfall intensity (Neff, 1977).

In terms of validation of the NEXRAD precipitation data, results of the Neff study discussed above should be kept in mind. Rain gauge estimates are point estimates, with some degree of measurement inaccuracies. Radar-estimated rainfall is generalized over a continuous surface and has other sources of inaccuracy, as discussed later in this chapter. Because of potential inaccuracies and differences in spatial and temporal resolution of the measurements, a direct comparison and comprehensive validation is not possible. However, we should expect some degree of correlation between gauge-measured and NEXRAD-estimated precipitation.

Hubbard (1994) points out that confidence in network measurements are more than a question of sensor accuracy. Measurements represent conditions at a station but are also often used to infer conditions between sites, in order to report basin or regional level data. Many studies have been performed to investigate the correlation of meteorological data between stations. Hendrick and Comer (1970) reported on space variations of precipitation and implications for rain gauge network design. In this study, 23 rain gauges in a 43 square mile watershed were used to examine the correlation of daily precipitation. They concluded that a 9-gauge network would be necessary for correlation of 90% or more for them more variable summer storms. This roughly translates to a distance of 2 miles (3.2 km) between stations. Note that this distance is slightly less than the resolution of NEXRAD data (4 km.) used in this research. Hendrick and Comer

(1970) also point out that, because of the spatial variability of storms, substantial errors will occasionally occur when a rain gauge is used to estimate rainfall at a nearby ungauged point regardless of the high correlation that may exist between rainfall at the two points. The time period of interest is an important factor to consider when assessing the accuracy and need for rain gauges. For long term (annual) estimation of rainfall data, Eagleson (1967) concluded that only two stations were necessary in a 1250 square mile watershed located in Australia. Long-term averages have little relevance to the subject of this dissertation, except to indicate ranges of precipitation totals that one might expect. Of more relevance are daily and weekly variations in rainfall.

In order to quantify the spatial variability for a number of daily meteorological variables from automated weather stations, Hubbard (1994) examined 5 years of data from 24 stations in the High Plains Automated Weather Data Network. The coefficient of determination (r^2) was used as the statistical measure to quantify spatial variability. Analyses were centered on Ord, Nebraska, with correlation calculated between the Ord station and all other stations. These results were then used to create contour maps of correlation fields (using a kriging technique). Variograms were prepared by plotting the r^2 between station pairs and their separation distance. When plotted by month, the annual variograms show the degree of separation (km) needed to achieve a certain level of correlation (r^2). The results show the seasonal variation in spatial variability for each weather variable. Generally, higher correlation was observed in spring and fall and lower correlation in middle summer and middle winter. Hubbard found that in order to achieve a correlation of 90% for maximum temperature, a station separation of 60 km or less would be required. For minimum temperature, relative humidity, solar radiation, and evapotranspiration, the separation distance for 90% correlation was found to be 30 km. For precipitation, a separation distance of 5 km or less would be required for a 90% correlation (10 km for 75% correlation). These results are indirectly applicable to this study, if summer precipitation patterns are somewhat similar between the High Plains area and Michigan. The NEXRAD resolution of 4 km. is slightly less than the separation distance of 5 km for 90% correlation found by Hubbard.

Huff and Shipp (1969) investigated the spatial correlation of different storm types in three Illinois rain gauge networks. Similar to other studies, they found that a greater density of rain gauges is needed in the warm season (May to September) than in the colder months of the year to achieve the same level of correlation. For all storms in May – September, a distance of 2 miles (3.2 km) or less was found to be necessary for an r^2 of .90. Stol (1972) also reported monthly differences in correlation coefficients between rain gauges in a study conducted in the Netherlands. A distance of roughly 4 km. was necessary to achieve a correlation of .90 in the summer months.

In a Texas study, Lyons (1990) examined monthly precipitation at 46 stations throughout the state over a continuous period from 1923 – 1984. As in the Hubbard (1994) study, higher correlation between gauge sites was found for winter and spring, and lower correlation in summer months. Large positive and negative anomalies were seen, and it was concluded that monthly precipitation anomalies could not be predicted or anticipated based on time-series or spectral analysis. Results of this study are not directly applicable to Michigan because of differences in location and climate regimes between Texas and Michigan. The lower correlation of summer rainfall between stations is again substantiated by this study, however. The study points out the spatial and temporal variability in monthly precipitation estimates over a large region. Berndtsson (1988) found that correlation fields defined as the area within a .7 correlation isoline were usually less than 8 km^2 in a study in Tunisia. Less than 50% correlation was found at distances of 50 km or more.

The use of rain gauge data to reconstruct the movement and spatial distribution of a storm was investigated by Niemczynowicz (1987). In this study, a network of 12 rain gauges in Lund, Sweden was used to assess the use of cross-correlation techniques to determine storm movement. Niemczynowicz concluded that an objective and reliable storm tracking method does not yet exist. Objective methods failed to accurately track storms if more than one rainfall cell existed over the network. Radar or other remote sensing technologies offer the best long-term solution to this problem.

Most of the studies reviewed used daily or monthly data in their evaluation of precipitation patterns. Using daily data, the general conclusion for rain gauge spacing is that the distance should be 4 km or less to achieve high correlation between sites. Experience suggests that convective rainfall (thunderstorms) often deposit rainfall in localized areas much smaller than 4 km. This has been confirmed by researchers using a dense rain gauge network in Spain (Lorente and Redano, 1990). If the pattern of rainfall deposited by thunderstorms is somewhat random in time and space, however, then it should be the case that as the time period of analysis is lengthened, the values of precipitation amounts should be more closely aligned. In this study, correlation of weekly precipitation data is likely more important than correlation of daily data. That is, irrigation decisions are likely based more on a weekly or greater time frame, not on the presence or absence of rain on a particular day. Chapter V present results of a correlation analysis of precipitation data for Michigan using weekly totals of precipitation.

2.4 Radar Measurement of Precipitation Data

The precipitation data used in this study was obtained from the National Weather Service NEXRAD (Next Generation Weather Radar) system of WSR-88D (Weather Surveillance Radar – 1988 Doppler) radar. This system is expected to provide high-quality, high-resolution precipitation data for the United States that meet a wide range of hydrologic applications (Smith et al., 1996). Because of the importance of precipitation in the SWBM, the scale of NEXRAD precipitation data (4 km) is the scale at which the model is run, with other data inputs aggregated or disaggregated to this scale.

In a study done prior to the introduction of the NEXRAD system, Austin (1987) discussed the complexity of the relation between measured radar reflectivity and surface rainfall. In the 1987 study, Austin compared rain gauge and radar measured data for twenty storms in New England. Results varied by storm, in seven of the twenty storms, the radar total precipitation was more than 20% below the gauge-measured precipitation.

In four storms the radar precipitation exceeded the gauge by 20%. For frontal storms, the radar measurements were consistently low compared to the gauge measurements. For convective stroms, radar measurements were generally higher. Austin (1987) points out that for highly convective storms, radar may be the only reliable data source for precipitation estimates. Austin (1987) also suggests that a scientist should use all available data (from both radar and gauges) if estimates of areal rainfall amounts or small-scale distribution of rain are needed. Austin found large and apparently random discrepancies between the amounts of rain collected by individual gauges and the radar-indicated amounts for the same area (at a resolution of 2 km.).

Smith et al. (1996) compared one year of NEXRAD data with rain gauge data in Oklahoma. Biases were examined for range dependent sampling, systematic differences between two radar sites observing the same area, and differences between radar and rain gauge estimates of rainfall. Range dependent biases were found. Mean rainfall increased from the radar out to a range of 100 km. and decreased from the 100 to 230 km. range. Kitchen and Jackson (1993) also found degradation of radar rainfall estimates at far range. To examine radar-radar biases, paired analysis of NEXRAD rainfall estimates from two stations with overlapping coverage was examined. Systematic differences were found, with one station showing a consistently larger rain area and amount than the other. Smith et al. (1996) indicate that the radar-radar differences are consistent with differences that could occur due to differences in radar calibration. When comparing rain gauge precipitation to NEXRAD, Smith et al. found rain gauge observation to be 48% larger in the range of 0 – 40 km., 18% in the 40 – 160 km. range, and 40% higher in ranges greater than 160 km. NEXRAD data was found to be much more capable for delineating areas of heavy rainfall during convective storms, however. Numerous storms producing hourly rainfall accumulation of 50 mm. were completely missed by the rain gauge network. Smith et al. suggest that the spatial analysis of heavy rainfall illustrate the fundamental advantage of NEXRAD estimates over rain gauge estimates.

It is clear from the studies reviewed that biases or inaccuracies in measurement are unavoidable in both rain gauge and radar measurements. Despite the potential inaccuracies, the use of NEXRAD estimates of precipitation would appear to be preferable to rain gauge estimates, given the highly variable spatial patterns of summer precipitation in the study area. Accuracy of radar estimates of precipitation can be improved by calibration with rain gauge data, as discussed by Collier (1986). For this reason, the scientist should make use of all available data, both radar and gauge measurements, when assessing precipitation levels for a region. With continued improvement in NEXRAD calibration and measurement capabilities, accuracy of estimates should continue to improve. Accuracy of a radar-based estimate is partially dependent on the features of the precipitation, with frontal storms more easily measured, and convective storms much less reliably measured. The scale of analysis should be considered when considering precipitation data. At the field or farm scale, (smaller than the 4 km. resolution of NEXRAD data), a network of rain gauges would undoubtedly provide more accurate estimates of precipitation than NEXRAD. This is impractical for large-scale implementation however, for obvious reasons. At the regional or statewide level, as in this study, NEXRAD estimates calibrated to rain gauge data should provide the best estimate of precipitation levels. Any assessment of the accuracy of a modeling effort should consider the difficulty and potential inaccuracies in measuring precipitation levels, given their high spatial and temporal variability.

Looking to the future, satellite measurement of precipitation may provide estimates of environmental variables on a much larger scale. As an example of the use of remote sensing of climatic variables, Hsu et al. (1996) report on precipitation estimation from remotely-sensed information using artificial neural networks. They state that with the current rapid growth in remote-sensing technology, we will soon be able to monitor the global distribution of rainfall. The system reported by Hsu, et al. however, currently requires ground-based measurements for system calibration. In two case studies, they found that it is much more difficult to produce accurate estimates of hourly rainfall than of monthly accumulated rainfall, due to random estimation errors. They present some positive results for monthly estimation, but admit that a great deal of work is still required to develop and strengthen the methods they propose. The spatial scale of rainfall estimates was .25° latitude by .25° longitude, (approximately 30 km. resolution). Remote sensing of rainfall from satellites could potentially provide accurate data at larger scales (30 km.), but this seems to be a technology very much in development and experimental stages at this time.

Future developments in remote sensing capabilities may also provide direct estimates of soil moisture that could be used to derive irrigation needs. Ulaby et al. (1996) show good agreement between estimated soil moisture and measured soil moisture using data collected from both a DC-8 aircraft (AIRSAR instrument) and the space shuttle's Shuttle Imaging Radar C (SIR-C) instrument. Data were collected for a watershed in southwestern Oklahoma. Ulaby et al. (1996) state that it is conceptually possible to image the terrain with a 30 m spatial resolution using SIR-C. SIR-C is currently an experimental system, however, so it will likely be many years before technology such as this could be used in an operational setting.

2.5 Spatial Scale and Regional Modeling

Easterling et al.(1998) examined the relationship between modeled and observed crop yields as a function of the spatial scale of input data. In this study, the EPIC model (Williams et al., 1990) was used to simulate crop yields in Missouri, Iowa, Nebraska, and Kansas using different scales of input weather data. The largest scale used corresponded to the scale typically used by global circulation models (GCMs). This is a 3 degree or larger grid cell (approximately 250 km x 350 km). The climate variables were calculated as averages of all stations within a cell, at the spatial resolution being modeled. County level yields from the National Agricultural Statistical Service were used to test the model results. EPIC simulations were performed for various levels of disaggregation of soils and climate data in order to examine scale effects on modeled and observed yields.

Easterling et al. (1998) found that at the GCM (250 km x 350 km) level, observed yields explained only 43% of the variation in simulated crop yields over the 1984 – 1992 period.

The r^2 was improved to .658 when a resolution of 79 km x 104 km was used for input data. No improvement in goodness of fit was found at higher resolutions (the finest resolution tested was 47 km. x 62 km.). Their results suggested that the disaggregation of climate data, not soils data, was the only factor that improved agreement between simulated and observed yields. This study points out the potential errors in using very coarse scale input data for modeling purposes. Results of such modeling can certainly be within reasonable ranges, but correlation with 'reality' is potentially low.

Klemes (1983) discussed the issue of conceptualization and scale in hydrology. He points out that we cannot impose scales on nature, but rather must search for those that exist and try to understand their interrelationships and patterns. Klemes contends that in nature, scales of things are not arbitrary, they arise as a function of their material substance and of the balance between the interacting forces. Scale, in this case, should be considered both in a spatial and temporal sense. The points made by Klemes (1983) are important to consider. What is the appropriate scale to model precipitation, variability in soil moisture, or cropping patterns? Currently, scale is constrained and imposed by the technology available. For example, the 4 km. resolution of NEXRAD data is the most detailed available, yet research and experience has shown that summer rainfall especially can occur at much smaller scales. The time dimension must be considered as well. Four km. may be a more appropriate scale if the time scale is measured in days or weeks, but not in hours. Theoretically, spatial correlation should be increased as the time dimension for measurement is increased. The modeling scale is also restricted by the resolution of digitized soil data (1:250,000 scale). In this study, scale is dictated by current technology and data availability, but we should always keep in mind the search for appropriate scales and the implications of our decisions in regards to the choice of scale used in a modeling environment.

Bergstrom and Graham (1998) discuss the issue of scale in hydrological modeling. They generally classify hydrological models as either physically or conceptually (empirically) based. The physically-based model is generally oriented towards detailed, small-scale modeling of processes, requiring high resolution input data. Expansion to a larger (basin) scale would require detailed information on the variability in the basin. Bergstrom and Graham point out that conceptual models generally have more straightforward water balance or runoff modeling as a goal, and treat a large basin as a sum of smaller ones.

The SWBM used in this study was developed as a functional model with both empirical and mechanistic elements. The goal of this approach is to provide the most detailed estimated possible for irrigation water use estimates using generally available data. As finer resolution input data becomes available, it will be possible to incorporate greater detail in the modeling effort. Variability and appropriateness of scale over space and time must be considered as the modeling approach used in this study is further developed or as new fine-scale data becomes available.

2.6 Summary

In multi-disciplinary studies such as this it is not possible to comprehensively review all literature related to the many components of the study. There is, for example, a vast amount of literature on each component of the general water balance equation; precipitation, evaporation, transpiration, and infiltration. An attempt has been made to review the literature most pertinent to this research project as it applies to the assessment of the use of different data sources, scales, and interpretation of model results. For the modeling of a soil water balance, the literature reviewed was directly related to the SWBM used in this study or provided examples of uses of the SWBM approach in other settings. The studies by Knox et al. (1996) that mapped the irrigation need for England and Wales are most closely related to this study in terms of objective and approach. The literature reviewed pertaining to meteorological variables focused on precipitation and it's variability over time and space. This was done because of the importance of precipitation as a driving variable in the SWBM. Most studies supported the need for high-resolution data (4 km. or less) to accurately represent precipitation patterns over space on a daily basis.

A basic premise in modeling should be that the more detailed the model inputs, the more realistic are the results. Review of the literature relating to spatial scale and model accuracy (Easterling et al., 1998) supports this premise. The increasing capabilities and development of GIS and remote sensing technology should only increase our ability to effectively model or monitor environmental processes. Many of the studies currently using GIS to for large-scale modeling or simulation use correspondingly large-scale (coarse-resolution) data inputs. This is largely a function of current data availability and computing capabilities. In the future, data availability and computing capabilities will increase, and spatially distributed models and simulations will be run using high-resolution data inputs. This study is a step towards the future, as are many of the current studies integrating GIS technology and biophysical models.

CHAPTER III

MODEL AND DATA DESCRIPTION

This chapter contains 7 sections. Section 3.1 discusses the Soil Water Balance Model (SWBM) used in this research. Section 3.2 discusses the source and derivation of soil data used by the SWBM. Section 3.3 discusses the temperature data used in the study. Section 3.4 discusses the solar radiation data used. Section 3.5 discusses the NEXRAD precipitation data. Section 3.6 discusses the database of historical weather data used in the soil simulation runs. Section 3.7 summarizes this chapter.

3.1. The Soil Water Balance Model

The core of the irrigation modeling component of this research is the soil water balance model (SWBM). References pertaining to the development and validation of the SWBM were cited in chapter II (Ritchie, 1972, Richardson and Ritchie, 1973, Ritchie, 1985, and Ritchie, 1998). This section contains a summary of the SWBM. A more detailed summary of the SWBM components is given in Appendix A. Additional details of the SWBM are given in Ritchie (1972), Ritchie (1985), and Gerakis and Ritchie (1998).

The basic soil water balance equation, without respect to changes in vertical distribution of water, can be written as:

$$dS/dt = P + I - R - E_s - E_t - D \quad (3.1)$$

where

dS/dt = the change in water storage (S) in time period t

P = precipitation

I = irrigation

R = runoff

E_s = evaporation from the bare soil surface

E_t = transpiration by plants

D = drainage to the sub-surface soil layers.

Precipitation and irrigation provide the water input to the system. In this research, precipitation is a direct input (source described below) and irrigation is a model output. That is, the variable 'I' in equation 3.1 is solved for based on a management strategy to maintain sufficient levels of soil water. Management options for controlling irrigation amount and frequency are described below. The SWBM is a multiple layer model that allows calculation of the vertical distribution of soil water as well as the total soil water content. In this research, 11 soil layers are defined. The depth of each of these layers is shown in Table 3.1. The change in volumetric soil water content for each layer is calculated on a daily basis. The routines involved in the soil water balance simulation are summarized below, with more detail given in Appendix A.

Potential evaporation (EO) is calculated as a function of the air temperature during daylight hours and solar radiation levels. Air temperature during daylight hours (TD) is approximated by a weighted mean of daily minimum (T_{Min}) and maximum (T_{Max}) air temperatures (°C) . Solar radiation (SR) is a direct input (source described below), in units of MJ m^{-2} day^{-1}. Potential soil evaporation (EO_S) is a function of the potential evaporation (EO) and the current leaf area index (LAI). LAI is the ratio of leaf area to ground area. As LAI increases during the growing season, potential soil evaporation is lessened because of the shading and protection from wind offered by the leaf cover. In this research, LAI values are generated for each crop as a function of time (days after planting). This is a simplified approach, meant to approximate the typical leaf development for each crop over the course of a growing season. In a more detailed simulation, a crop growth model could simulate LAI as a function of growing degree days.

Root mass and distribution are important parameters for the estimation of the amount of water taken up by the roots. New root growth (NRG, grams m^{-2} day^{-1}) is estimated as a function of solar radiation (SR) and the current leaf area index (LAI). The root length distribution is calculated for each soil layer as a function of the new root growth, layer water content and a root water uptake coefficient (RWUCON). Root length distribution is used later in the calculation of water uptake.

Ponding refers to the accumulation of standing water on the soil surface. The ponding routine calculates ponding based on the rainfall intensity and a function for hydraulic conductivity. It calculates the daily amounts of infiltration, runoff, and changes to the height of the ponded water. The ponding routine also calls a routine for soil compaction due to rainfall action. The NEXRAD hourly rainfall rates are used in this routine to determine the maximum rainfall intensity during the precipitation event. This is the only routine in which hourly values are used, in all others the time step is daily. The result of the ponding routine is a distribution of any incoming precipitation to runoff, infiltration, or additional ponding. If irrigation occurs for the day, the irrigation amount is added to infiltration.

The downward movement of water is calculated next. Two major factors affect the downward movement of water: the hydraulic force (mostly gravity for downward flow) and the hydraulic conductivity of the soil (Brady, 1990). Hydraulic conductivity is a basic property of each soil layer (see derivation below). Based on the soil water content at each layer in relation to the layers drained upper limit (DUL), saturation level (SAT), and hydraulic conductivity (KsMatrix), the amount of water percolating to each soil layer is calculated, with upper layers providing water to lower layers.

Water moves upward in a soil as a function of the same two factors controlling the downward flow described above (Brady, 1990). Evaporation at the soil surface dries out soil in the top layers, creating a potential gradient between the dry and moist soil areas. Water will move in the direction of the drier soil, in this case upwards. The SWBM uses the available energy for soil evaporation (EO_s) to estimate the amount of water moving upward and the amount evaporated from the surface layer.

The amount of water taken up by the roots is a function of the potential plant evaporation and transpiration for the day, bounded by potential evaporation minus soil evaporation. Potential plant evaporation (EO_P) is a function of the potential evaporation and the leaf area index. Water is removed from each soil layer as a function of the soil water content, the layer lower limit (LL), the root length distribution of the layer, and the root uptake coefficient (RWUCON). The total amount of water taken up by roots is equal to EO_P if the plant can transpire at potential levels. Otherwise the total amount of water taken up by the roots is equal to $EO - EO_S$, the potential evaporation minus soil evaporation.

The decision of whether or not to apply irrigation water is based on the ratio of extractable soil water to the potential extractable soil water, calculated as:

$$ESW = \sum (SW_i - LL_i) * Di \text{ for } i = 1 \ldots n. \tag{3.2}$$

$$PESW = \sum (DUL_i - LL_i) * Di \text{ for } i = 1 \ldots n.$$

$$DI = ESW/PSW$$

Where

SW_i	=	Current volumetric soil water content, layer i
DUL_i	=	Drained upper limit, volumetric soil water, layer i
LL_i	=	Lower limit, volumetric soil water, layer i
DI	=	Drought Index
n	=	the total number of layers tested (see below).

The current soil water content is the current value for the day being simulated. The drained upper limit (DUL) is the highest field-measured water content of a soil after thorough wetting and draining until drainage becomes negligible. The DUL corresponds to water content at 'field capacity'. The lower limit is the lowest, field-measured volumetric water content of a soil after plants stop extracting water due to premature death or dormancy as a result of water deficit. LL corresponds to the 'permanent wilting point' commonly referred to in the literature.

The number of layers tested (n) in Equation 3.2 is a variable that can be set by the operator. The default value is 6 (depth = 57 cm.). If the value for root length distribution is greater than .05, however, that layer is also included. The Drought Index (DI) is the variable used to test for the irrigation threshold value (T_c). The default value for T_c is .5. If DI is less than or equal to .5, an irrigation event is triggered. The irrigation amount is a specified value that differs by crop, see Appendix B for a complete listing. A typical value is 2.5 cm. for each irrigation event. Both the threshold value (T_c) and the irrigation amount are management parameters. The sensitivity of the SWBM to changes in these management parameters was tested as part of this research and is discussed in chapter VI.

To summarize the SWBM, it is a model that has been thoroughly tested and validated in a research setting over the past 25 years. It has also been used in an operational setting to provide estimates of soil moisture in the Midwestern United States (Kunkel, 1990). The use of readily available data for soil and climatic data inputs enhances it's potential for use in a variety of settings. Some soil parameters are not obtainable directly from readily available sources, but their derivation is well documented. 'Calibration' for a particular crop or region should be possible by adjustment of the irrigation management parameters.

In the implementation of the SWBM for this research, simplified but realistic assumptions pertaining to leaf area development (LAI) and root growth have been used. In future development, it is possible that these components could be simulated using a crop growth model. In view of the relatively coarse resolution of other data inputs (such as soils and precipitation) it is probably not necessary to incorporate detailed crop growth models at this time. This could be done when the resolution of other input data becomes finer and there is a need to estimate water use in finer scales (temporally and spatially) than is currently possible.

3.2 Temperature Data

Temperature data consisted of daily minimum and maximum temperature (degrees centigrade) obtained from the Michigan State University Agricultural Climatology Division. A kriging procedure was used to create a continuous surface of temperature for the state of Michigan. Resolution of the temperature data was 20 km. in 1996 and approximately 16 km in 1997 and 1998. There were 271 cells in the 1996 grid (Figure 3.1), and 550 cells in the 1997 grid (Figure 3.2)

3.3 Solar Radiation Data

Solar radiation data for the State of Michigan was also obtained from the Michigan State University Agricultural Climatology Division. Daily solar radiation estimates were provided in units of MJ/M^2. The spatial resolution of the solar radiation data matched the temperature data; 20 km. in 1996 and 16 km. in 1997 (Figures 3.1 and 3.2).

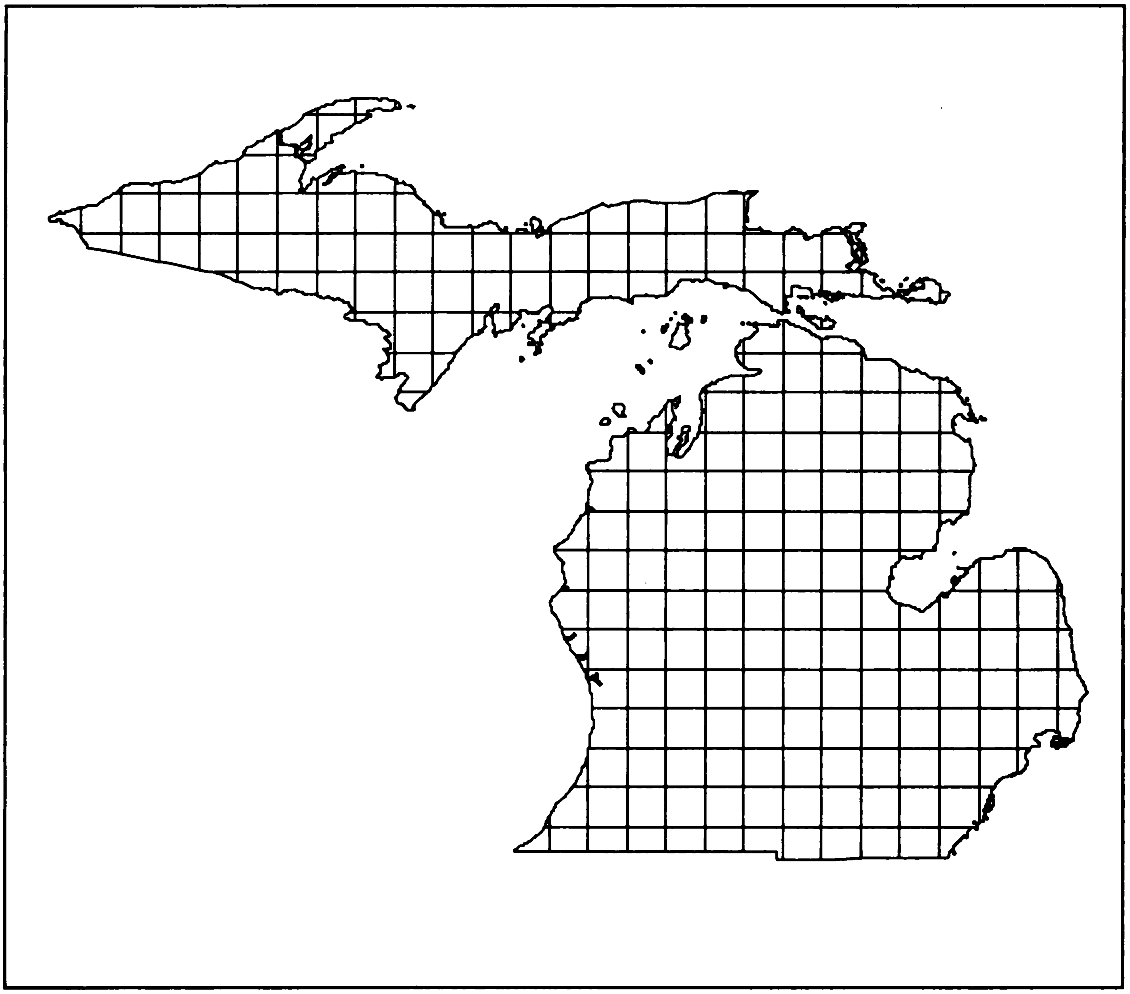

Figure 3.1. 20 kilometer temperature and solar radiation cells for the state of Michigan used in 1996. Note: Isle Royale is excluded on this and other maps in this text.

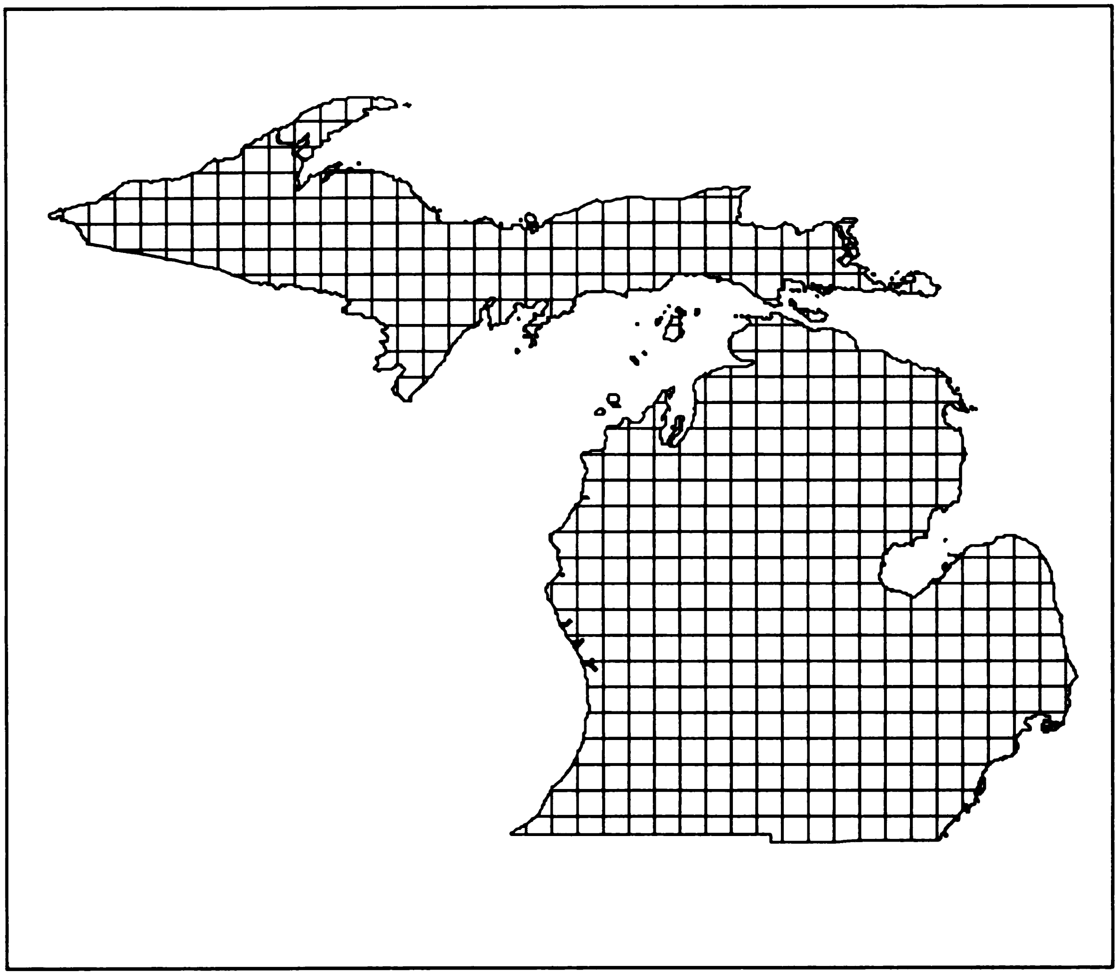

Figure 3.2. 16 kilometer temperature and solar radiation cells for the state of Michigan used in 1997.

3.4. NEXRAD Precipitation Data

Hourly precipitation data at a resolution of 4 km. from the NEXRAD (Next Generation Weather Radar) system (Hudlow, 1988; Hudlow et al. 1991) was obtained from the National Weather Service. There are a total of 7,446 NEXRAD cells covering the land area of Michigan (Figure 3.3).

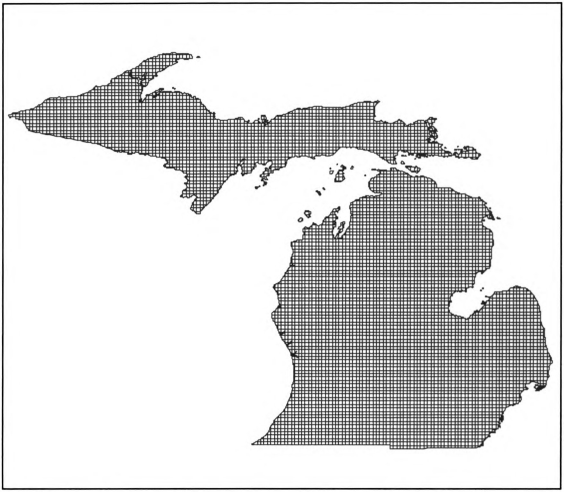

Figure 3.3. 4 kilometer NEXRAD cells for the state of Michigan (Isle Royale excluded).

Significant processing was involved in converting the raw NEXRAD data to a format used in the integrated modeling environment (IME) in which the SWBM was implemented. These processing steps involved processing of the data on a UNIX system, which created ASCII files that were read into an MS Access database on the MS Windows platform.

3.5 Soil Data

The State Soil Geographic (STATSGO) database (USDA, 1994) provided the statewide soils data for this research. The STATSGO soil association maps are compiled from generalized soil survey maps at 1:250,000 scale. A soil association, or Map Unit, represents mixtures or pattern of soils that occur together on the landscape. Individual soils in the Map Unit are referred to as Components of the Map Unit. The Component soils may be similar to each other or they may be very different. A STATSGO Map Unit has a minimum resolution of 625 ha (1544 acres) and, for Michigan, can contain from 2 to 21 soil series. The average number of soil series in a Map Unit is 13. The percentage of each Component in the Map Unit is known, but the spatial distribution of each soil within each Map Unit is not known. A total of 468 individual soils are identified in the STATSGO data for Michigan, organized into 190 distinct Map Units (Figure 3.4).

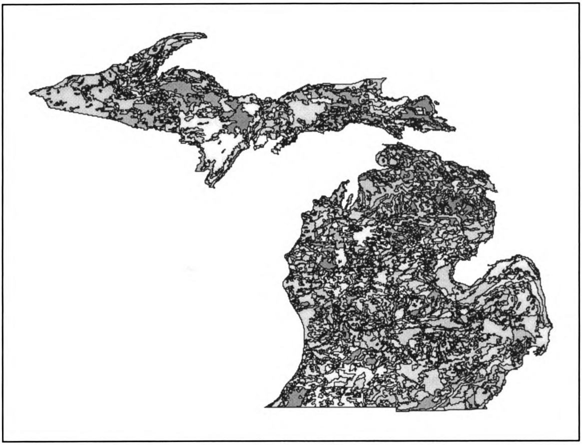

Figure 3.4. STATSGO Map Units for Michigan. 190 unique map units are defined for 2,235 polygons. Colors on this map identify unique soil map unit areas. Source: State Soil Geographic Database (USDA, 1994)

STATSGO Map Units are of relatively coarse resolution compared to the size of an irrigated field. The USDA cautions that the level of mapping of the STATSGO data is designed for broad planning and management uses covering state, regional, or multi-state areas. A more detailed database called the Soil Survey Geographic (SSURGO) database is available from the USDA. SSURGO mapping scales generally range from 1:12,000 to 1:63.300, and each Map Unit contains one to three soil series. SSURGO data are only available for selected counties however. At the time of this writing, only 7 of the 83 Michigan counties were available. Because of the unavailability of the SSURGO database on a statewide basis, the STATSGO database was used for this research. The minimum size of the STATSGO Map Unit (625 ha) corresponds to an area of about 6.25 $km.^2$. The area of the NEXRAD cell (discussed below) is approximately 4 km^2, slightly smaller than the smallest STATSGO soil map unit. Most soil map units are much larger than 6.25 $km.^2$, however, because of the homogeneity of soils and the groupings of many soil series in to a single soil map unit.

Soil parameters required by the SWBM were not in all cases directly available from the STATSGO data. It was necessary to derive some parameters based on fields available in the STATSGO database. Conversion of STATSGO soil data to SWBM soil data was a two step process. In step 1, STATSGO layers were converted to the 11 layers used by the SWBM (Table 3.1). STATSGO defines from 1 to 6 layers for each soil series, with depth generally defined to 152.5 cm (60 inches). Some STATSGO soils are defined to a depth of 251 cm. (99 inches). To create the 11 SWBM layers, values were weighted by percent contribution in those cases where an SWBM layer contained values from more than one STATSGO layer. If an SWBM layer corresponded to only one STATSGO layer, values for the STATSGO layer were used without weighting. The result of this step was a standardized set of soil layers for each soil series in the Map Unit, corresponding to the layers in Table 3.1.

In step two of the STATSGO processing, a Composite soil for each STATSGO map unit was calculated as the average of all Component soils in the Map Unit, weighted by area (percent composition). Table 3.2 lists the soil parameters that were derived from the STATSGO database and the formulas used in their derivation.

Table 3.1. Soil layers and depth (cm.) used in the SWBM. A = top depth of layer, Z = bottom depth of layer.

Layer	A (cm.)	Z (cm.)
1	0	2
2	2	7
3	7	15
4	15	26
5	26	40
6	40	57
7	57	77
8	77	100
9	100	125
10	125	150
11	150	175

Table 3.2 Soil parameters derived from the STATSGO database.

Field	Formula or Value
BD	(bdh + bdl)/2
OC	(omh + oml)/2
Clay	(clayh + clayl)/2
Sieve10	(no10h + no10l)/2
Sieve200	(no200h + no200l)/2
Sand	((Sieve10 - Sieve200) / Sieve10) * 100
Inch10	(inch10h + inch10l) / 2
Inch3	(inch3h + inch3l) / 2
Stones	Inch10 + Inch3
SoilWt	(Sieve10 * (100 - Stones)) / 100
BDM	2.65
Mfactor	(SoilWt / BD) / ((SoilWt / BD) + (1 - SoilWt) / BDM)
LL	.015 + (.0037 * Clay) * BD
PESW	.138 - (1.6E-11 * (Sand - 25)5
SAT	(1 - (BD/ BDM)) * .92
DUL	IF (SAT – (LL + PESW)) > .01, DUL = LL + PESW ELSE DUL = SAT - .01
LL	LL * Mfactor

Table 3.2 (Cont'd)

Field	Formula or Value
DUL	DUL * Mfactor
SAT	SAT * Mfactor
AD	.44 * DUL2
FlowUCO	.63 / Z2 * .495 * e(2.804 – 10.76 * DUL) if layer = 1 THEN adjust by multiplying by .82 – 4.7 * (.45 – DUL2)
Silt	100 – (Clay + Sand + Stone)
KsMatrix	See Table 3.3.
SettledSWCN	(3 – (Sand * .015)) * KsMatrix
SWCN	SettledSWCN

Table 3.3. Values for KsMatrix as a function of Clay and Sand %

	Sand %	0	20	30	40	50	60	70	80	90	100
Clay %	0	12	24	72	84	90	96	96	96	106	110
	10	9.6	19.2	60	72	78	84	90	96	106	
	20	7.2	14.4	48	60	67.2	72	84	96		
	30	4.8	9.6	36	48	56.4	60	72			
	40	3.6	4.8	6	7.2	8.4	9.6				
	50	2.4	3.12	3.12	3.12	3.12					

The result of the soil data processing was a standardized Composite soil for each soil Map Unit, based on the Component soils defined for the Map Unit, with a standardized set of layers (Table 3.1). The Map Unit Composite soil is used, during the model run, to calculate soil characteristics at the level of the NEXRAD cell. Some NEXRAD cells contain only one soil Map Unit, others contain several. Figure 3.5 shows the STATSGO map units for Barry County with the NEXRAD cells superimposed. The NEXRAD cells are recognized by their rectangular pattern. Because the SWBM is run at the resolution of the NEXRAD cell, soil parameters must be provided at the same level. Visual inspection of Figure 3.5 shows that most NEXRAD cells in this area contain 3 or 4 STATSGO map units. The soil parameters for each NEXRAD cell is calculated as the average (weighted by area) of the Map Units contained within the NEXRAD cell.

Calculation of the NEXRAD soil parameters is done dynamically during the model run for two reasons. First, to minimize storage space for the soils database. It is not necessary to store and maintain soil characteristics for each of the 7,446 NEXRAD cells since they are composed of only 190 unique Map Unit Composite soils. Disk space requirements are lessened by storing records for the 190 Map Units rather than for each NEXRAD cell. Second, data for the STATSGO map units may be periodically updated, or formulas for the derived parameters (discussed above) may be modified. When this occurs, the operator only needs to recalculate the Map Unit Composite soil table (190 records). Modifications to the NEXRAD soils are made during the next model run, when modified Map Unit Composite soils are used to dynamically build a set of soil parameters at the NEXRAD cell level.

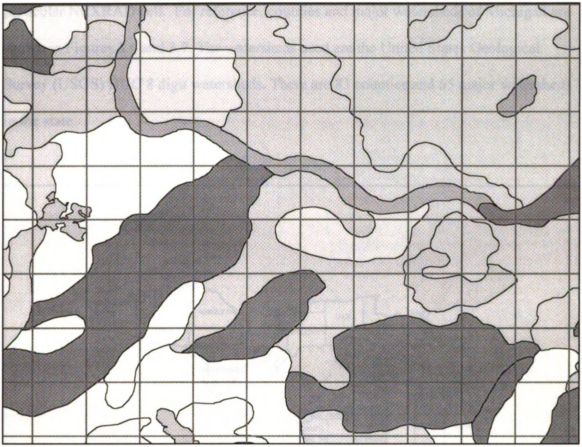

Figure 3.5. STATSGO Map Units for Barry County, Michigan with 4 km. NEXRAD grid cells superimposed.

3.6 Other GIS Data Layers

The MDEQ must report water use estimates at the county and watershed level on an annual basis. Data layers in GIS format corresponding to these two reporting scales were obtained. Because the borders of NEXRAD cells do not coincide with county or watershed borders, it is necessary to associate a county and watershed with each irrigator record. That is, a NEXRAD cell ID is not sufficient to permit aggregation to the county and watershed levels because more than one county or watershed may be contained in a particular NEXRAD cell. For reference, counties and major watersheds of Michigan are shown in Figures 3.6 and 3.7. The watersheds used are the United States Geological Survey (USGS) HUC 8 digit watersheds. There are 83 counties and 65 major watersheds in the state.

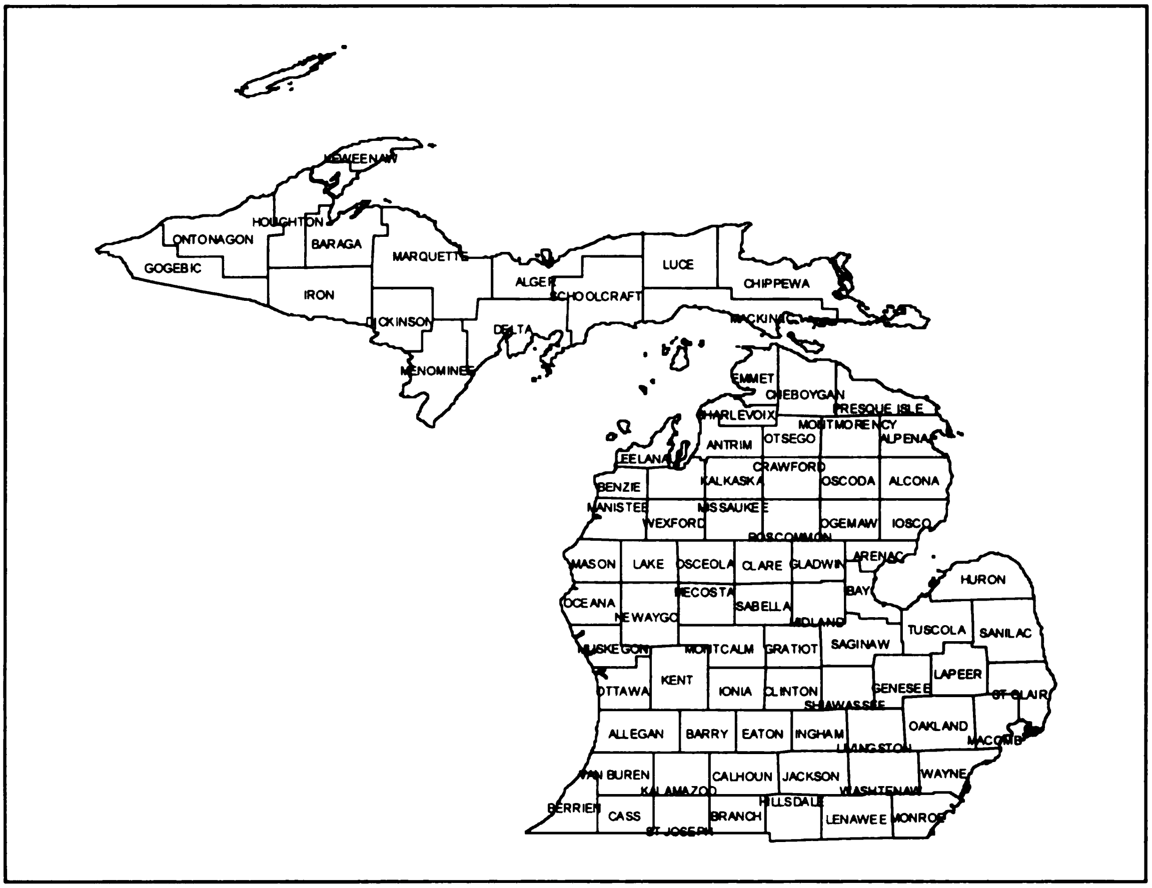

Figure 3.6 Counties of Michigan.

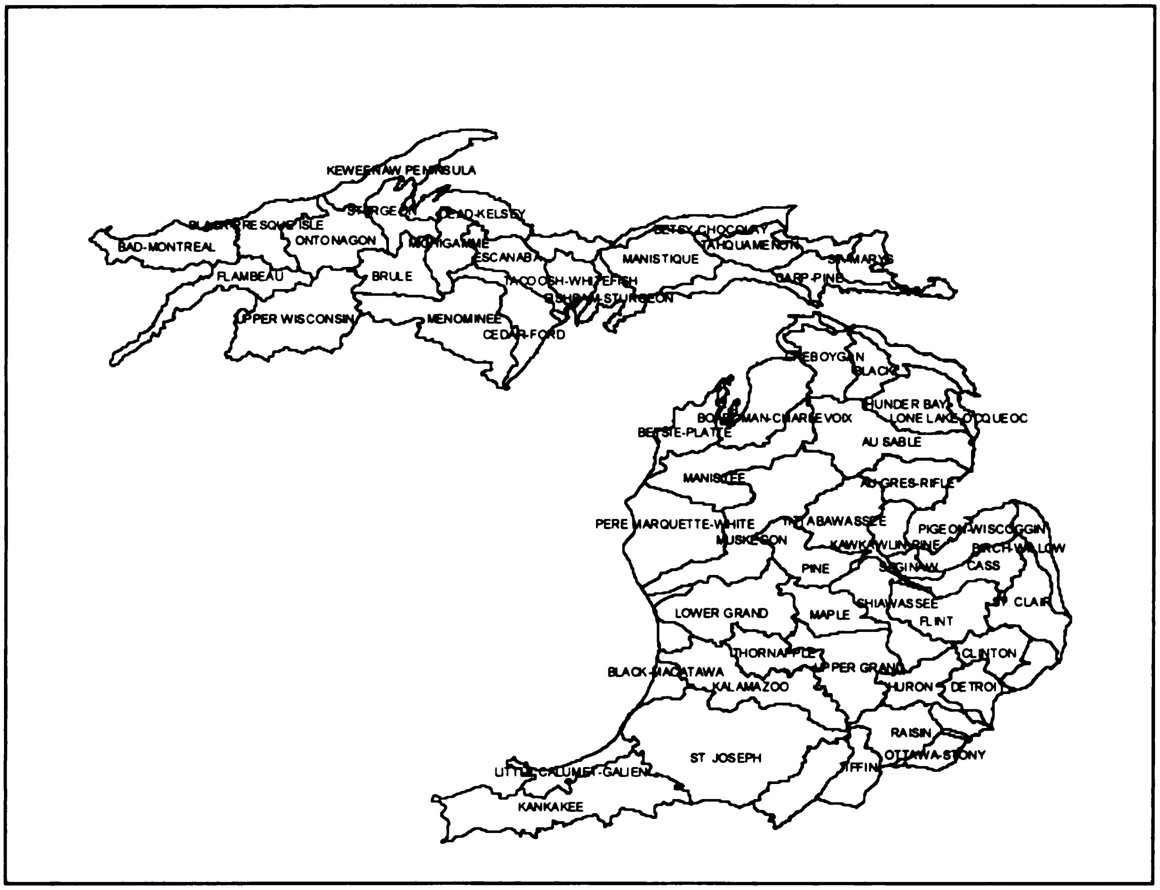

Figure 3.7. Watersheds of Michigan (USGS 8 digit).

3.7 Irrigation in Michigan

Bedell and Van Til (1977) reported that irrigation was practiced in every county in Michigan in 1977. In that year, more than 2,800 irrigators applied an estimated 2,852,000 acre-inches of water on approximately 325,000 acres. 85.5% of the total irrigated acreage was agricultural. Bedell and Van Til (1977) compared the 1977 numbers to a 1970 report and concluded that the total irrigated acreage increased by 217% between 1970 and 1977. In addition, the total quantity of water applied increased by 268% and the number of irrigators increased by 8%. In relation to other water uses, Bedell and Van Til (1977) report that irrigation represented 1.4% of the total water used in the state in 1977 and accounted for 33.3% of the water withdrawn and 66.8% of the water diverted during the summer months from inland surface and ground-water sources. Sweat and Van Til (1987) reported that in 1985 agriculture accounted for 2.1% of all water withdrawals and 39.3% of total consumptive use of water. Thermoelectric power plants withdraw the largest amounts of water in the state (73.5% in 1985) but account for less consumptive loss than irrigation. The 1992 Federal Agricultural Census showed 3,331 irrigators (irrigating more than 10 acres) and a total of 365,578 acres.

Center-pivot sprinkler irrigation is the predominant method of irrigation in Michigan (Sweat and Van Til, 1987). Although irrigation is practiced in all counties, a large portion occurs in the southwestern part of the state. Major irrigated crops include corn, soybeans, potatoes, and vegetables. In the limited survey done by the MDA in 1997, corn accounted for 43% of the reported irrigated acreage, with soybeans and potatoes each approximately 10% of the total.

3.8 Summary

This chapter has provided a summary of the calculation steps of the SWBM, the source and derivation of data inputs, and irrigation in Michigan. The SWBM method is a data-intensive approach, especially when implemented over large spatial areas such as the state of Michigan. GIS technology was used to prepare and view the spatially related data, but is not necessary for the operation of the SWBM, which is implemented as a Microsoft Windows application. In this research every attempt has been made to use the most detailed data available. As data of higher resolution becomes available, this data can be incorporated in the modeling effort.

CHAPTER IV

SOIL DATA ANALYSIS

This chapter contains 5 sections. Section 4.1 discusses the objectives of the soil data analysis. Section 4.2 discusses the methodology used. Section 4.3 presents the results and analysis. Section 4.4 presents further analysis pertaining to mapping irrigation need and characteristics of outlier soils. Section 4.5 summarizes this chapter and discusses conclusions from this analysis.

4.1 Objectives

In the ideal modeling situation, soil parameters would be defined on a site-specific basis. In this study, however, the location of irrigators is known only at a resolution of 4 km (the NEXRAD grid cell). Because of this, it is necessary to estimate soil characteristics by creating a composite soil for the 4 km. cell, as discussed in the previous chapter. For this research, the STATSGO soil database (described in chapter III) provided the base soil data inputs. For Michigan, there are 190 map units defined, each map unit consisting of from 2 to 21 soil series. The composite percentage of each series in the map unit is given, indicating the percentage of the map unit that is composed of the particular soil series. Because the SWBM is run at the resolution of the NEXRAD cell (4 km), it is necessary to calculate a composite soil for each NEXRAD cell based on the STATSGO data. The composite soil data are calculated dynamically during the model run as the average (weighted by area) of the soil map units within the NEXRAD cell. The composite NEXRAD soil is based on a composite map unit soil that was calculated from weighted averages at the STATSGO map unit level (as discussed in chapter III).

The purpose of the soil data analysis is to determine the sensitivity of the SWBM, in terms of irrigation amounts, to changes in soil characteristics at the STATSGO map unit level. The composite soil generated for the 4 km. NEXRAD cell does not represent a specific soil series, rather it is a weighted combination of soil map units, which themselves are a weighted combination of soil series mapped at a relatively coarse (1:250,000) scale. It is relevant to question whether a simpler soil database can be used without loss of accuracy as compared to the use of NEXRAD level soil parameters. That is, if irrigation amounts are similar (not different) for many of the soil map units, these map units could be combined and treated as a single soil by the SWBM. If however, there is high variability between map units, then the calculation and use of composite soils, as is currently done, is justified. The result of the analysis will be used to assess the potential for using simplified soil data inputs for the SWBM. The results of this analysis also have implications for use of the SWBM in areas where detailed soil data is not available.

4.2. Methodology

To test for differences in irrigation estimates by soil map unit, a matched-pairs experiment was run. 30 years (1961 – 1990) of daily weather data from the Lansing, Michigan station was used to provide a representative range of climatic conditions. Four crops (corn, soybeans, strawberries, and sod) were simulated to assess differences between crop type. The SWBM was run for each of the 190 soil map units, for each of the 4 crops, for each of the 30 years of historical data. Total irrigation amount was recorded for each year/crop simulated.

The 30 year data set from Lansing, Michigan provided precipitation estimates on a daily basis, not hourly as with the NEXRAD data set. Before running the simulations, it was necessary to convert the SWBM to run using daily precipitation amounts. The ponding sub-routine was the only portion of the model affected by this difference. Rather than change the model code, the daily data were converted to hourly during the model run according to the following methodology:

A threshold value of .254 cm./hour was used to distribute the daily rainfall to hourly. If total rainfall for the day equaled or exceeded 6.1 (.254 * 24) cm, rainfall was distributed as:

$$Precip_i = Total/24, \; i = 1 .. 24 \qquad (4.1)$$

where

Total = total precipitation for the day

$Precip_i$ = hourly precipitation for i = 1 to 24

If total rainfall for the day was less than 6.1 cm., rainfall was distributed as

$$Precip_i = Total/NumHours, \; i = 1 \;..\; NumHours \qquad (4.2)$$

where

Total = total precipitation for the day

NumHours = Total/.254

$Precip_i$ = hourly precipitation

The irrigation model was tested for differences using hourly vs. daily precipitation. The model was run using the 1997 MDA reported irrigators using 1) Hourly and 2) Daily precipitation amounts. Results using hourly precipitation showed a total application of 1,137,534 acre-inches of water. Using daily precipitation records, the total was 1,138,883 acre-inches of water. There was slightly more irrigation (.12%) using daily precipitation records but the difference is an insignificant amount. These results show that SWBM irrigation estimates obtained using daily precipitation will be nearly identical to those obtained using hourly precipitation.

The SWBM was run for each map unit, for each of 4 crops, using the Lansing 30 year data set as weather input. It was assumed that the daily weather (temperature, precipitation, and solar radiation) was experienced uniformly across the entire state. Differences in model results for each crop were therefore due only to differences between soil map units. The result of this simulation run were, for each of the 4 crops, a set of 190 records (one for each map unit), with each map unit record consisting of a series of 30 irrigation totals (one for each year). Each irrigation total is the total amount of irrigation applied for each crop for year n (n = 1 to 30).

4.3. Results and Analysis

Results of the matched-pairs simulation were tested for significant differences in irrigation amounts between pairs of soil map units. To test for significant differences, the mean difference of the paired irrigation amounts was tested. The number of combinations to be tested was potentially a very large number, since the number of combinations of *n* objects taken *r* a time is:

$$n!/r!(n-r)! \qquad (4.3)$$

In this case, n = 190 (soil map units) and r = 2. Equation 5.1 evaluates to 17,955.

Not all of the possible 17,955 combinations needed to be tested, however. If map units were found to be similar, they were grouped and no further testing was necessary. For example, if map unit 3 was found to be the same as map unit 1, then no further combinations using map unit 3 needed to be tested, since map unit 3 was 'assigned' to the map unit 1 group. An example is presented below (Example 4.1) to illustrate the methodology used to test for differences in irrigation counts between map units. The test involved determining if the mean difference of the paired observations for each map unit was significantly different than zero.

Tests for differences between pairs of all data series were conducted according to the methodology described in Example 4.1. Groups of map units with no significant difference were created. In testing map unit A vs. map unit B, if map unit B was found to not differ from A, then B was added to the "A" group and excluded from further testing. Results are summarized in Table 4.1, which shows the number of groups and number of soil map units in each group for each of the four crops.

Example 4-1. Testing the Paired Differences.

The mean difference for each year is tested between two map units soil A and B. Assume that the results show the following irrigation amounts:

Year	A	B	Difference
1	73	68	5
2	85	79	6
3	64	60	4
4	90	84	6
5	69	65	4

The mean difference, denoted μ_D, is tested. The test statistic is

$$t = (x_D - \mu_D) / (s_D / \mathrm{sqrt}(n_D)) \qquad (4.4)$$

where

x_D = the sample mean

s_D = the sample standard deviation

n_D = the number of paired observation

This test requires the assumption that the differences are normally distributed. The test statistic has $n_D - 1$ degrees of freedom. The test is

H_o: $\mu_D = 0$

H_A: $\mu_D <> 0$

The rejection region for $t_{.025,\,4}$ (from the Student t distribution) is $|t| > 2.776$

For this example,

$$t = (5 - 0) / (1 / \mathrm{sqrt}(5)) = 11.18$$

$$11.18 > t$$

Conclusion: Reject H_o.

There is sufficient evidence to conclude that a difference exists in the mean irrigation count of soil map unit A and soil map unit B.

Table 4.1. Results of the test for paired differences (by map unit count).

	--Count of Soil Map Units by Crop --			
Soil Group	Corn	Soybeans	Strawberries	Sod
1	133	127	129	119
2	13	16	35	24
3	13	13	10	16
4	7	12	4	13
5	6	5	3	4
6	3	4	2	3
7	2	3	1	2
8	2	2	1	2
9	2	2	1	2
10	2	1	1	1
11	2	1	1	1
12	1	1	1	1
13	1	1	1	1
14	1	1		1
15	1	1		
16	1			
Total	190	190	190	190

Table 4.1 is interpreted as follows. For corn, 133 of the 190 soil map units showed no significant differences in irrigation amount over the 30 year simulation period. Of the soil map units remaining, they could be aggregated to groups of 133, 13, 13, 7, etc. For corn, 5 soil map units showed results that could not be grouped with any other soil map unit. In terms of number and distribution of groupings, results were similar for the other crop types. These results indicate that, for a given crop type, the majority of soil map units in the state will not show significant differences in irrigation amount, if each map

unit were to experience the same weather conditions during the growing season. However, there are exceptions in every case. Some soil map units show different irrigation totals and could not be grouped with any other soil map unit.

The results from Table 4.1 should be interpreted by area as well. Table 4.2 shows the breakdown of soil groups as a percentage of land area in Michigan. For corn, 80% of the land area in Michigan is covered by the first soil group. The land area considered includes all land cover types. If forest and other non-tillable land were excluded, the percentage would be higher. The corresponding land coverage is 69%, 63%, and 58% for soybeans, strawberries, and sod, respectively. If the top five soil groups are considered, then the percentage of land coverage is over 90% for all crops simulated (the range is 90.7% to 95.0%). Based on this analysis, it can be concluded that the majority of soil map units in Michigan (and correspondingly the majority of land area) will give similar (non-different) results in terms of total irrigation for a growing season when simulated for a number of seasons for a particular crop. This analysis considers only total irrigation over a season, not the timing of irrigation, which could potentially differ among similar soil map units.

Results of the map unit grouping should also be viewed in their spatial context. This gives an indication of the differences in location of the major soil groups by crop type. Figures 4.1 – 4.4 show the spatial patterns of the grouped map units for each for each of the crops simulated. For reference, the county boundaries for Michigan are shown on the maps. Note that many of the grouped map units cover areas larger than one county.

Review of Figures 4.1 – 4.4 indicate the differences in groupings by crop type. That is, the spatial pattern of soil groupings is not consistent across crops. The same two pairs of soil map units may show similarity for one crop, but not for another. This is an important result in terms of the potential for creating major soil groups.

Table 4.2. Results of the test for paired differences (by percentage of land area).

	-- Percentage of Land Area --			
Soil Group	Corn	Soybeans	Strawberries	Sod
1	80.1	69.4	63.0	58.1
2	5.1	12.2	26.2	16.0
3	3.2	5.7	3.9	9.5
4	2.3	3.9	1.9	8.3
5	2.1	0.7	1.3	1.9
6	0.4	1.8	0.7	1.4
7	0.7	1.8	0.3	0.7
8	1.2	0.7	0.1	1.2
9	0.1	1.3	0.2	1.3
10	1.3	0.1	0.7	0.3
11	0.6	0.7	1.1	0.1
12	0.5	1.1	0.1	0
13	0.1	0.1	0.4	0.7
14	0.7	0.2		0.4
15	0.5	0.4		
16	1.1			
Total	100	100	100	100

Based on these results, 4 major soil groups could be created to capture over 90% of the variability in irrigation amount, but the soil characteristics for each major group and the spatial distribution and area for each group would differ by crop type. There are over 30 different crops potentially irrigated in Michigan. 'Simplification' of the soil data would potentially require the creation of unique soil groups for each of the 30+ crops, each with four or five soil groupings. The variation of irrigation counts between crop types essentially makes the creation of major soil groups impractical for this application. Information would be lost in attempting to create four or five major soil groups that apply to all crops. The results in Figures 4.1 – 4.4 provide useful information beyond viewing the spatial distribution of similar soil groups on a statewide basis. Some general patterns can be seen. On a regional basis, the soils in southeast Michigan show more variability than soils in other parts of the state. With the exception of strawberries, soils in Huron County (the thumb area) show differences with respect to other soil groups. On a county basis, some counties show little or no variation in irrigation counts. This would indicate the similarity of soils in the county from the standpoint of irrigation requirements.

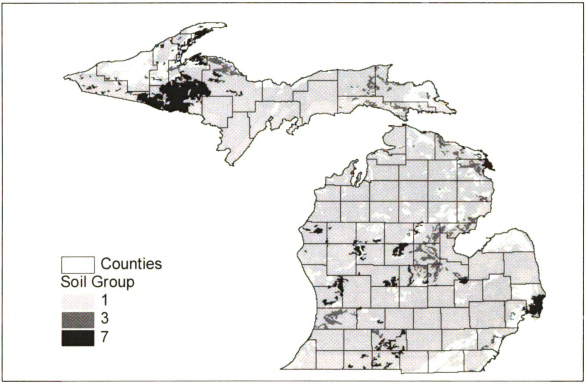

Figure 4.1 Soil groups with non-different irrigation amount for corn.

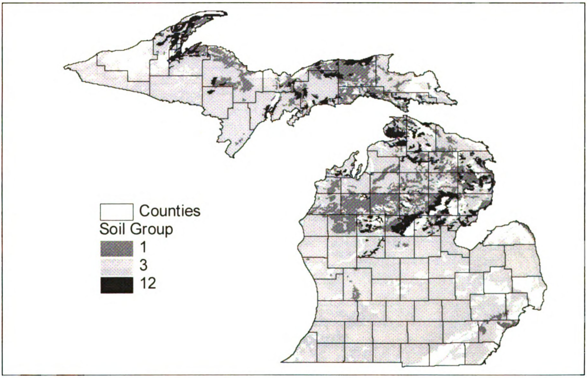

Figure 4.2 Soil groups with non-different irrigation amount for soybeans.

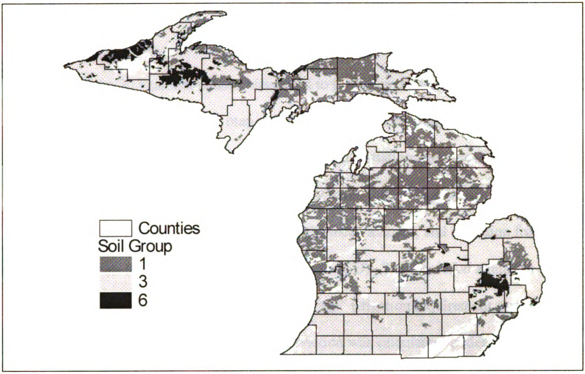

Figure 4.3 Soil groups with non-different irrigation amount for strawberries.

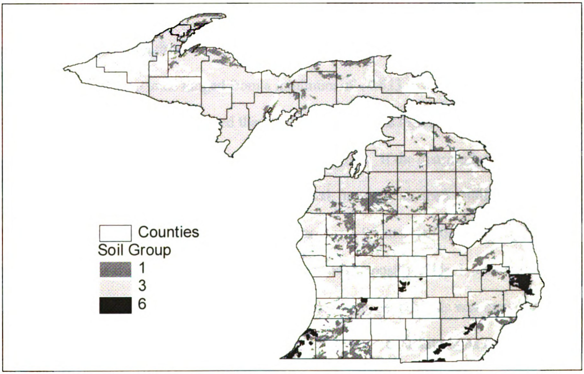

Figure 4.4 Soil groups with non-different irrigation amount for sod.

4.4 Outlier Soil Analysis

The results of the 30 year simulations were used to further investigate the potential irrigation differences between soil map units. For each year and crop type, the mean irrigation count, mean irrigation amount, and standard deviation was calculated. The results of each soil map unit were compared to the mean for the year by calculating the deviation from the mean count, deviation from the mean amount, and deviation from the standard deviation (in terms of number or fraction of SD). This provided a relative measure for each map unit compared to the "average" irrigation requirement over the 30 year simulation period. The mean standard deviation was calculated to identify soil map units that differed significantly from other soils (termed 'outlier' soils). The results for corn are shown in Figure 4.5. Soils showing standard deviations of greater than +/- one from the mean are shown. The sandy soils of Huron County are notable in their increased irrigation requirement compared to the rest of the state. The mean standard deviations for all map units ranged from a minimum of –4.633 to a maximum of +1.936. The lower value of –4.633 indicated that a few soil map units had significantly lower irrigation amounts than the majority of the soil map units. If the distribution of irrigation amount by soil map unit is considered to be normal, or nearly so, then 'outlier' soils can be identified as those that are less than or greater than 1.96 standard deviations (SD) from the mean. In the case of corn, no soils are outliers on the positive side, but 8 map units showed negative differences of less than -1.96 SD. A similar analysis was done for the other 3 crops simulated. Results are tabulated in Table 4.3. Soil map units that were less than -1.96 SD from the mean were consistent across crop type, although strawberries and sod included additional map units than corn and soybeans. In total, there were 11 map units that showed standard deviation less than -1.96 from the mean. The 8 common map units were analyzed for common characteristics that would indicate a physical basis for decreased irrigation need.

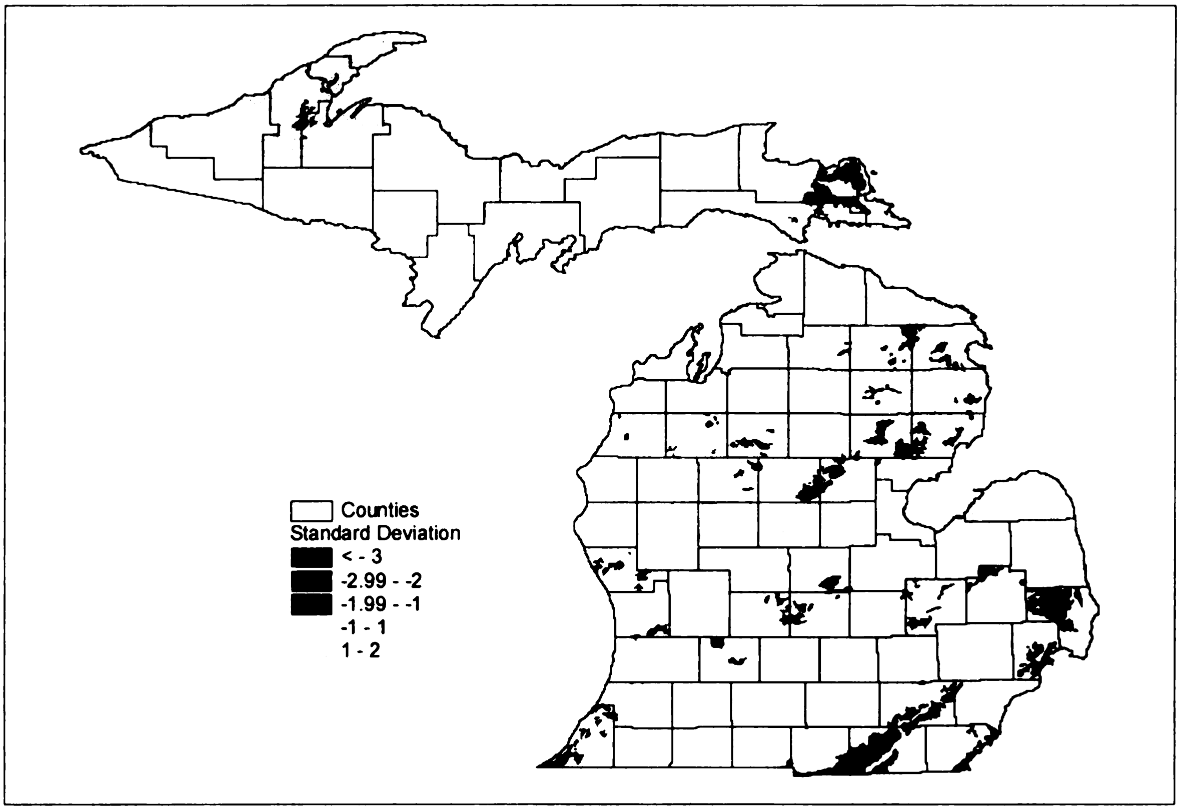

Figure 4.5. Standard deviation groupings for corn computed from the 30 year simulation runs showing soil areas with irrigation +/- one or more standard deviations from the mean irrigation amount.

Table 4.3. Soil map units with irrigation counts less than -1.96 SD from the mean, by crop type.

-- Outlier Soil Map Units by Crop --

	Corn	Soybeans	Strawberries	Sod
	MI008	MI008	MI008	MI008
	MI009	MI009	MI031	MI031
	MI097	MI031	MI019	MI009
	MI176	MI097	MI009	MI019
	MI031	MI019	MI097	MI055
	MI019	MI176	MI055	MI097
	MI055	MI055	MI176	MI006
	MI006	MI006	MI006	MI176
		MI184	MI185	MI185
		MI185	MI184	MI184
				MI096
Count	8	10	10	11

Soil map unit 'MI008' showed the highest deviation from the mean for all crops. The map unit name for 'MI008' is LENAWEE-TOLEDO-FULTON. This map unit is composed of 14 soil series, as shown in Table 4.4. The dominant soil in this map unit (LENAWEE) has a surface texture classified as 'clay', and other major soil components are either silty clays or clays. The lower infiltration rates of a clay soil should result in greater water retention and lower irrigation need, and the model results are consistent with these expectations. For five of the eight common map units, the surface texture of the predominant soil is classified as either clay or silty-clay. For the remaining three, 'MI055' is composed of both silt and silty-clay soils, MI006 is predominately loam soil with 5% muck, and MI076 is predominately silty-loam with 10% muck. The presence of muck soils in a soil map unit should decrease irrigation need estimates, due to the higher organic matter, higher water holding capacity, and poor drainage of these soils.

Table 4.4. Component soils of soil map unit 'MI008' showing the name, ID, percentage, and surface texture of each component.

COMPNAME	S5ID	COMPPCT	SURFTEX
LENAWEE	MI0002	45	CL
FULTON	OH0080	12	SICL
TOLEDO	OH0081	12	SICL
PERT	MI0197	8	CL
DEL REY	IL0022	7	SICL
CORUNNA	MI0088	5	SL
GRANBY	MI0029	2	LFS
PEWAMO	MI0042	2	CL
LENAWEE	MI0314	2	CL
OAKVILLE	MI0349	1	FS
OAKVILLE	MI0038	1	FS
PIPESTONE	MI0257	1	S
SELFRIDGE	MI0081	1	LS
ARKONA	MI0264	1	LS

Examination of the textural classification of the surface layer of the eight outlier soils showed that they generally are higher in clay, with correspondingly less sand than other soils. The mean clay percentage for all 190 soils at the surface layer is 10.6%. Table 4.6 shows the breakdown by major textural class of the eight outlier soils. With the exception of MI097, all have clay levels of 20% or higher. MI097 appears to be an exception, but further examination revealed high clay content (> 33%) starting at a depth of 26 cm. This illustrates the need to examine soil characteristics by depth when evaluating soils for irrigation requirements. As seen here, the surface layer will generally indicate potential irrigation requirements, but not in all cases.

Table 4.5. Surface layer textural class composition (percentage) of the eight outlier soil map units (Other = larger material such as stones and pebbles).

	-- Textural Class --			
Map Unit	Sand	Silt	Clay	Other
MI008	25.9	45.4	28.5	0.2
MI009	15.4	58.6	26	0
MI097	58.4	27.1	12	2.5
MI176	20.6	59.3	19.5	0.6
MI031	12.8	59.5	26	1.7
MI019	23.8	44.6	29.5	2.1
MI055	15.9	56.8	25.5	1.8
MI006	13	60.1	24	2.9

Analysis of the soil map units with consistently higher irrigation need was also done. Five soil map units that showed higher irrigation need for each of the four crops simulated were analyzed (MI130, MI173, MI180, MI189, and MI208. The surface texture of the major component of MI130 is defined as a somewhat-poorly or poorly drained 'cobbly-loam'. MI173 is predominately a silt-loam (moderately well-drained) with 10% sand, MI180 is a well drained silt-loam, MI189 is silty-clay and loam (well-drained), and MI208 is predominately silt (well-drained).

The STATSGO soil drainage class of the predominant soil is 'well-drained' or 'moderately well-drained' for four of the five soils analyzed. For these cases, the model results are consistent with the general STATSGO classification of soil texture. Based on the STATSGO soil drainage classification, the presence of MI130 (classified as somewhat-poorly drained) as a high irrigation need soil was inconsistent with expectations. The amount of coarser soil material (cobbles) in MI130 was very high (19.2%) as shown in Table 4.6. If sand % is calculated excluding the larger fragments, then the effective percentage is 61%, closer to the sand percentage of other high irrigation soils (MI173 and MI180, for example), which would explain the model estimation of higher irrigation need. Whether or not this correlates with reality is subject to further investigation.

The average sand percentage at the surface layer for all soils is 56.2%. Three of the five "high-irrigation" soils (Table 4.6) are below the average. It is evident from this that the sand % at the surface layer cannot be used, by itself, as an indicator of potential irrigation need. In addition, STATSGO classification of soil drainage and model results may not necessarily coincide in all cases, as demonstrated by soil MI130.

Table 4.6. Surface layer textural class composition (percentage) of five soil map units with high irrigation need. (Other = larger material such as stones and pebbles).

	-- Textural Class --			
Map Unit	Sand	Silt	Clay	Other
MI130	49.3	19.5	12	19.2
MI173	61.2	26.2	8.5	4.1
MI180	62.1	25.2	8.5	4.2
MI189	29.5	49.1	19.5	1.9
MI208	28.5	50.8	16	4.7

To summarize the outlier analysis, it can be stated that the model results are generally consistent with a priori expectations of irrigation requirements based on general soil descriptions. That is, soil map units showing lower irrigation needs are generally high clay soils with few or no coarser fragments (stones and pebbles). Those soils showing higher irrigation needs are less identifiable based on soil textural classification, although the clay % is generally lower than other soils. It is not possible to assess the potential irrigation need of a soil map unit based on the texture at the surface layer of the predominant component. Changes in soil characteristics with depth play a large role in determining irrigation need. It is also shown that model results may be inconsistent with the STATSGO soil drainage classification (MI130) in some cases.

This discussion is based on the general premise that the composition of a soil by major textural class has some correlation with the soil's potential irrigation requirements. The use of soil textural classes to estimate porosity has been a subject of discussion in the soil science literature. Saxton et al. (1986) present equations for estimating hydraulic conductivity as a function of sand, silt, and clay percentages. Schuh and Bauder (1986) found that sand to silt ratio was a better predictor of hydraulic conductivity than soil particle size percentages alone. Helalia (1993), however, reported that the textural variables (clay %, silt %, and clay pus silt) showed weaker correlation with the infiltration rate than the structural variables (total porosity, effective porosity, and bulk density).

4.5 Composite Soil Analysis

The results of the soil map unit analysis discussed above indicate that the majority of soil map units show insignificant differences in terms of estimated irrigation amounts. This lends support to the use of a composite soil at the 4 km. NEXRAD cell level in the modeling process. Since each irrigator is only identified at the 4 km. cell resolution, the soil series under irrigation could be any soil series within the 4 km. area. To further examine the potential range of irrigation estimates by soil series, an additional simulation was run using the actual 1997 reported irrigated acreage. In this simulation, the SWBM was run for each soil series in the NEXRAD cell for each crop irrigated. This provided a potential range of values for irrigation estimates for those cells in which more than one soil series was present. Irrigation amounts were aggregated at the county level and reported as "low" and "high" estimates. The low estimate represents the irrigation estimate if all crops were raised on the soil series in each NEXRAD cell requiring the least amount of irrigation. The high estimate, conversely, represents the irrigation estimate if all crops were raised on the soil series requiring the highest amount of irrigation. Results of the simulation for those counties reporting more than 1,000 irrigated acres are shown in Table 4.7.

Table 4.7. Range of irrigation estimates for counties reporting more than 1,000 acres of irrigation in 1997. Low = irrigation estimate (cm.) using soil series with least irrigation requirement. High = irrigation estimate (cm.) using soil series with highest irrigation requirement. Difference (cm.) = High – Low.

County	Acres	Low	High	Difference
St. Joseph	36211	14.10	14.50	0.41
Montcalm	27888	10.64	11.43	0.79
Branch	17367	15.01	15.16	0.15
Kalamazoo	12540	16.56	17.20	0.63
Van Buren	12363	11.94	12.17	0.23
Cass	10789	14.33	14.66	0.33
Ottawa	9224	5.49	6.12	0.64
Allegan	6975	10.11	10.34	0.23
Calhoun	6157	15.93	16.10	0.18
Berrien	4963	8.31	10.72	2.41
Monroe	4589	7.92	8.18	0.25
Mecosta	4398	9.55	10.54	0.99
Bay	4183	7.98	8.03	0.05
Kent	3410	13.21	13.44	0.23
Oceana	3358	11.20	11.51	0.30
Kalkaska	3035	17.53	18.08	0.56
Genesee	2850	11.68	11.68	0.00
Hillsdale	2798	12.88	13.31	0.43
Leelanau	2797	14.99	15.39	0.41
Sanilac	1545	2.97	2.97	0.00
Huron	1537	11.13	11.53	0.41
Lapeer	1528	1.78	2.03	0.25
Ionia	1461	13.46	15.44	1.98
Newaygo	1455	4.83	5.72	0.89
Osceola	1450	13.51	14.33	0.81
Saginaw	1348	12.75	12.75	0.00
Mason	1217	15.06	15.62	0.56
Washtenaw	1181	12.01	16.36	4.34
Tuscola	1151	9.91	10.31	0.41
Gratiot	1109	14.25	14.50	0.25
Antrim	1049	21.49	21.56	0.08
Lenawee	1040	3.89	11.35	7.47

For most counties, the difference in irrigation estimates between the low and high estimates was less than 1 cm. Lenawee and Washtenaw counties showed greater variation, with differences of 7.47 cm. and 4.34 cm., respectively. For all counties combined, the low estimate for 1997 was 973,166 acre-inches and the high estimate was 1,023,738 acre-inches. These results indicate that for most counties, identification of the site-specific soil series would not significantly alter the irrigation estimate as compared to the use of a composite soil. As with most results of this research project however, there are exceptions to the general rule, as evidenced by Lenawee and Washtenaw counties. The total irrigation amount for the 1997 data set estimated using a composite soil was 1,008,205 acre-inches, which as expected lies between the low and high estimates of 973,166 and 1,023,738.

4.6 Conclusions and Recommendations

The test for differences between means of paired time series data was used to group soil map units into groups of soils with similar irrigation requirements. Groupings proved to be dependent on crop type. Because of the differences by crop type and the number of unique groups, results of the time series analysis could not be used to create a simplified 'coarse-resolution' data set that would apply for all crops. Analysis of outlier soils showed general agreement between surface layer textural class and irrigation need, but not in all cases. While major textural class can be used to generally classify soils by irrigation need, exceptions will exist. Because of these exceptions, it is recommended that all available soil information be used in the modeling process. In the state of Michigan, the similarity of many soil series in regards to irrigation requirements allows for the use of a composite soil in the modeling process. As discussed above, most counties showed little variation in irrigation estimates obtained between low and high irrigation soils. This is not true in all cases, however. For those counties that show a high variation between low and high estimates, accuracy could be improved by obtaining site-specific soil data.

Ultimately, the need for detailed soil information is dependent on the degree of heterogeneity in the regional soils and the required degree of accuracy for the modeling effort. As shown in this chapter, the SWBM is sensitive to changes in soil characteristics. Any attempt to simplify the soil data would potentially result in a loss of accuracy, if we assume that the results obtained with the most accurate data represent the best estimate. The estimate using 'detailed' soil information must be viewed not as the ultimate 'truth', however, but rather as a best estimate. If a confidence interval could be associated with the best estimate, what might this interval be at the 95% level? The answer to this could only be obtained by additional research. It is quite possible that simplified soil groupings could result in estimates that are within an acceptable range (+/- x%) of the best estimate using detailed soil data. As a general rule, if detailed information is available, it should be used, as this will provide the best estimate regardless of the confidence level associated with it. Site-specific data, if available, is the best option. Researchers must always be aware of the degree of precision and accuracy by which input data is measured, as this is correlated with the confidence interval one can attach to a best estimate.

CHAPTER V

PRECIPITATION DATA ANALYSIS

This chapter contains nine sections. Section 5.1 presents the research objectives for the precipitation data analysis. Section 5.2 presents a statistical summary of the rain gauge precipitation data used for NEXRAD validation. The spatial correlation of rain gauge data is discussed in section 5.3. Sections 5.4 - 5.6 present a statistical summary of the NEXRAD data for 1996 - 1998. The correlation between NEXRAD data and rain gauge data is discussed in section 5.7. A comparison of SWBM estimates of irrigation requirements using gauge data versus estimates using NEXRAD data is presented in section 5.8. Section 5.9 discusses conclusions that can be made from this analysis.

5.1 Objectives

The availability of NEXRAD precipitation data was the major force for the initiation of this project (as explained in chapter I). The use of NEXRAD data, however, requires the model operators to be responsible for the conversion, validation, and maintenance of this data. Technical expertise in relational database design and management, as well as expertise in GIS-based data conversions is required. In addition, significant storage space (on a personal computer) is required to physically store the NEXRAD data. Similar to the STATSGO soils data discussed in the previous chapter, NEXRAD data requires a significant amount of processing to be converted to the format used by the SWBM. In addition to the processing and storage requirements, the availability of NEXRAD data is an issue to be considered. The data used in this project is available through an informal agreement between the National Weather Service (NWS) and Michigan State University, but is not a standard NWS product at the time of this writing.

Chapter II reviewed literature pertaining to the spatial and temporal variability of precipitation. Most studies examined daily or storm-level variability in precipitation levels. Irrigation decisions, on the other hand, are likely to be made with a longer time frame in mind. It is reasoned that irrigators do not respond to hourly or daily changes in precipitation but rather to weekly or longer time intervals. That is, the decision to irrigate is based on the current soil water status (a function of the season to date) and the forecast or expectations for precipitation in the future (one week or more). It is further reasoned that spatial variance in precipitation should be lessened as the time frame for analysis is expanded. Monthly and weekly totals of adjacent NEXRAD cells should be more highly correlated than daily totals, given the somewhat random nature of precipitation on a daily basis. If the spatial correlation of NEXRAD cells is high, and the correlation of these cells to nearby weather station data is high, then the potential exists for the use of a less-detailed (but more readily available) data set as the precipitation input to the SWBM.

In view of the technical, storage, and availability issues regarding the NEXRAD data, the investigation of the use of a surrogate data set for precipitation estimates (gauge data) is pertinent to this research. This is even more evident when considering the potential for expansion of the SWBM methodology to other states in the Great Lakes region, some of which may not have NEXRAD data available.

The objectives of the weather data analysis are:

1. Partial validation of the NEXRAD data. NEXRAD precipitation estimates will be compared to rain gauge measurements. Outlier data will be detected (Section 5.3).

2. Determination of the degree of spatial correlation between gauge-measured precipitation on a weekly basis and comparisons of totals on a seasonal basis. (Section 5.4)

3. Determination of the degree of correlation between NEXRAD data and gauge data on a weekly basis and comparisons of seasonal totals. (Section 5.7)

4. Determination of potential differences in irrigation estimates by the SWBM using NEXRAD hourly and nearest-gauge daily data. (Section 5.8)

5.2 Weather Station Data: Statistical Summary

Daily reported weather station rain gauge data for the years 1996 – 1998 were obtained for use as a basis for partial validation of the NEXRAD precipitation data and also to assess the potential for the use of rain gauge data from existing weather stations in the SWBM. The number and location of reporting gauges differed slightly in each year. There were 86, 91, and 96 rain gauge stations in 1996, 1997, and 1998 respectively. A complete listing of the stations for each year is given in Appendix B. Included in Appendix B is a listing of the highest daily rainfall for each station. The maximum daily rainfall reported is summarized in Table 5.1. Maximum daily rainfall was used to identify a threshold value for detection of outliers in NEXRAD precipitation. Table 5.1 is interpreted as follows. For 1996, 1.42 to 12.19 represents the range of maximum daily precipitation reported for all 86 stations for all days during the period May 1 to August 31.

Table 5.1. Summary of maximum daily rainfall reported for May – August, 1996 – 1997 by all rain gauges (cm.).

Year	Min	Max	Mean
1996	1.42	12.19	5.43
1997	1.85	14.73	4.06
1998	1.35	12.19	4.02

Table 5.2. Minimum, maximum, mean, and standard deviation of total precipitation (cm) reported by all stations for May – August, 1996 – 1998.

Year	Min	Max	Mean	SD
1996	11.86	56.03	32.97	8.30
1997	18.01	48.92	31.35	6.14
1998	13.00	46.05	25.02	7.25

Table 5.2 summarizes the seasonal precipitation totals for all reporting stations for May – August, 1996 – 1998. The range of total precipitation for the four month period is quite large. The lowest reported total precipitation by any one station was 11.86 cm., while the highest was 56.03 cm. There was an average of 32.97 cm. of precipitation for the four month period. Comparing across years, it can be seen in Table 5.2 that 1996 and 1997 had similar (on average) precipitation totals, and 1998 was slightly drier.

To compare the 1996 – 1998 station data to long term averages, summary statistics were computed for the Lansing and Flint stations for the period 1961 – 1990. These stations were chosen because they had a complete data set for the period 1961 - 1990. Other stations in Michigan had incomplete or missing data for some portion of the 30 year reporting period. The maximum daily reported rainfall over the 30 year period during the 4 month period May to August was 12.57 cm for Lansing and 11.30 cm for Flint. This compares favorably with the maximum reported by all stations for 1996 – 1998 (Table 5.1).

A summary of May – August precipitation totals for the 30 year period is shown in Table 5.3. The mean precipitation over the 30 year period was essentially the same (30.6 cm.) for Lansing and Flint. The values are within the range of the reported average values for 1996 – 1998 station data (Table 5.2), with 1998 being a slightly drier year than normal.

Table 5.3. Minimum, maximum, mean, and standard deviation of total precipitation (cm) reported by Lansing and Flint stations for May – August, 1961 – 1990.

Station	Min (cm.)	Max (cm.)	Mean (cm.)	SD
Lansing	18.74	46.17	30.60	7.34
	(1965)	(1975)		
Flint	19.24	54.24	30.64	7.45
	(1966)	(1975)		

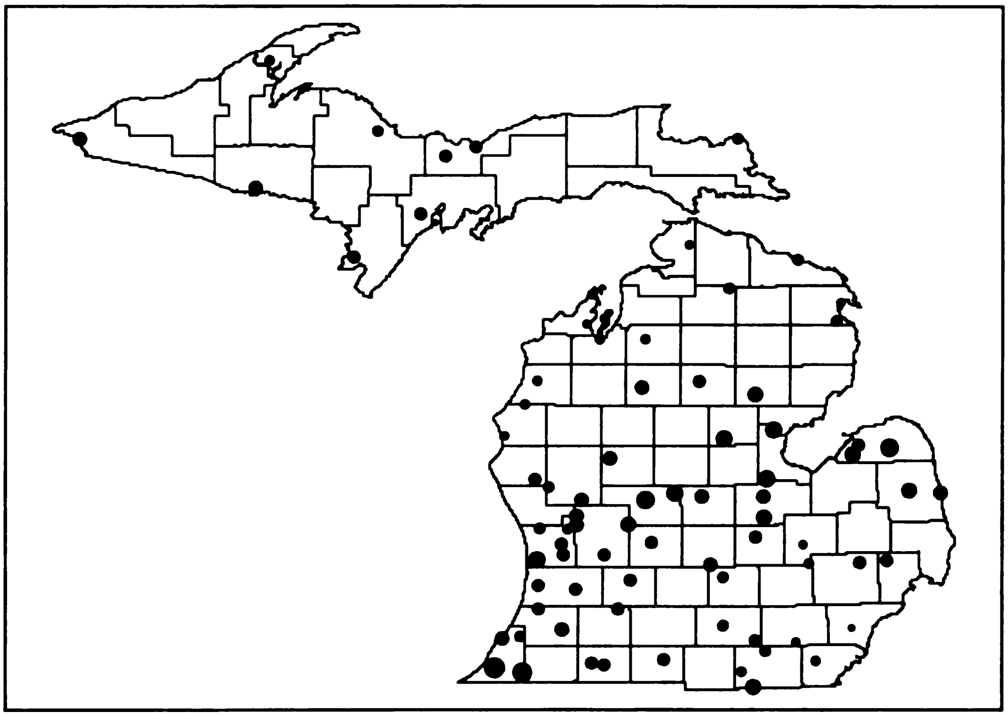

Figure 5.1a. Spatial distribution of May – August 1996 total precipitation (size indicates amount of precipitation. Range = 11.86 to 56.03 cm.

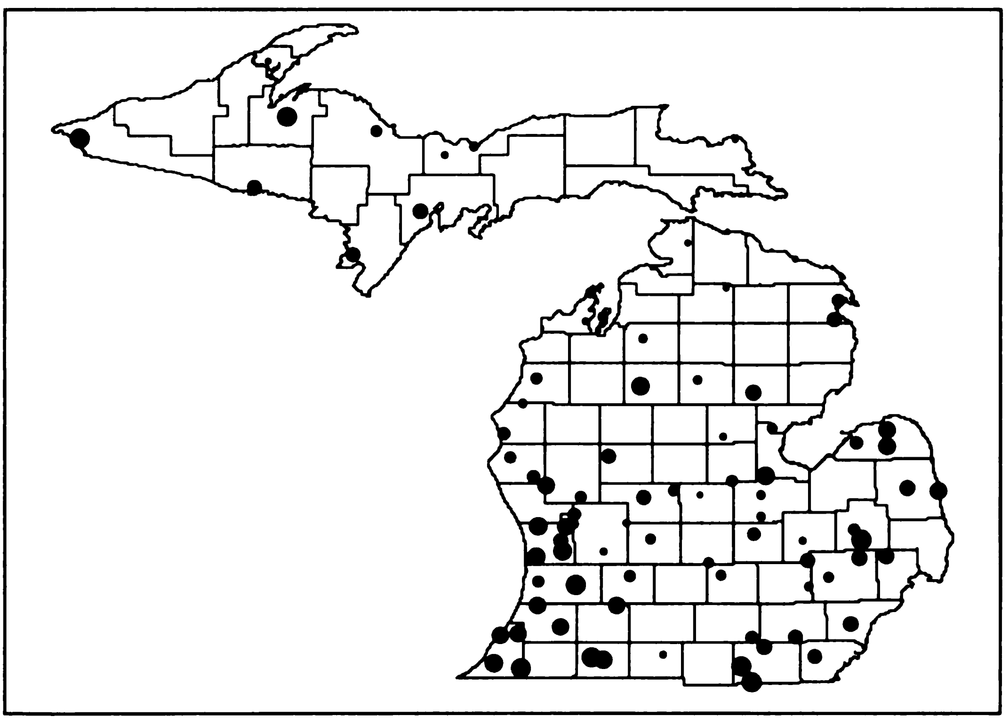

Figure 5.1b. Spatial distribution of May – August 1997 total precipitation (size indicates amount of precipitation. Range = 18.01 to 48.92 cm.

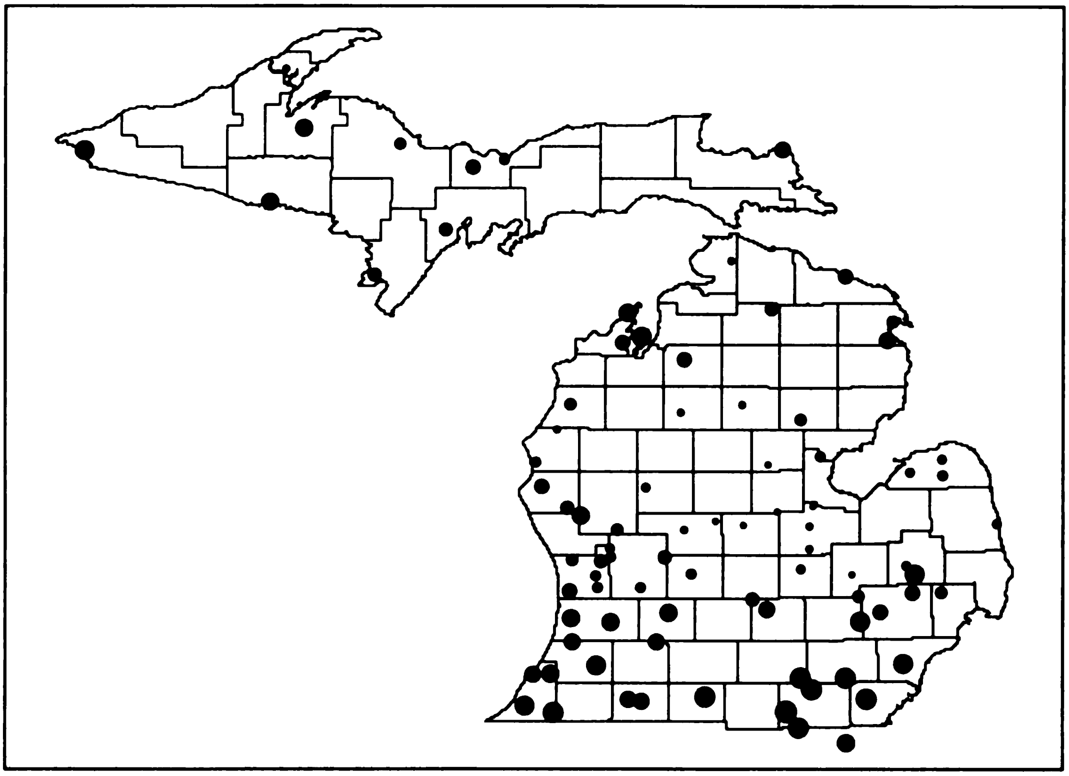

Figure 5.1c. Spatial distribution of May – August 1998 total precipitation (size indicates amount of precipitation. Range = 13.00 to 46.05 cm.

The spatial distribution of total May – August precipitation for the years 1996, 1997, and 1998 is shown in Figures 5.1 (a – c). A pattern that is apparent from visual inspection of these three years is the generally higher levels of precipitation in southwest Michigan. In addition, lower precipitation values are seen in the central part of the state in 1997 and 1998. The occurrence of small and large values in close proximity to each other is an indication of either high variability of rainfall in nearby locations, differences in measurement precision and techniques between stations, or some combination of both.

5.3 Spatial Correlation of Gauge Measured Precipitation

The correlation of weekly precipitation totals between rain gauge sites was computed in order to determine if the correlation of rainfall was related to distance between sites. The coefficient of determination (r^2) was calculated for each pair of gauge sites for each year. For example, for the Lansing station in 1996, the correlation of weekly precipitation values between the Lansing site and each of the other 85 sites was calculated. This resulted in 85 r^2 values, showing the degree of correlation of weekly precipitation values. For Lansing, the r^2 values ranged from a low of .00002 to a high of .88. The range of values covers the spectrum from essentially no correlation to very high correlation of weekly precipitation values. Figures 5.2 (a-c) show the results from a spatial standpoint for Lansing in 1996, 1997, and 1998.

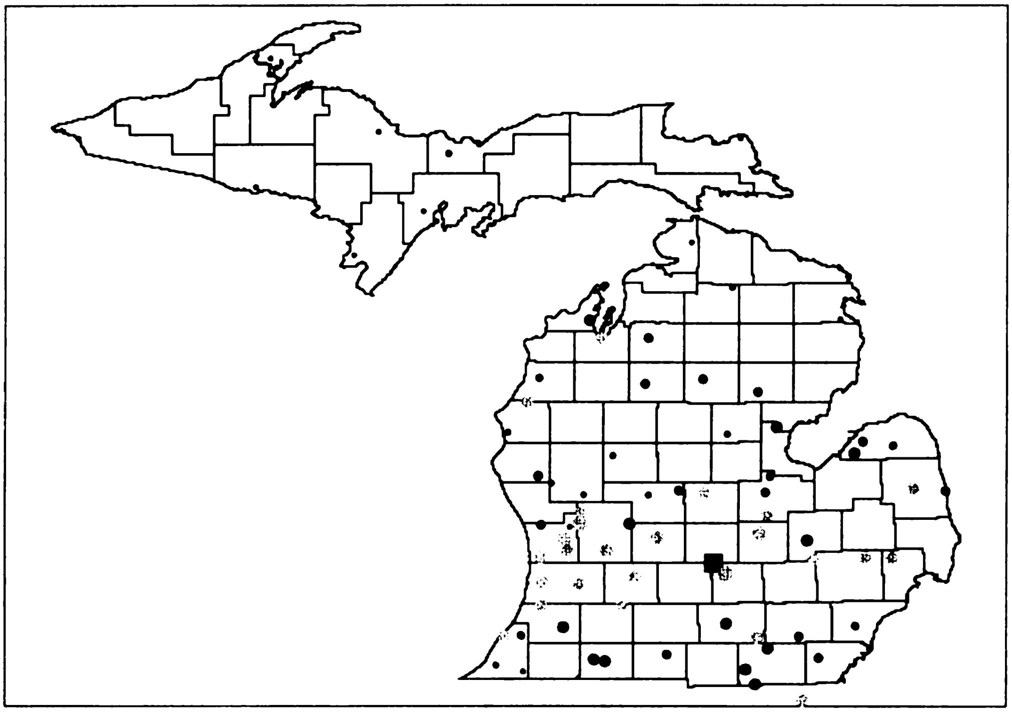

Figure 5.2a. Spatial correlation of weekly precipitation between Lansing (square) and all other stations, May – August 1996. (Size = value of r^2, light color = $r^2 > .50$).

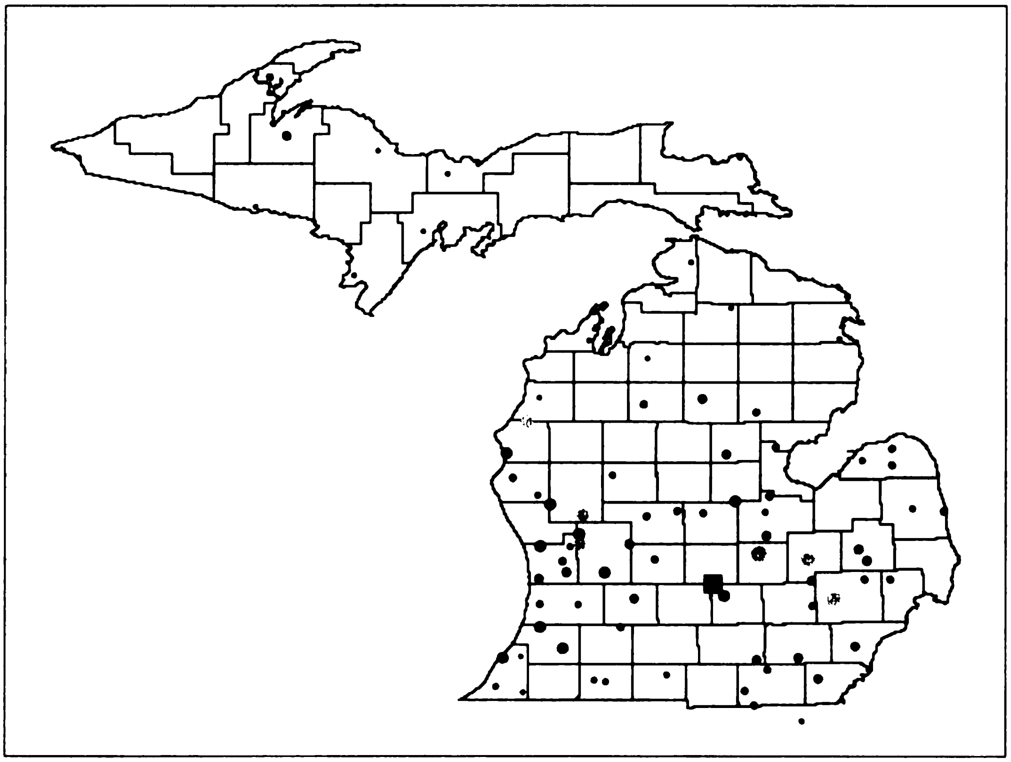

Figure 5.2b. Spatial correlation of weekly precipitation between Lansing (square) and all other stations, May – August 1997. (Size = value of r^2, light color = $r^2 > .50$).

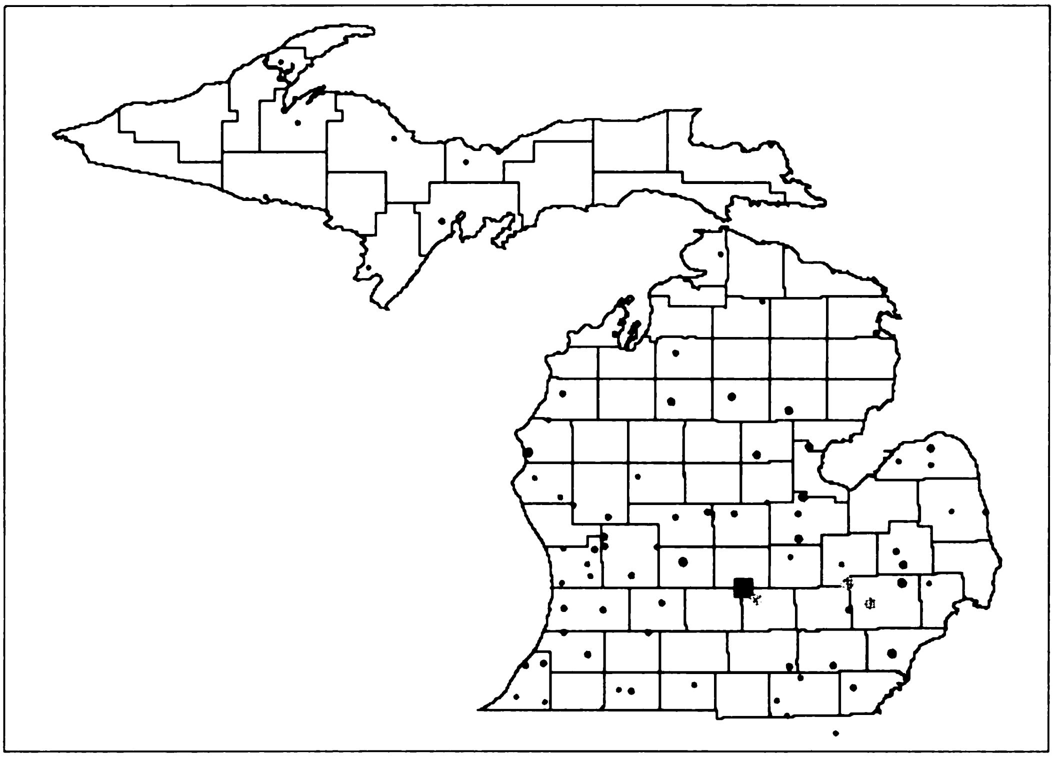

Figure 5.2c. Spatial correlation of weekly precipitation between Lansing (square) and all other stations, May – August 1998. (Size = value of r^2, light color = $r^2 > .50$).

Differences in the number of stations that show significant correlation ($r^2 > .50$) with the Lansing station are evident between years. In 1996, 26 of the 85 stations had r^2 values of .50 or greater. Only 6 and 4 stations had significant correlation in 1997 and 1998, respectively. The figures show a general, although certainly not conclusive, relationship between r^2 and distance. That is, higher r^2 values are generally seen closer to the station being analyzed. This is not consistent in all cases, however. For example, in 1997, the Muskegon station had higher correlation (.57) with Lansing than the MSU Horticultural station (.42). Muskegon is located 127 miles from the Lansing station, while the MSU Horticultural facility is 9 miles from the Lansing station. Muskegon and Lansing were certainly not affected by the same rainstorms (at least for summer convective storms), so results such as this are due to the random component of rainfall distribution. In this case, total precipitation for the four months was nearly identical for the Lansing and MSU Horticultural stations; 27.1 and 27.4 cm. A relatively low r^2 value indicates that the timing of the precipitation differed between stations. The Muskegon station reported a total of 26.1 cm in 1997.

To illustrate the difference in results obtained for other stations, correlation with the Allegan station, located in southwest Michigan, are shown in Figures 5.3 (a-c).

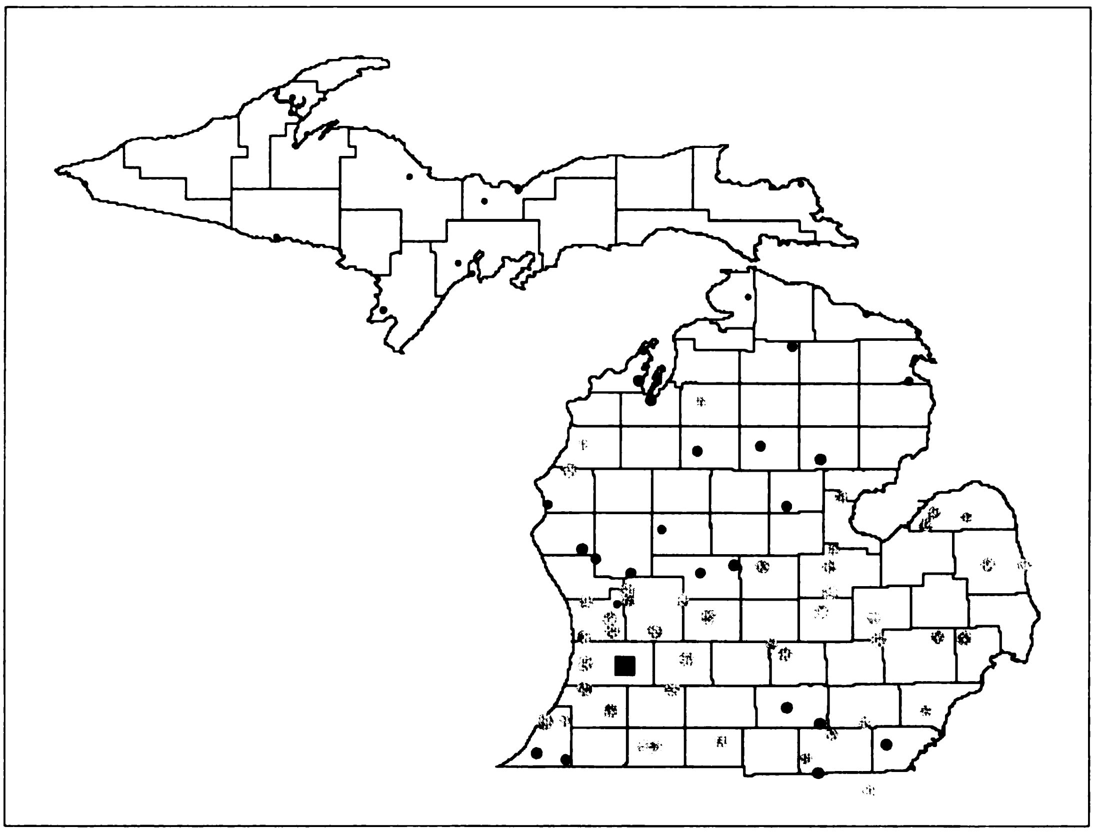

Figure 5.3a. Spatial correlation of weekly precipitation between Allegan (square) and all other stations, May – August 1996. (Size = value of r^2, light color = $r^2 > .50$).

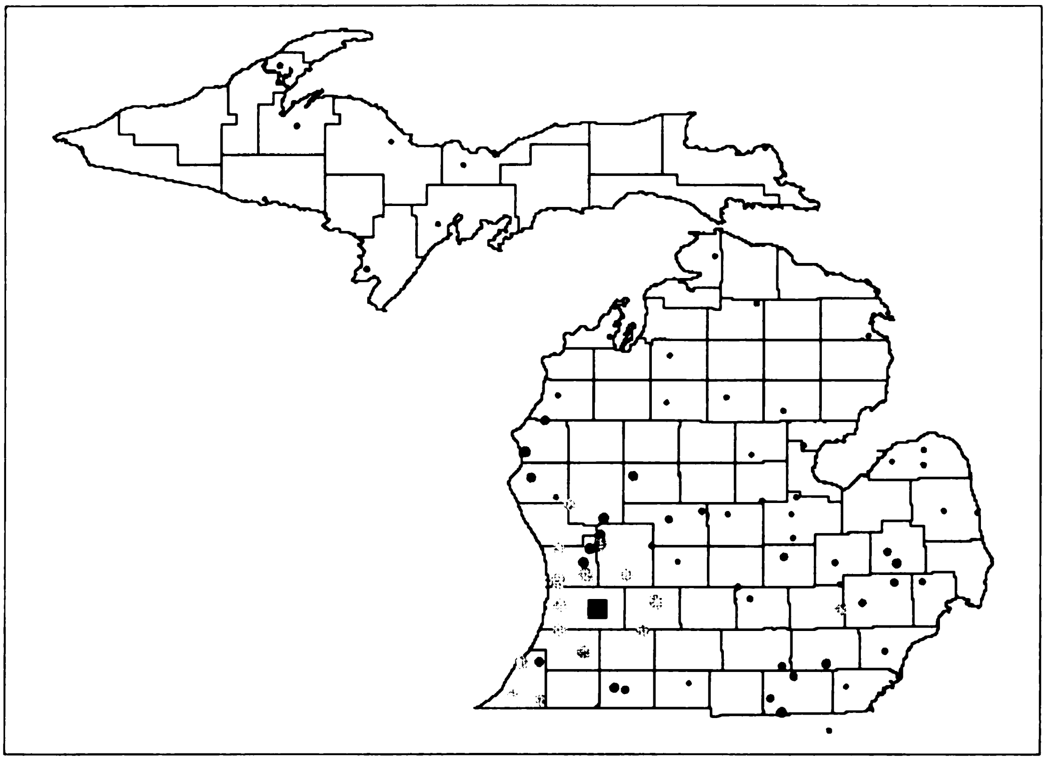

Figure 5.3b. Spatial correlation of weekly precipitation between Allegan (square) and all other stations, May – August 1997. (Size = value of r^2, light color = $r^2 > .50$).

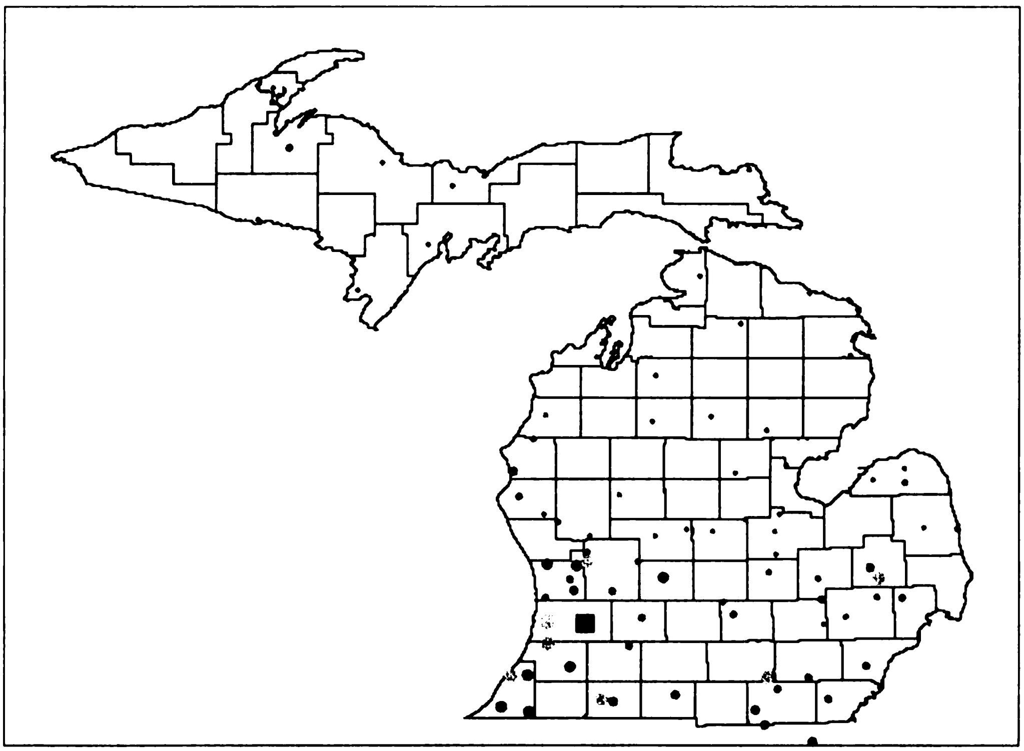

Figure 5.3c. Spatial correlation of weekly precipitation between Allegan (square) and all other stations, May – August 1998. (Size = value of r^2, light color = $r^2 > .50$).

The results for Allegan show the generally negative relationship between r^2 value and distance between stations. Stations in southwest Michigan are likely to be more highly correlated with Allegan precipitation than stations in other parts of the state. As in the Lansing case, none of the Upper Peninsula stations were highly correlated with Allegan. The number of high correlation stations also declined from 1996 to 1998 as in the Lansing case. 47, 17, and 7 stations had r^2 values greater than .50 for 1996, 1997, and 1998 respectively.

Analysis of the rain gauge data has shown the high degree of variability in measured rainfall amounts for the May – August period between rain gauge site located throughout Michigan. In terms of weekly precipitation totals, it can be concluded that higher correlation generally exists between closer stations, but not in all cases. The exceptions to this show that there can be high variability of total precipitation on a weekly basis between stations located a short distance apart. This would lend support for the use of more detailed precipitation estimates (such as the NEXRAD data) in the modeling process.

5.4 NEXRAD Data: Statistical Summary (1996)

The NEXRAD data used in this study were made available on an experimental basis to MSU Agricultural Climatology by the Midwest office of the National Weather Service.

NEXRAD precipitation data were reported at hourly intervals in units of 1/100th mm for cells of approximately 4km x 4km resolution for the state of Michigan. In all, there are 7,446 cells in the State (see Figure 3.3). Because of the experimental nature of this data, it was necessary to perform a partial validation of the data by comparing to rain gauge measurements. The gauge-observed precipitation data from weather stations discussed in the previous sections was used as a basis for comparing NEXRAD and gauge precipitation amounts.

Table 5.4. Minimum, maximum, mean, and standard deviation of May – July precipitation totals (cm.) for all NEXRAD cells, 1996, 1997, and 1998. (* = data corrected for outliers.)

Year	1996	1997	1997*	1998
Min	0.009	0.09	0.09	0.03
Max	135.93	197.39	52.59	45.55
Mean	20.81	28.17	21.45	16.34
SD	9.15	19.11	8.42	5.47

To begin the analysis, precipitation totals for each NEXRAD cell were summed for the 4 month period May 1 – August 31. Table 5.4 summarizes the seasonal totals for all NEXRAD cells. In 1996, the minimum value for total May – August rainfall was .009 cm., and the maximum reported was 135.93 cm.. The mean value for 1996 was 20.81 with a standard deviation of 9.15. Total precipitation values were compared to data from the weather stations. In 1996, the highest reported NEXRAD-reported precipitation total was 135.93 cm., much higher than the highest value by all weather stations (56.03 cm., see Table 5.2). The cell with the extreme value of 135.93 was located in Alger County on the south shore of Lake Superior. The next highest cell had a total of 69.89 cm. of precipitation, and was located adjacent to the highest cell. The third highest cell had a value of 61.04 and was located in Monroe County (Southeast Michigan) along the Lake Erie shoreline. Precipitation totals for all other cells were below 52 cm.. The value of 135.93 cm. is extremely high, more than double it's neighboring cells. The higher probability of fog and cloud cover along Great Lakes shorelines may contribute to these high values. While the three highest values are all higher than expected, they cannot be discounted as they are within potentially feasible ranges.

A number of factors can contribute to errors in radar estimation of precipitation, including ground clutter and instrument calibration. Given the inexact nature of this measurement, we can expect some values to be in the extremes of the distribution, while most should be within expected ranges. This is the case for 1996 NEXRAD data. Figure 5.4 shows a frequency distribution of 1996 precipitation totals for all NEXRAD cells. The frequency distribution illustrates the presence of a few outlier cells in the upper range, and only one cell with a very low value (.09 cm).

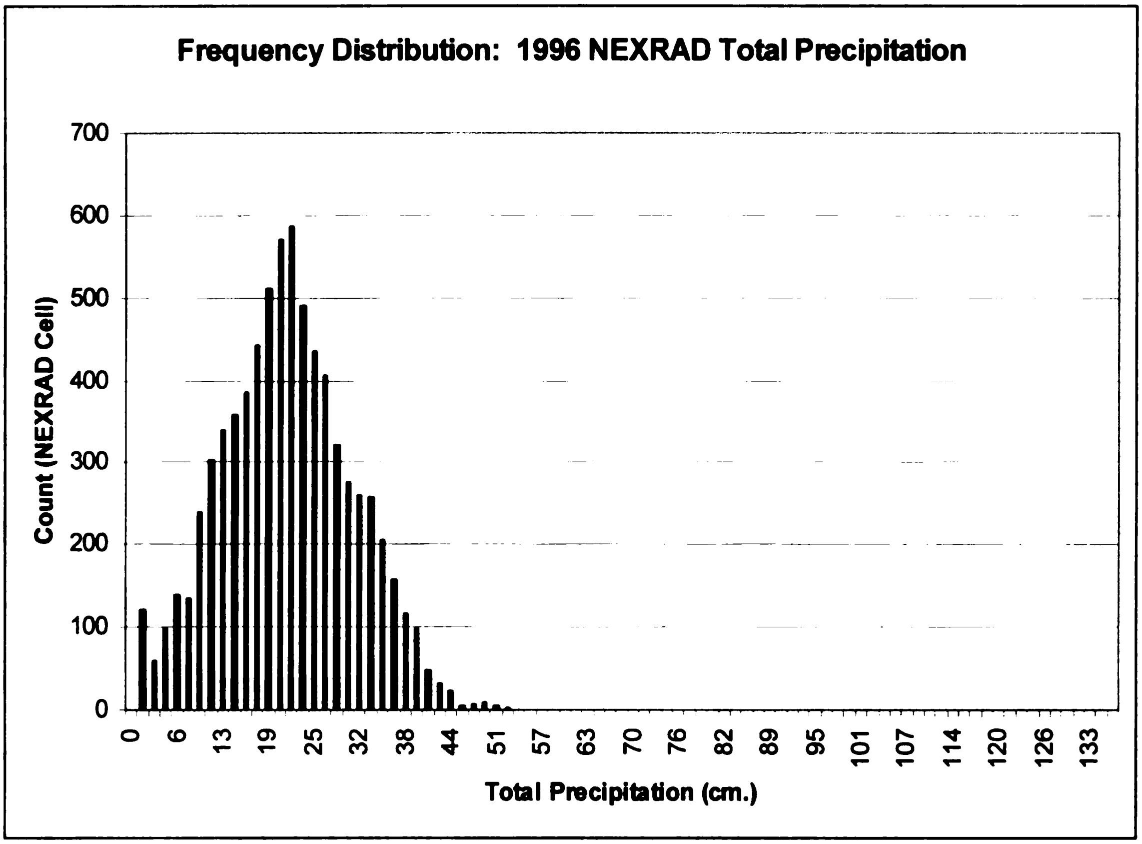

Figure 5.4. Frequency distribution of 1996 NEXRAD precipitation (cm) for the period May 1 – August 31.

In terms of daily rainfall amounts, for 1996 the maximum reported daily precipitation from the 383,157 records was 30.52 cm, with the next value being 16.14, and all other values below 15 cm. While the value of 30.52 cm. is likely not valid, all other values lie within a reasonable (i.e., potential) range of daily precipitation. No data deletions or adjustments were made to the 1996 NEXRAD precipitation data, it was concluded that there were no clearly identifiable outlier values.

Table 5.5. Minimum, maximum, mean, and standard deviation of precipitation totals by month for all NEXRAD cells, 1996.

Month	May	June	July	August
Min	0	0	0	0
Max	38.5	57.9	20.7	21.3
Mean	4.3	6.2	5.1	5.2
SD	3.2	3.9	2.8	2.7

Maps were produced showing the spatial distribution of rainfall by month over the four month period and seasonal totals based on the NEXRAD data. These maps not only provide a visual means of assessing rainfall patterns but also can be used to compare rainfall distribution patterns between NEXRAD and station data. Figures 5.5 a-e show total rainfall by NEXRAD cell for May, June, July, August, and Season Totals for 1996.

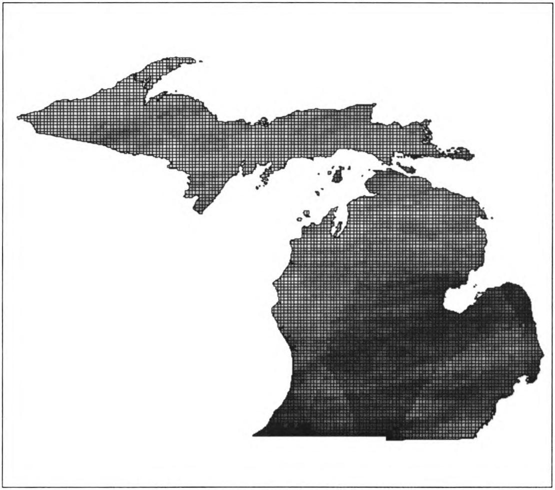

Figure 5.5a. Total precipitation by NEXRAD cell for May, 1996 (Darker color indicates more precipitation).

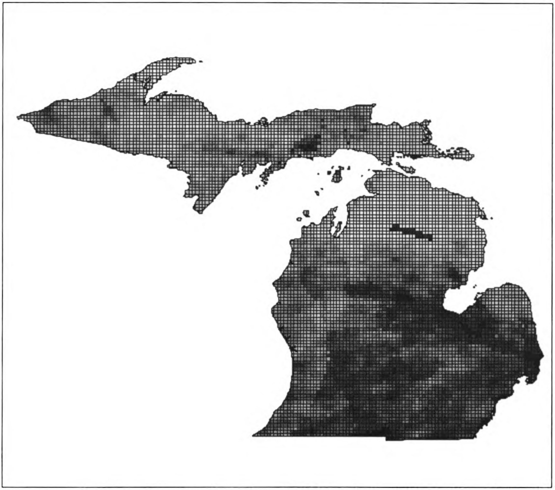

Figure 5.5b. Total precipitation by NEXRAD cell for June, 1996 (Darker color indicates more precipitation).

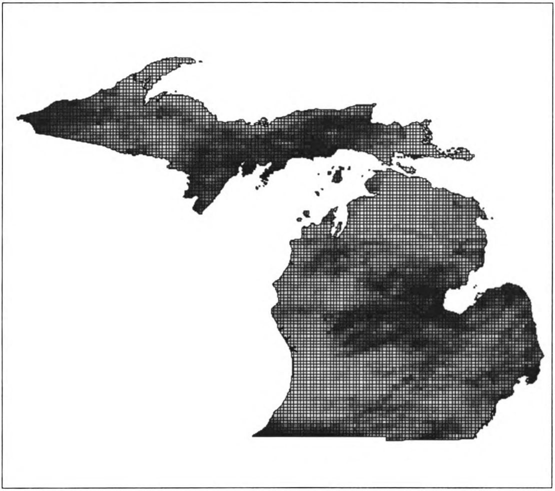

Figure 5.5c. Total precipitation by NEXRAD cell for July, 1996 (Darker color indicates more precipitation).

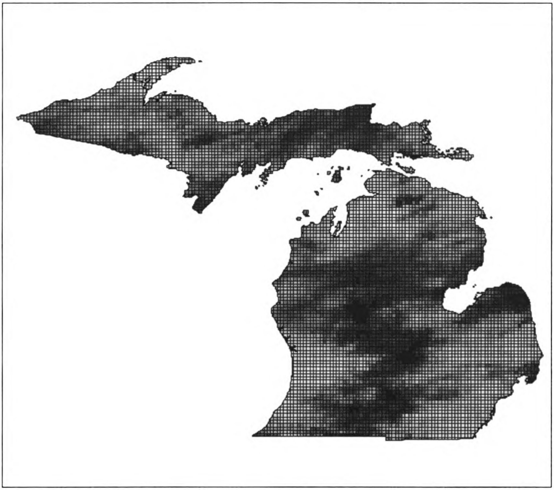

Figure 5.5d. Total precipitation by NEXRAD cell for August, 1996 (Darker color indicates more precipitation).

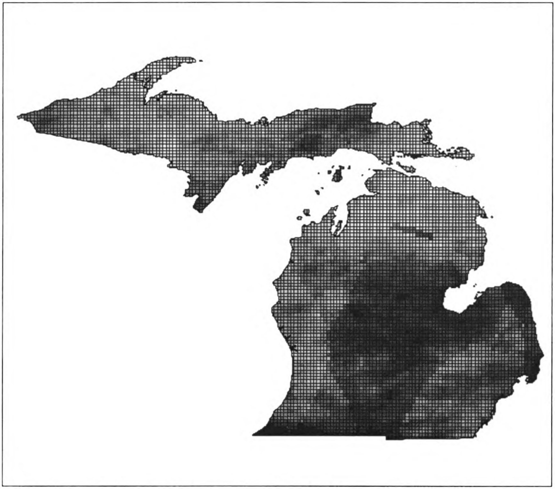

Figure 5.5e. Total precipitation by NEXRAD cell for May – August , 1996 (Darker color indicates more precipitation).

Higher precipitation levels in southwest Michigan are evident from the monthly and seasonal totals shown in Figures 5.5 (a-e). For 1996, spatial distribution of the areas with heaviest rainfall differed by month. In July, for example, the Upper Peninsula experienced relatively more rainfall compared to the rest of the state than in May and June. Figure 5.5e can be compared to Figure 5.1a to visually assess the correlation between NEXRAD precipitation estimates and station totals (rain gauge measurement) for the four month period. The general pattern of higher precipitation in a band from the southwest to the Saginaw Bay area can be seen in both the NEXRAD and the rain gauge precipitation totals. Correspondingly, lower precipitation is seen in other areas of the state, that is, the Upper Peninsula, northern Lower Michigan, and southeast Michigan. A more detailed discussion on the correlation of NEXRAD data and rain gauge measurements will be given later (section 5.6). Figure 5.5a shows the total monthly precipitation by NEXRAD cell for May, 1996. A demarcation of the outer range of the NEXRAD radar appears to be visible in the southeast and southwest portions of the state. These range lines are also visible in the four month totals (Figure 5.5e). The same range line can be seen in the totals for May, 1997 (Figure 5.7a), but not in other months for 1997. The reason for this apparent range-dependent bias for May is currently not known.

5.5 NEXRAD Data: Statistical Summary (1997)

1997 NEXRAD precipitation data were summarized in the same manner as for 1996. Initial analysis showed a maximum cell value of 197.39 cm. for the 4 month totals, a value much higher than any of the reporting weather stations during the 3 year period 1997 – 1998. Inspection of the daily rainfall amounts showed a high value of 171.52 cm., an unrealistically high daily rainfall amount. For comparison, the highest daily rainfall reported for the Station data over the 3 year period was 14.73 cm. This clearly indicates the presence of outlier values containing incorrect values in the 1997 data.

Further investigation revealed that all NEXRAD data with unrealistic precipitation amounts for 1997 was associated with day 182 (July 1, 1997). Most of the high precipitation values for day 182 were in Southeast and North-Central MI but high values (over 50 cm) appeared randomly in some of the Upper Peninsula counties as well. It was initially thought that the outliers on day 182 might be caused by incorrect calibration or data processing that resulted in a systematic shift of the numbers to a higher order of magnitude. A visual comparison with gauge data for day 182 however, revealed little correlation between the NEXRAD data and ground-measured gauge data. Except for isolated high reports, most gauges in Lower Michigan reported 0 or trace rainfall for this day. Lapeer, Dryden, and Chesaning were the highest reporting gauges, with 2.33, 2.06, and 1.83 cm of reported rainfall. 41 of the 91 gauges reported 0 precipitation, 70 of the 91 reported less than .254 cm for this day. Based on the gauge data, this appears to be a day of isolated thunderstorms with localized heavy rainfall in a few areas. For purposes of this analysis, it was decided to eliminate the NEXRAD data for this day on the grounds that precipitation values were unrealistically high and could not be attriuted to invalid calibration or data processing. According, all NEXRAD precipitation values for day 182, 1997 were set to 0. All original values were stored in a table called DATA_PRECIP_ERRS, in the event that they could be useful for tracing errors in the future. The adjusted 1997 NEXRAD data was used for all further analysis. Differences between the original and adjusted 1997 data are shown in Table 5.4.

A frequency distribution of NEXRAD data precipitation totals is shown in Figure 5.6. The frequency distribution shows a bimodal distribution, unlike the more normally distributed values for 1996 (Figure 5.4). While the mean cell value is very similar for the two years (20.8 in 1996, 21.4 in 1997) the distribution across cells is very different. The range of values is much greater for 1996 data, as shown in Table 5.4. In the upper range, the 1996 maximum was 135.93 cm. while the 1997 maximum was 52.59 cm. The distribution of total May – August precipitation differed between 1996 and 1997. In 1996 (Figure 5.5e) more rain was reported in the central part of the state, while in 1997 (Figure 5.7e) the heaviest concentration was in the western part of the state and in portions of Menominee County in the Upper Peninsula. The May totals for 1997 (figure 5.7a) show a range-dependent bias as does the 1996 May totals (Figure 5.5a).

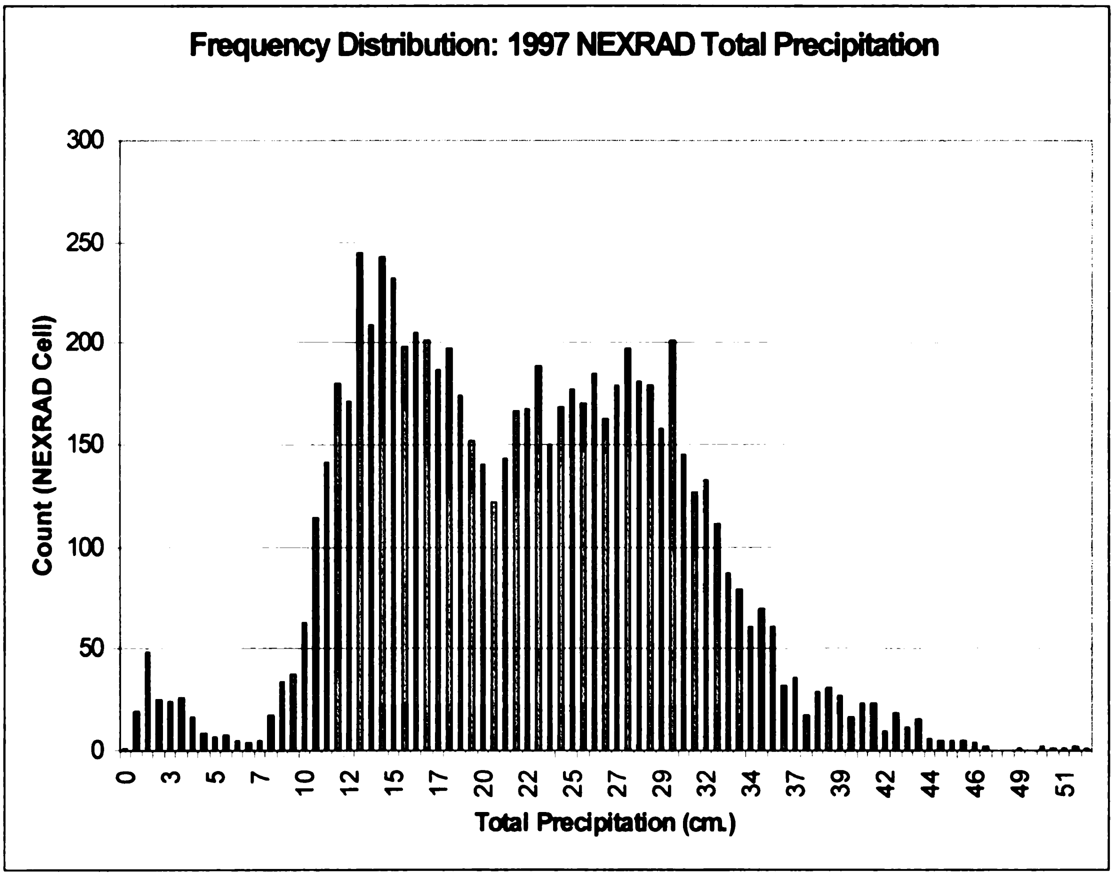

Figure 5.6. Frequency distribution of 1997 NEXRAD precipitation (cm) for the period May 1 – August 31.

Table 5.6. Minimum, maximum, mean, and standard deviation of precipitation totals by month for all NEXRAD cells, 1997.

Month	May	June	July	August
Min	0	0	0	0
Max	16.1	30	24.2	19.5
Mean	3.6	6.7	5.7	5.3
SD	2.6	4.4	2.7	2.4

Maps were produced showing the spatial distribution of rainfall by month over the four month period and seasonal totals based on the NEXRAD data for the 1997 data. Figures 5.7 (a-e) show total rainfall by NEXRAD cell for May, June, July, August, and Season Totals for 1997.

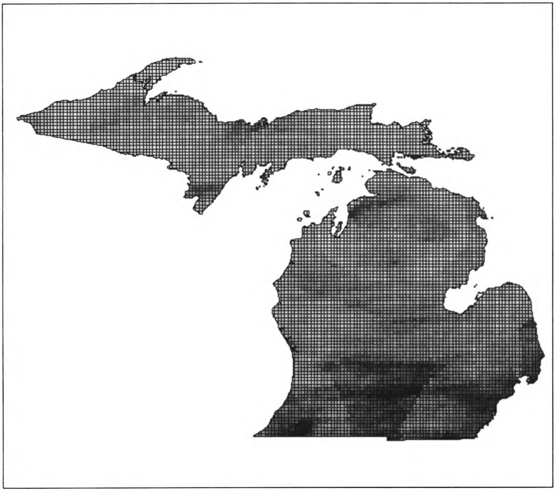

Figure 5.7a. Total precipitation by NEXRAD cell for May, 1997 (Darker color indicates more precipitation).

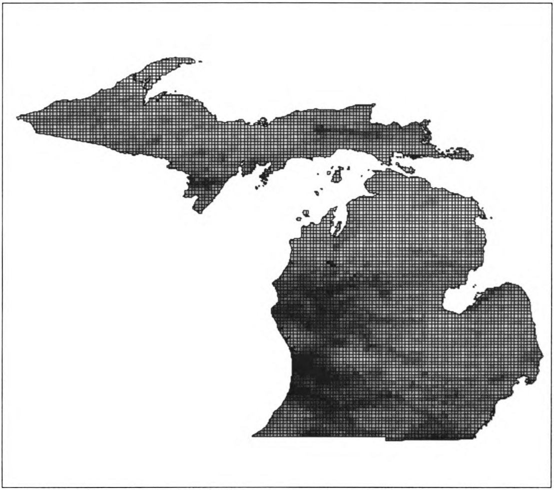

Figure 5.7b. Total precipitation by NEXRAD cell for June, 1997 (Darker color indicates more precipitation).

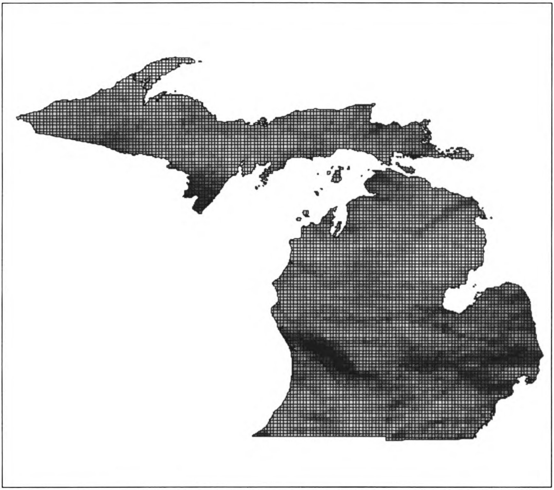

Figure 5.7c. Total precipitation by NEXRAD cell for July, 1997 (Darker color indicates more precipitation).

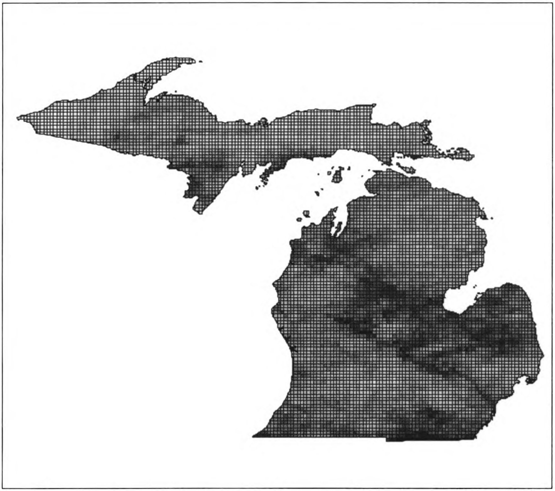

Figure 5.7d. Total precipitation by NEXRAD cell for August , 1997 (Darker color indicates more precipitation).

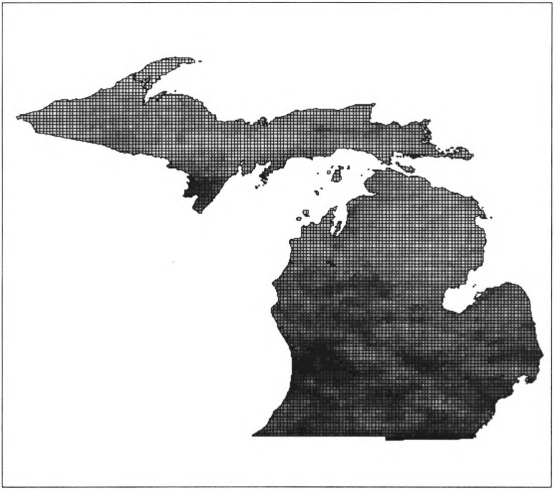

Figure 5.7e. Total precipitation by NEXRAD cell for May – August , 1997 (Darker color indicates more precipitation).

5.6 NEXRAD Data: Statistical Summary (1998)

The range of May - August precipitation totals for 1998 NEXRAD data was .03 to 45.55 cm (Table 5.4). Because the maximum value of 45.55 cm. is within feasible amounts, no outlier correction was necessary for 1998 NEXRAD precipitation data. Comparison of the mean value for all NEXRAD cells in 1998 with 1996 and 1997 reveals the lower amount of summer precipitation for 1998. Mean values were 20.8, 21.4, and 16.3 cm. for

1996, 1997, and 1998 respectively (Table 5.4). Table 5.7 shows a statistical summery by month for 1998, which shows that the lower 1998 precipitation totals were largely due to a very dry July period. Monthly averages for the other three months are comparable to 1996 and 1997 values, however July is significantly lower. The frequency distribution of 1998 NEXRAD cell totals is shown in Figure 5.8. Unlike the 1997 bimodal distribution (Figure 5.6) the 1998 distribution more closely approximates the classical normal distribution. As for 1996 and 1997, the distribution of monthly and seasonal precipitation totals for 1998 are shown in Figure 5.9 (a-e).

Table 5.7. Minimum, maximum, mean, and standard deviation of precipitation totals by month for all NEXRAD cells, 1998.

Month	May	June	July	August
Min	0	0	0	0
Max	13.6	18.5	12.7	31.4
Mean	3.1	5.4	2.2	5.6
SD	1.7	2.8	1.7	3

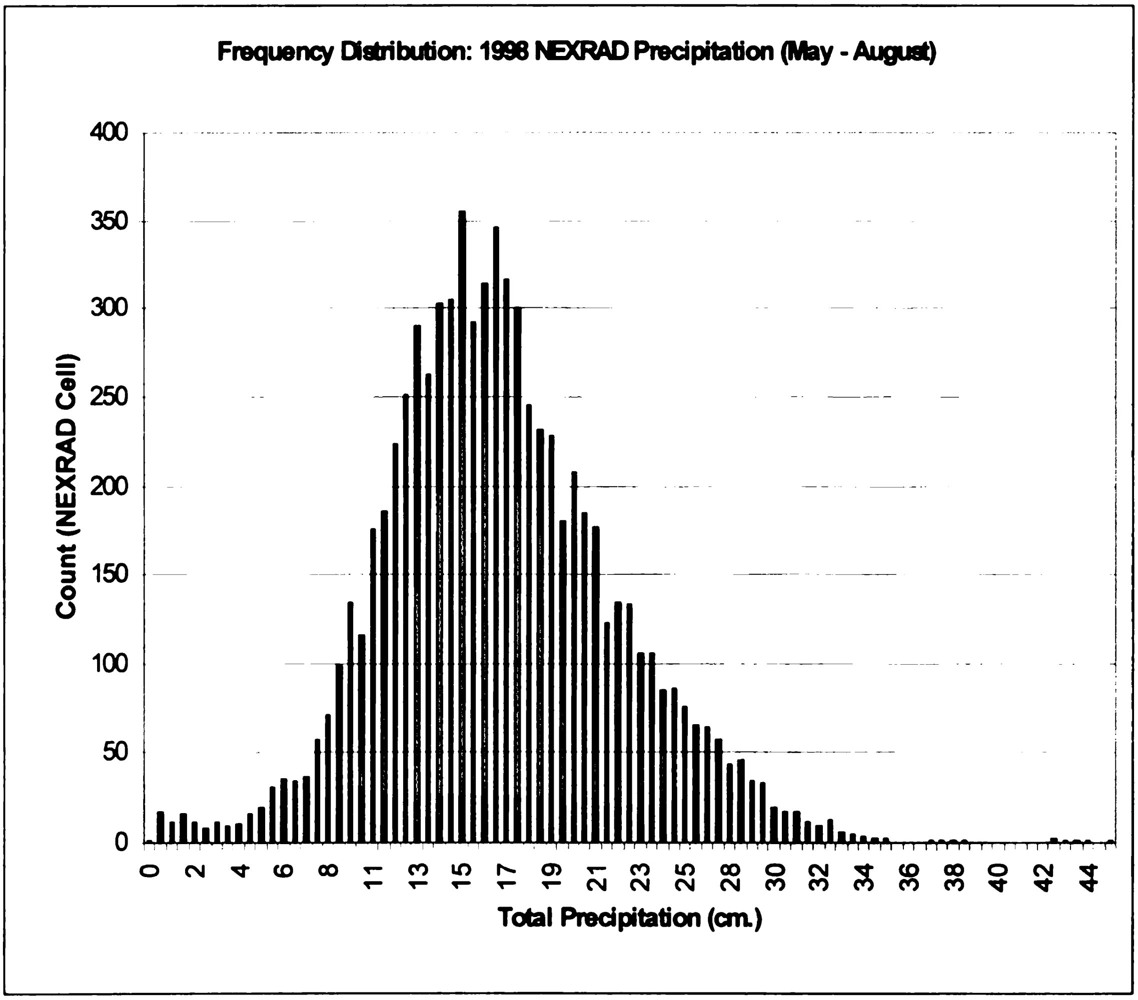

Figure 5.8. Frequency distribution of 1998 NEXRAD precipitation (cm) for the period May 1 – August 31.

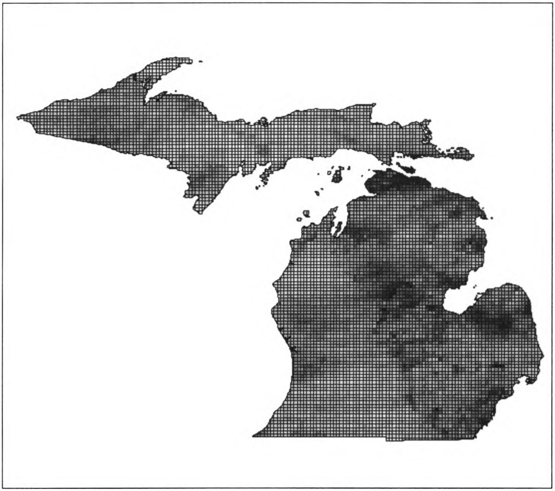

Figure 5.9a. Total precipitation by NEXRAD cell for May, 1998 (Darker color indicates more precipitation).

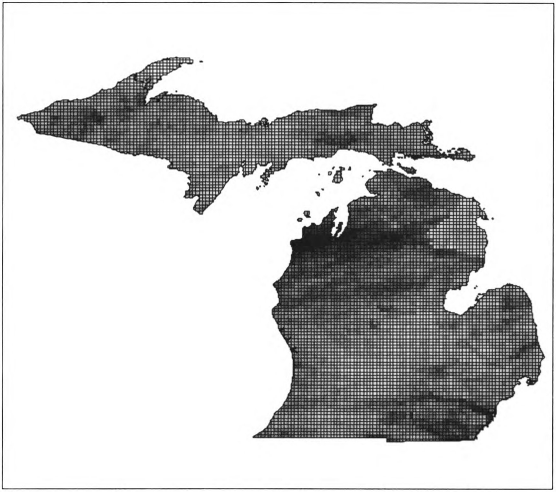

Figure 5.9b. Total precipitation by NEXRAD cell for June, 1998 (Darker color indicates more precipitation).

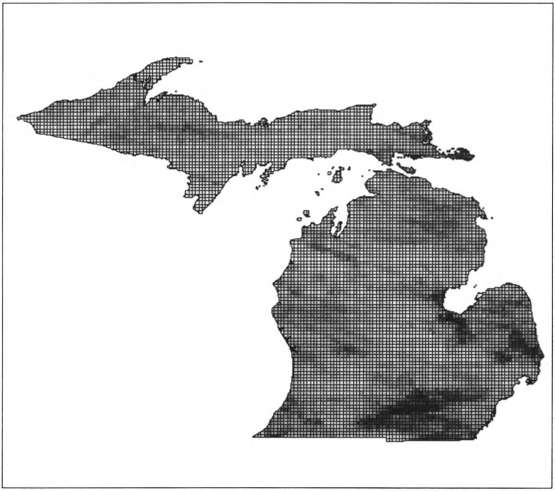

Figure 5.9c. Total precipitation by NEXRAD cell for July, 1998 (Darker color indicates more precipitation).

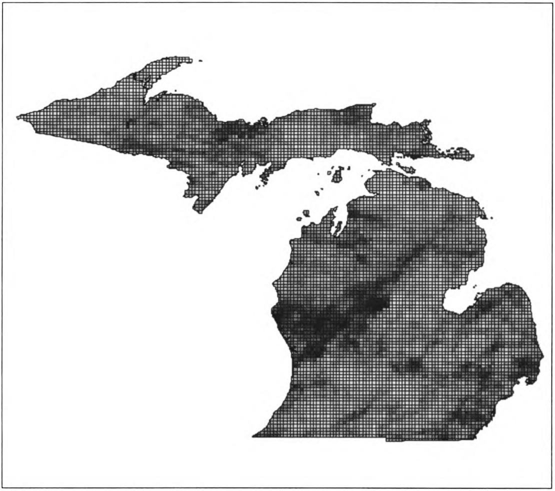

Figure 5.9d. Total precipitation by NEXRAD cell for August, 1998 (Darker color indicates more precipitation).

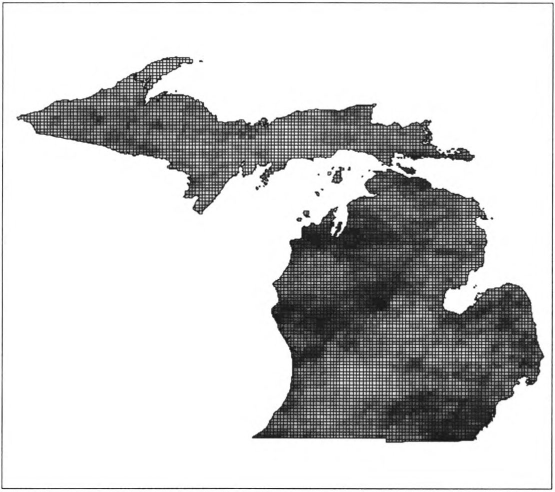

Figure 5.9e. Total precipitation by NEXRAD cell for May – August, 1998 (Darker color indicates more precipitation).

5.7 Correlation Between Rain Gauge and NEXRAD Precipitation Data

The literature reviewed in chapter II pertaining to the validation of radar data showed generally good agreement between rain gauge measured data and radar estimates, although radar estimates tended to show less precipitation than rain gauges. These studies were conducted in an experimental setting with greater control and a higher density of rain gauges than is often encountered in an operational setting. Readily available precipitation estimates are usually only available from a relatively sparse network of weather stations, as is the case for Michigan. Because of this, a complete validation of the NEXRAD data is not possible in this study. However, assessment of the degree of association and correlation between NEXRAD data and available station data provides valuable information. If the two data sources are highly correlated and show similar values, then the potential exists for using station data as a surrogate for NEXRAD data, if NEXRAD data are not available. If they are not highly correlated or do not show good agreement, then further investigation and more detailed research will be necessary to explain the discrepancies.

In the first phase of this analysis, the seasonal (May – August) totals for each rain gauge station are compared to the NEXRAD seasonal totals for the NEXRAD cell in which the station is located. It should be a fair assumption that seasonal rainfall totals will not be highly variable within a 4 km area of a given point (or rain gauge). Given this assumption, and the assumption that rain gauge measurement is accurate, then we would expect to see a high correlation between the rain gauge measured precipitation and the NEXRAD measured precipitation for the same area. Table 5.6 shows total May – August precipitation measured by each of the 79 common stations for the two years 1996 - 1998. The R/G ratio, calculated as Radar Total/ Gauge Total, is also shown. The R/G ratio gives an indication of the relative discrepancy between the two estimates. Table 5.7 summarizes the results of this comparison. For 1996, the difference between radar and gauge reported precipitation totals ranged from -24.1 to +9.2 cm. That is, the radar estimate for one cell was 24.1 cm less than the rain gauge estimate in the cell, while another radar estimate was 9.2 cm. more than reported by the rain gauge. The average discrepancy was -10.6 cm. in 1996, -5.5 cm. in 1997, and –7.5 cm in 1998. The average R/G ratio was .68, .83, and .75 for 1996, 1997, and 1998, respectively.

Frequency distributions of the R/G ratio for 1996 – 1998 are shown in Figures 5.8a, 5.8b, and 5.8c, respectively. The frequency distributions shown in Figure 5.8 illustrate the tendency for NEXRAD estimates of precipitation to be lower than gauge measured precipitation. Assuming that the range of .7 to 1.3 for the R/G ratio is a range of reasonably good correlation, in 1996, 29 of 83 stations (35%) were within this range. For 1997, 58 of 89 (65%) and for 1998 41 of 88 (47%) were within the range of .7 to 1.3.

Table 5.8. May – August precipitation totals (cm.) for NEXRAD Radar (R) and Rain Gauge (G) and R/G ratio for all stations reporting in 1996, 1997, and 1998.

	1996			1997			1998		
Station	R	G	R/G	R	G	R/G	R	G	R/G
ALLEGAN	18.6	34.1	0.55	35.5	43.3	0.82	16.9	29.5	0.57
ALLENDALE	15.4	33.2	0.46	41.7	30.9	1.35	26.9	21.4	1.26
ALMA	33.5	39.0	0.86	24.0	22.4	1.07	11.1	14.5	0.77
ALPENA	11.1	21.8	0.51	12.4	28.8	0.43	10.9	22.4	0.49
BADAXE	28.2	48.2	0.59	21.5	37.7	0.57	23.3	20.8	1.12
BALDWIN	16.3	27.0	0.60	43.1	36.2	1.19	26.3	23.8	1.11
BEARLAKE	18.2	25.7	0.71	22.7	28.0	0.81	18.2	22.8	0.80
BEAVERTON	41.4	46.2	0.90	21.0	25.6	0.82	18.9	13.0	1.45
BELDING	29.4	42.2	0.70	23.9	24.4	0.98	19.9	23.9	0.83
BEULAH	19.2	31.5	0.61	29.3	29.9	0.98	22.9	23.6	0.97
BIGRAPIDS	16.8	35.8	0.47	30.6	32.6	0.94	20.5	19.0	1.08
BROOKLYN	21.6	28.5	0.76	29.4	29.4	1.00	21.3	36.4	0.59
CENTREVL	30.5	32.4	0.94	28.8	38.4	0.75	15.5	27.1	0.57
CHATHAM	14.7	33.6	0.44	15.9	26.1	0.61	16.4	24.0	0.68
CHESANING	33.1	40.3	0.82	22.0	26.2	0.84	14.1	16.6	0.85
COLDWATER	37.9	33.0	1.15	24.4	24.2	1.01	18.3	44.1	0.41
CORNELL	20.7	33.6	0.62	18.2	33.1	0.55	10.2	23.6	0.43
DETROIT	17.0	17.6	0.97	34.4	33.4	1.03	25.9	35.3	0.73
DUNDEE	20.1	26.5	0.76	29.7	31.9	0.93	28.2	40.3	0.70
EATNRAPIDS	28.0	28.5	0.98	29.1	34.6	0.84	9.9	35.6	0.28

Table 5.8 (Cont'd)

	1996			1997			1998		
Station	R	G	R/G	R	G	R/G	R	G	R/G
ENTRICAN	32.2	48.7	0.66	31.6	31.6	1.00	22.5	17.4	1.29
FENNVILLE	17.9	32.7	0.55	33.8	27.7	1.22	20.6	30.7	0.67
FENTON	17.3	25.3	0.68	29.3	30.8	0.95	17.0	22.4	0.76
FLINT	20.6	19.9	1.04	24.5	25.8	0.95	9.2	14.2	0.65
FREMONT	17.2	29.5	0.58	29.7	36.7	0.81	26.7	28.5	0.94
GLENDORA	43.2	56.0	0.77	28.7	38.8	0.74	20.8	33.1	0.63
GRANDJUNC	19.8	32.8	0.60	37.9	36.1	1.05	16.4	27.9	0.59
GRANT	20.0	36.5	0.55	27.7	28.6	0.97	24.3	22.6	1.08
GRAPIDS	25.8	31.3	0.82	38.1	23.8	1.60	14.0	20.9	0.67
GULLLAKE	27.5	32.7	0.84	30.0	36.6	0.82	13.3	28.1	0.47
HASTINGS	27.5	33.5	0.82	38.6	27.6	1.40	5.5	30.7	0.18
HOLLAND	21.6	44.8	0.48	39.4	38.3	1.03	25.3	24.7	1.02
HOUGHTON	1.2	24.0	0.05	3.0	17.6	0.17	8.3	17.5	0.47
HTNLAKE	23.5	33.0	0.71	18.7	26.3	0.71	18.9	14.7	1.29
HUDSNVLLE	17.1	33.3	0.51	36.6	38.5	0.95	19.9	20.7	0.96
HUDSON	25.1	24.5	1.02	31.6	39.5	0.80	19.2	46.1	0.42
IONIA	26.6	34.2	0.78	21.0	27.3	0.77	14.8	20.2	0.73
IRONWOOD	21.2	38.1	0.56	14.0	38.9	0.36	9.5	35.1	0.27
KALKASKA	12.1	26.0	0.47	18.4	26.3	0.70	32.1	26.3	1.22
KENTCITY	19.8	36.6	0.54	33.1	29.6	1.12	23.1	19.9	1.16
LAKECITY	18.8	35.7	0.53	23.0	38.3	0.60	19.7	15.8	1.25
LANSING	37.5	35.9	1.04	25.2	27.1	0.93	17.3	23.7	0.73
LUDINGTON	14.7	22.1	0.67	26.3	30.6	0.86	19.9	20.6	0.97
MARQUETTE	6.3	30.4	0.21	8.1	27.9	0.29	12.6	21.8	0.58
MORENCI	28.5	39.6	0.72	44.0	43.1	1.02	20.8	45.3	0.46
MSUHORT	24.6	28.8	0.85	24.8	27.3	0.91	14.5	27.0	0.54
MTCLEMENS	25.1	25.3	0.99	24.5	35.0	0.70	15.2	28.1	0.54
MUNISING	13.0	34.8	0.37	17.5	26.1	0.67	16.0	21.3	0.75
MUSKEGON	17.4	26.2	0.66	25.4	26.2	0.97	18.7	17.6	1.06
NILES	38.5	53.7	0.72	36.0	48.6	0.74	17.5	35.8	0.49
NORTHPORT	13.0	25.8	0.50	15.3	26.8	0.57	21.0	31.5	0.67
NUNICA	14.6	30.8	0.47	32.1	38.7	0.83	18.7	22.4	0.83
NWMIHORT	10.3	22.6	0.46	15.9	24.8	0.64	24.7	25.5	0.97
OLDMISSION	8.8	23.0	0.38	17.3	26.6	0.65	23.9	34.4	0.69
OSSINEKE	13.7	27.8	0.49	9.9	31.9	0.31	9.5	26.5	0.36
OWOSSO	26.6	35.2	0.76	22.1	30.7	0.72	15.2	19.0	0.80
OXFORD	25.7	34.9	0.74	25.3	33.7	0.75	16.3	25.2	0.65
PAWPAW	23.2	35.4	0.66	34.2	36.0	0.95	14.2	32.1	0.44
PEACHRIDG	20.1	39.1	0.51	40.9	26.7	1.53	25.4	20.0	1.27
PELLSTON	4.5	21.0	0.21	17.8	20.9	0.85	14.0	16.8	0.83
PIGEON	28.0	33.7	0.83	30.6	29.7	1.03	14.7	17.7	0.83
PORTSANILA	20.8	35.8	0.58	24.9	36.1	0.69	16.7	19.1	0.87
ROGERCITY	10.0	27.8	0.36	10.4	23.1	0.45	15.3	24.2	0.63
ROMEO	25.3	31.9	0.79	22.6	34.2	0.66	16.0	22.3	0.72

Table 5.8 (Cont'd)

	1996			1997			1998		
Station	R	G	R/G	R	G	R/G	R	G	R/G
SAGINAW	32.0	47.1	0.68	25.0	37.9	0.66	11.5	14.7	0.78
SAGVALLEY	34.5	36.8	0.94	20.9	26.5	0.79	14.3	14.8	0.97
SALINE	22.3	22.6	0.99	27.4	31.9	0.86	25.7	37.4	0.69
SSMARIE	10.2	29.5	0.35	18.4	20.0	0.92	14.1	28.4	0.50
STAMBAUGH	19.9	39.2	0.51	17.9	31.4	0.57	16.1	29.3	0.55
STANDISH	39.5	44.2	0.89	20.1	27.2	0.74	14.5	20.8	0.70
STEPHENSON	21.5	32.8	0.66	41.2	32.4	1.27	13.0	23.8	0.55
SWMIHORT	21.1	37.4	0.56	28.5	36.1	0.79	16.2	27.9	0.58
THREERIVER	31.2	33.2	0.94	30.6	48.6	0.63	15.8	26.7	0.59
TIPTON	24.7	27.6	0.89	32.4	34.1	0.95	23.6	36.5	0.65
VANDERBILT	5.7	28.6	0.20	10.7	23.8	0.45	14.2	23.7	0.60
VESTABURG	32.3	46.4	0.70	27.2	27.2	1.00	17.5	14.7	1.19
WATERVLIET	21.9	30.4	0.72	26.6	35.5	0.75	20.5	28.8	0.71
WESTBRANCH	24.0	40.7	0.59	15.6	35.5	0.44	13.4	23.4	0.57

Table 5.9. Summary of differential between radar and gauge-measured precipitation for a) May – August totals, 1996 – 1998 and b) July –August totals. n = number of stations, Min = minimum of radar – gauge (cm.), Max = maximum of radar – gauge (cm.), Mean = mean of radar – gauge, R/G = radar/gauge, and SD = standard deviation of R/G.

a) May – August

Year	n	Min	Max	Mean	R/G	SD
1996	83	-24.1	9.2	-10.6	.68	.25
1997	89	-27.8	14.3	-5.5	.83	.26
1998	88	-26.9	5.8	-7.5	.75	.27

b) July - August

Year	n	Min	Max	Mean	R/G	SD
1996	83	-15.2	9.5	-1.8	.91	.41
1997	89	-18.6	14.3	-2.7	.88	.38
1998	88	-23.1	8.2	-4.8	.74	.27

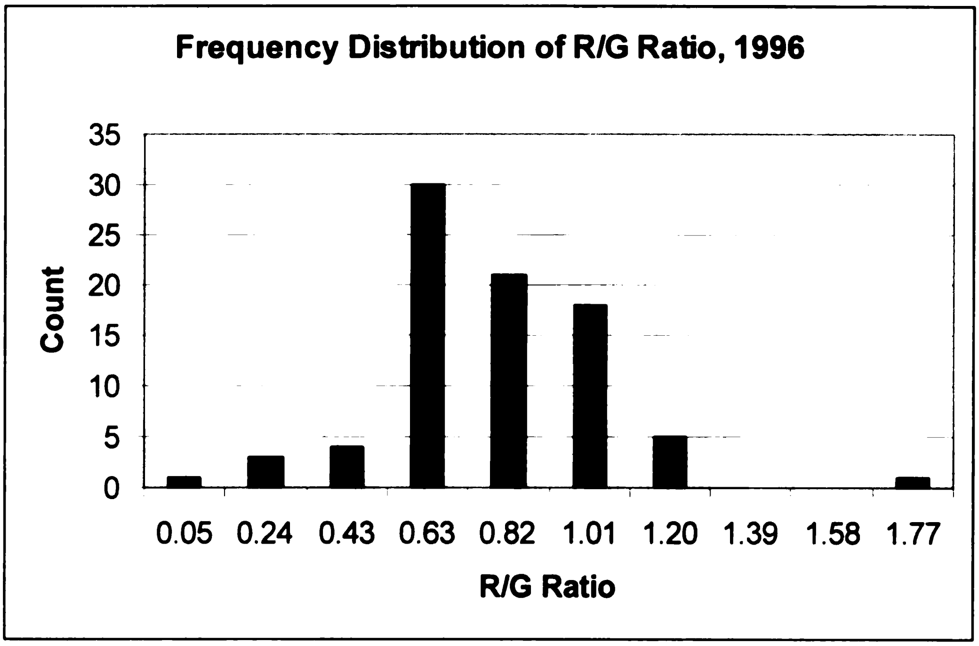

Figure 5.10a. Frequency distribution of R/G ratio, 1996.

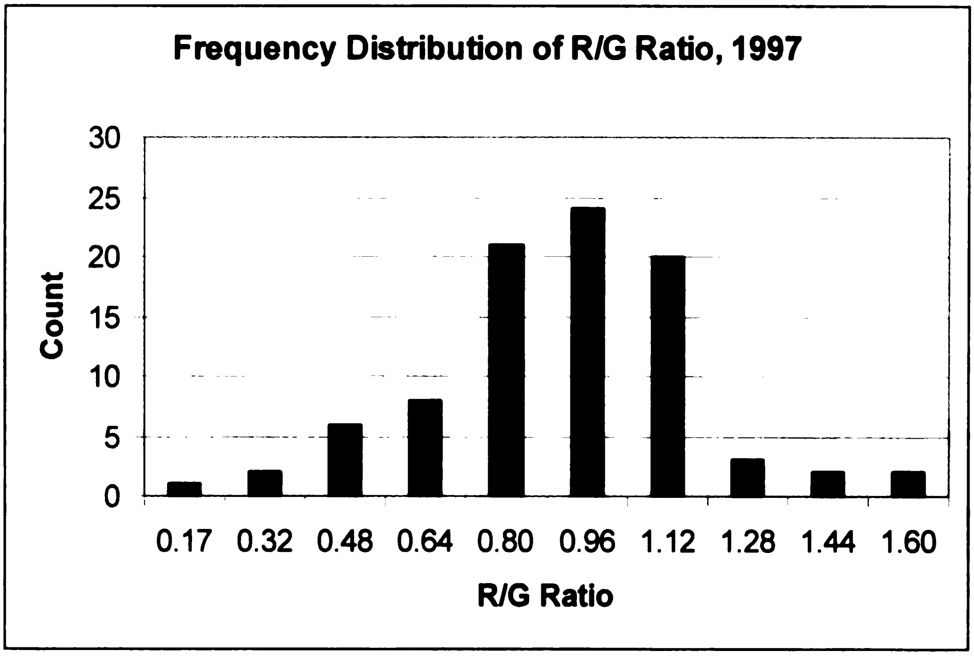

Figure 5.10b. Frequency distribution of R/G ratio, 1997.

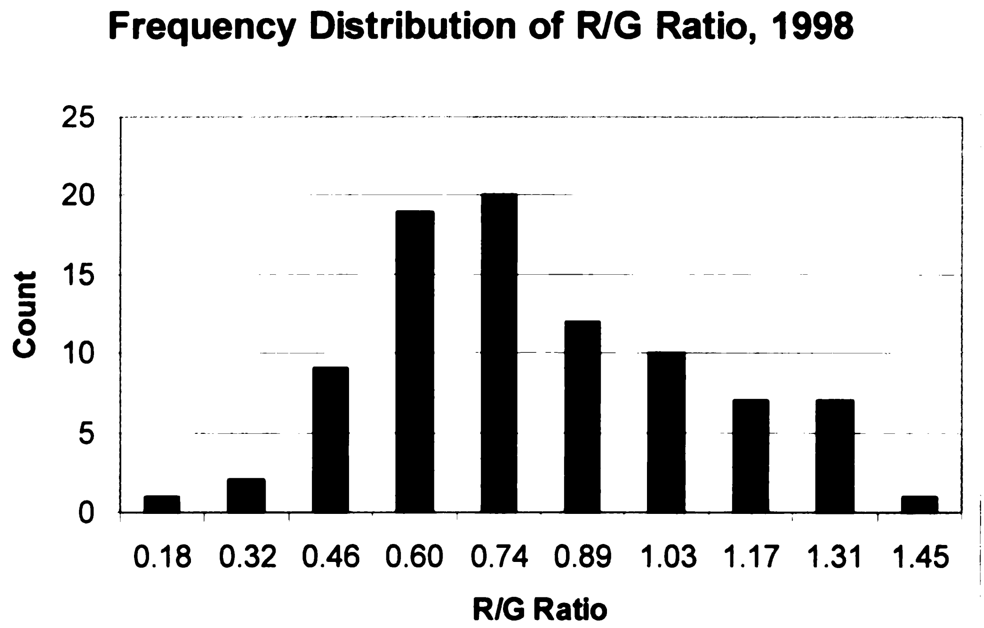

Figure 5.10c. Frequency distribution of R/G ratio, 1998.

Maps were produced to assess the spatial pattern of correlation between the radar (R) and rain gauge (G) precipitation totals for 1996 – 1998 (figures 5.11 a-c). Values of the R/G ratio in the range of .7 – 1.3 are shown as the darker color. The size of the circle indicates the value of the R/G ratio. Two patterns emerge from these maps; consistently lower NEXRAD precipitation estimates in the Upper Peninsula and northern Lower Michigan compared to rain gauges, and, consistently better agreement between NEXRAD and rain gauge estimates in southern and central Michigan. In Figure 5.11b it can be seen that most of the R/G ratios in the southern and central part of the state (where most irrigation takes place) fall within the .7 – 1.3 range. Of note are the values for Huron and Sanilac counties (the 'thumb' area), which show low R/G ratios for both 1996 and 1997.

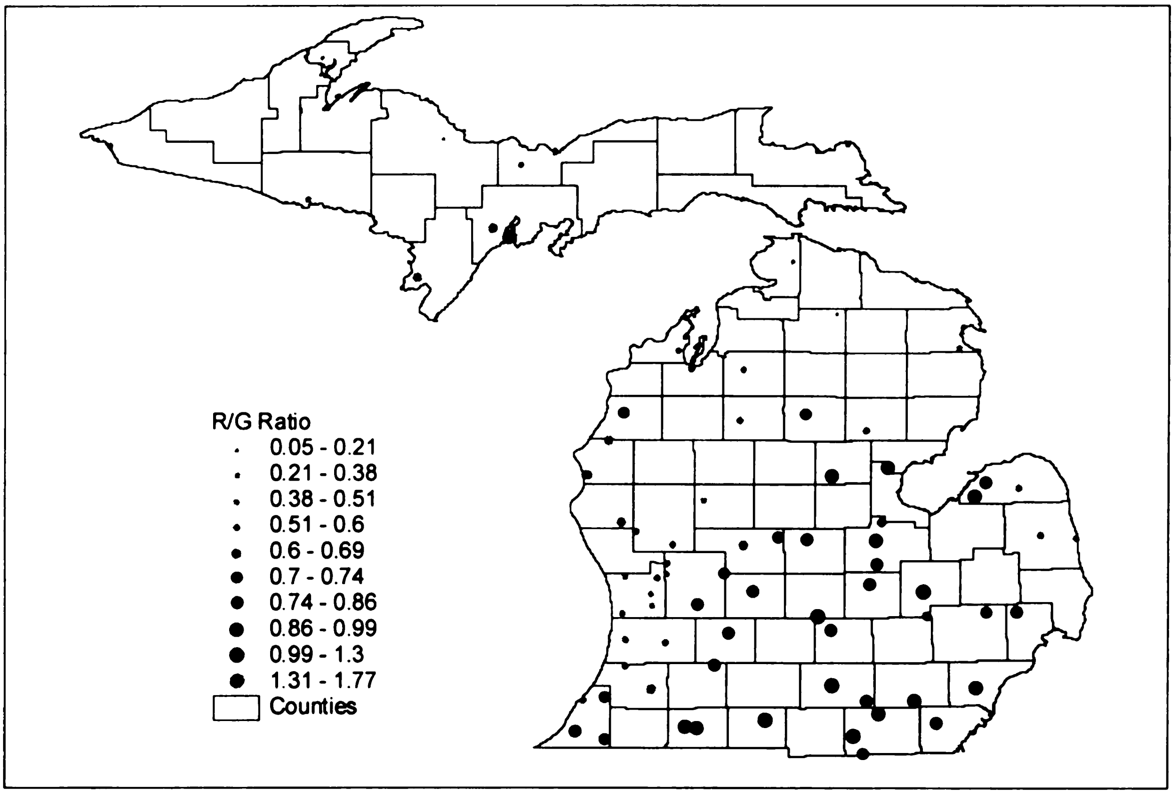

Figure 5.11a. Spatial distribution of the R/G ratio, 1996.

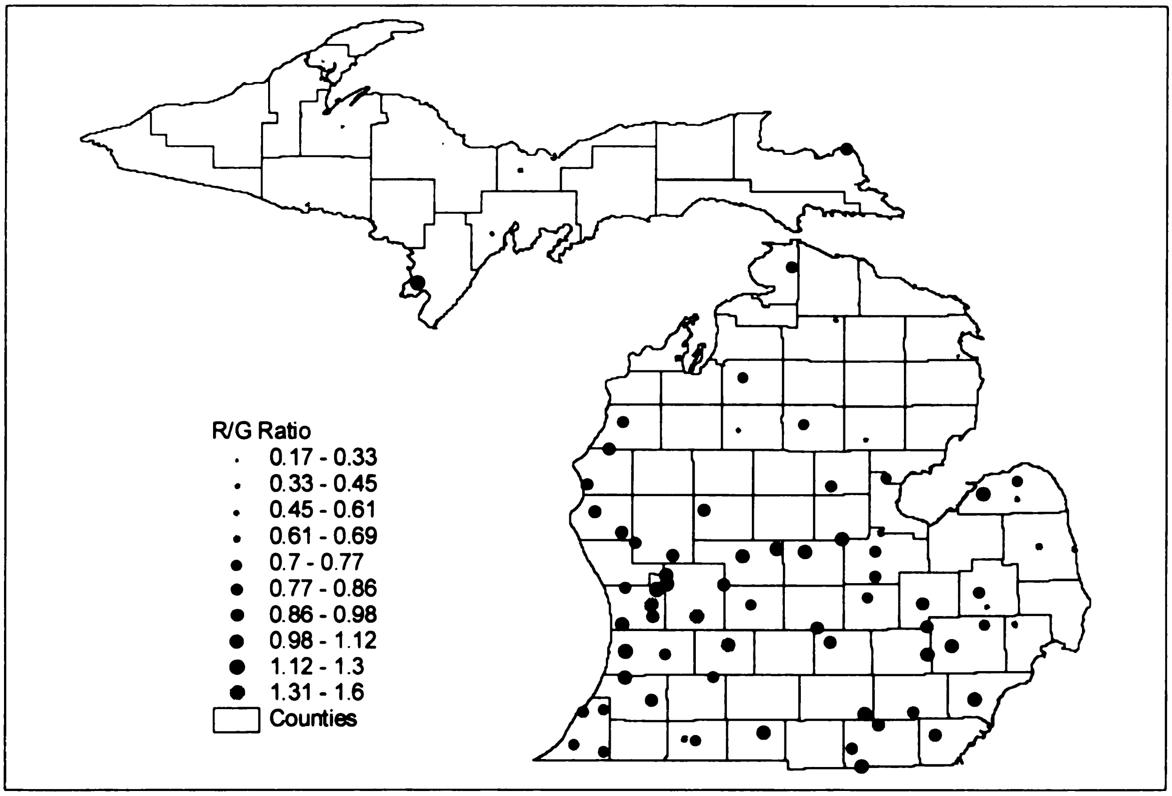

Figure 5.11b. Spatial distribution of the R/G ratio, 1997.

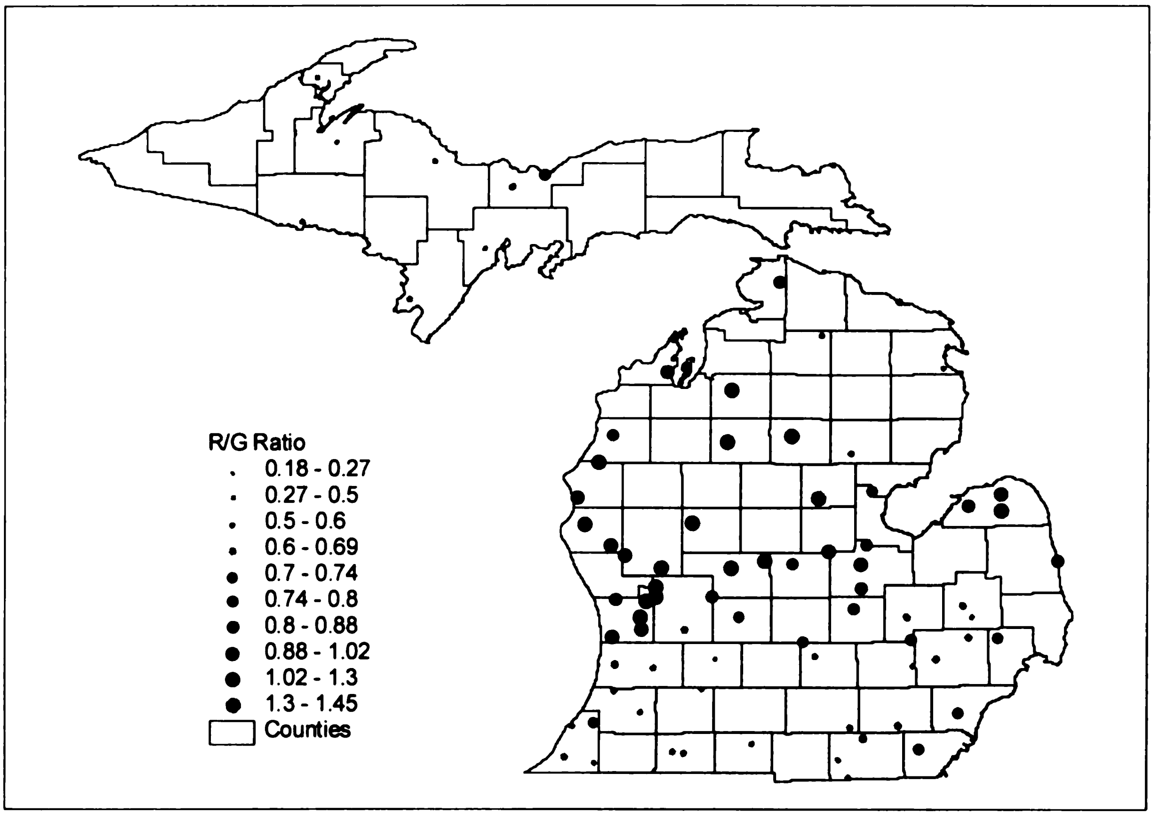

Figure 5.11c. Spatial distribution of the R/G ratio, 1998.

R/G ratios for 1998 indicate better agreement between radar and gauge estimates in the central part of the state, with lower radar estimates for most sites in the southern and northern parts of the state. Spatial grouping of the R/G ratio can be seen for all three years, but this pattern differs each year. Such patterns may be indicative of calibration-based errors in the NEXRAD data.

To visually assess the correlation between rain gauge observed precipitation levels and radar estimates, figures 5.12 a – c show the rain gauge totals super-imposed on the NEXRAD totals for 1996 – 1998.

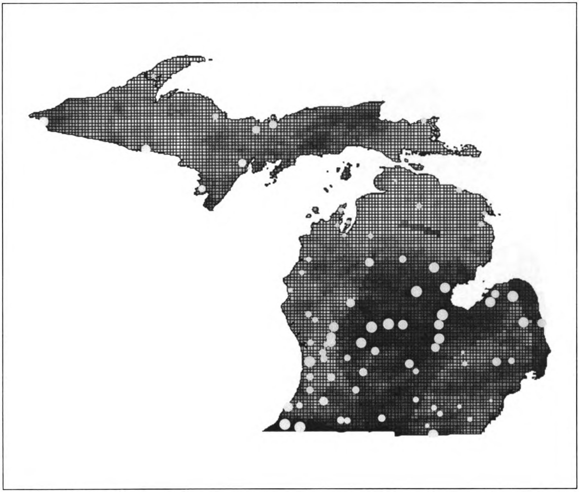

Figure 5.12a. Rain gauge totals versus NEXRAD totals for May - August 1996. (Size indicates value of the gauge observation)

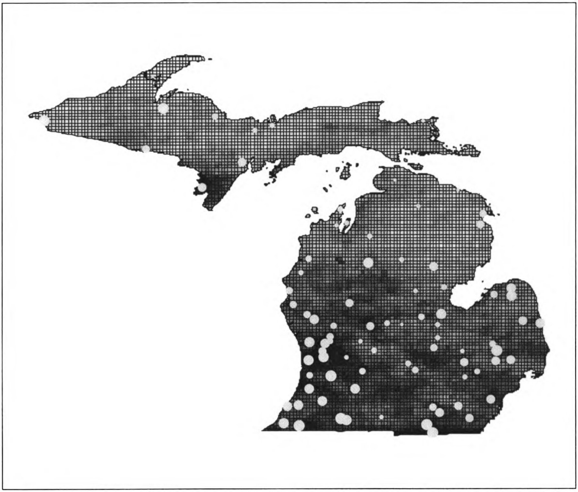

Figure 5.12b. Rain gauge totals versus NEXRAD totals for May - August 1997. (Size indicates value of the gauge observation)

Figure 5.12c. Rain gauge totals versus NEXRAD totals for May - August 1998. (Size indicates value of the gauge observation)

The above analysis has been concerned with the correlation of seasonal totals (May – August) of precipitation between rain gauges and NEXRAD. Another important consideration is the timing of rainfall over the course of a season. In order to assess this, the coefficient of determination (r^2) was calculated for weekly precipitation totals between each station and the nearest NEXRAD cell. Results of this analysis are shown in Table 5.8. Simple linear regression was used to estimate the equation:

$$y = a + bx \qquad \text{(Eq. 5.1)}$$

Where

y = Radar (NEXRAD) precipitation

a = y intercept

b = slope

x = Rain gauge observation.

For 1996, 55 of the 83 sites had r^2 values greater then .50. In 1997, only 11 of the 89 stations had r^2 values greater then .50 (Table 5.10) and in 1998, 19 of 88 sites had r^2 values greater then .50. While the correlation between radar and gauge seasonal totals for 1997 appeared to be best for the three analysis years, correlation of the weekly totals was the weakest for 1997. For 1997 and 1998, the general conclusion can be made that for most rain gauge sites, changes in gauge-measured precipitation on a weekly basis had little correlation with the NEXRAD measured weekly precipitation for the surrounding area. Results are shown for 1996 – 1998 in Figures 5.13 a – c.

Table 5.10. Summary of linear regression of 1997 weekly NEXRAD precipitation totals on Gauge totals, ordered by r^2 (descending).

Station	a	b	r-squared
DRYDEN	0.221	0.493	0.68
KALKASKA	0.107	0.623	0.66
GRANT	0.122	0.889	0.57
FREMONT	0.055	0.782	0.56
GULLLAKE	0.164	0.731	0.54
IONIA	0.097	0.706	0.54
FLINT	0.542	0.553	0.52

Table 5.10 (Cont'd)

Station	a	b	r-squared
WHEELER	0.236	0.865	0.51
MTCLEMENS	0.431	0.469	0.51
SAGVALLEY	0.072	0.741	0.5
NILES	0.291	0.624	0.5
LUDINGTON	0.28	0.684	0.48
PELLSTON	0.35	0.528	0.48
MUNISING	0.205	0.516	0.46
CHATHAM	0.106	0.535	0.45
LANSING	0.589	0.517	0.44
HTNLAKE	0.508	0.343	0.41
PEACHRIDG	0.711	1.022	0.4
NUNICA	0.449	0.608	0.38
SALINE	0.397	0.622	0.38
BEAVERTON	0.54	0.422	0.36
HART	0.185	0.845	0.35
IRONMTN	0.323	0.768	0.35
DETROIT	0.73	0.613	0.35
ROMEO	0.541	0.36	0.34
ROGERCITY	0.223	0.265	0.32
SAGINAW	0.194	0.558	0.31
OLDMISSION	0.5	0.296	0.31
BIGRAPIDS	0.581	0.605	0.3
ENTRICAN	0.371	0.78	0.29
ALPENA	0.405	0.163	0.27
ALLENDALE	0.351	1.135	0.27
MSUHORT	0.517	0.547	0.26
KENTCITY	0.424	0.846	0.26
CHESANING	0.495	0.479	0.25
WESTBRANCH	0.283	0.287	0.25
MORENCI	0.673	0.725	0.24
NWMIHORT	0.437	0.309	0.23
STANDISH	0.65	0.288	0.23
MUSKEGON	0.733	0.439	0.23
CORNELL	0.28	0.393	0.22
LAPEER	0.58	0.459	0.21
LAKECITY	0.679	0.261	0.2
HASTINGS	1.389	0.442	0.19
BADAXE	0.718	0.207	0.18
OSSINEKE	0.371	0.091	0.18
CENTREVL	0.914	0.297	0.18
OWOSSO	0.783	0.237	0.17
VANDERBILT	0.351	0.17	0.17
KINDE	0.667	0.367	0.17
BELDING	0.675	0.456	0.16

Table 5.10 (Cont'd)

Station	a	b	r-squared
VESTABURG	0.862	0.4	0.15
HOUGHTON	0.08	0.081	0.14
IRONWOOD	0.514	0.108	0.13
CLARKSVL	0.905	0.325	0.13
BEULAH	0.474	0.678	0.13
HOLLAND	1.313	0.379	0.13
STAMBAUGH	0.452	0.296	0.12
DUNDEE	1.034	0.314	0.12
BEARLAKE	0.796	0.271	0.11
BROOKLYN	0.935	0.396	0.1
FENNVILLE	1.079	0.48	0.1
HUDSON	0.996	0.323	0.1
SSMARIE	0.423	0.52	0.09
GLENDORA	1.14	0.182	0.09
EATNRAPIDS	1.069	0.253	0.08
MILFORD	1.034	0.293	0.07
SANDUSKY	0.878	0.184	0.07
PORTSANILA	0.857	0.24	0.07
HUDSNVLLE	1.343	0.289	0.07
ALLEGAN	1.49	0.166	0.06
SWMIHORT	1.173	0.173	0.06
WATERVLIET	1.183	0.114	0.05
BALDWIN	1.315	0.498	0.05
PIGEON	1.18	0.275	0.05
OXFORD	0.987	0.194	0.04
ALMA	0.987	0.235	0.04
MARQUETTE	0.304	0.083	0.04
HELL	0.948	-0.098	0.03
GRANDJUNC	1.166	0.439	0.03
GRAPIDS	1.609	0.317	0.03
WHITE LAKE	1.822	-0.203	0.02
PAWPAW	1.345	0.241	0.02
STEPHENSON	1.928	0.14	0.01
TIPTON	1.471	0.131	0.01
COLDWATER	1.364	-0.062	0.01
FENTON	1.471	0.044	0
THREERIVER	1.691	-0.033	0
NORTHPORT	0.788	0.011	0

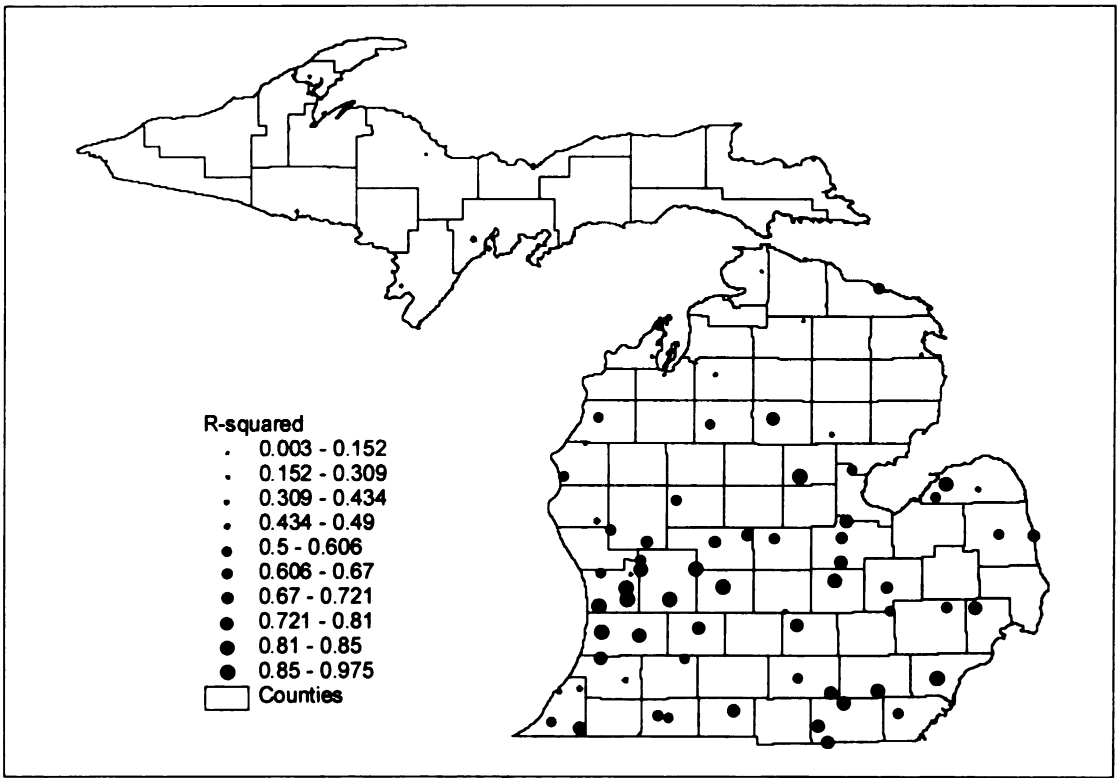

Figure 5.13a. Spatial distribution of r^2 values for correlation of weekly radar precipitation on gauge measured precipitation, 1996. (Size indicates value of r^2).

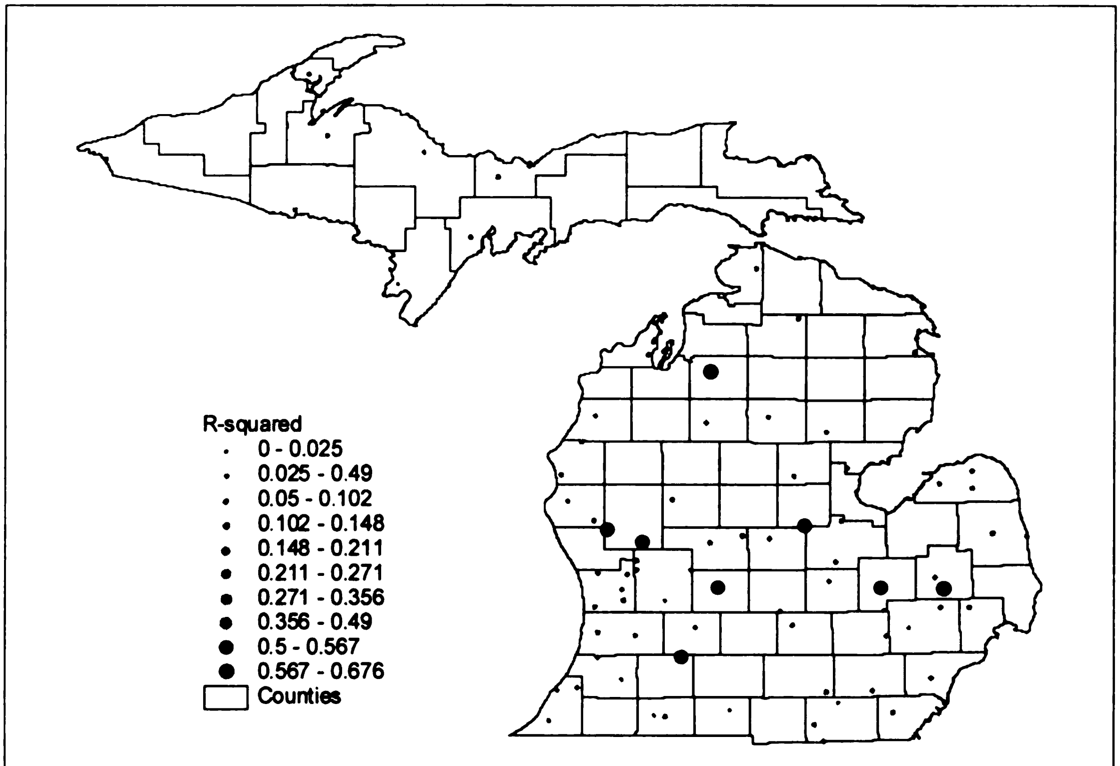

Figure 5.13b. Spatial distribution of r^2 values for correlation of weekly radar precipitation on gauge measured precipitation, 1997. (Size indicates value of r^2).

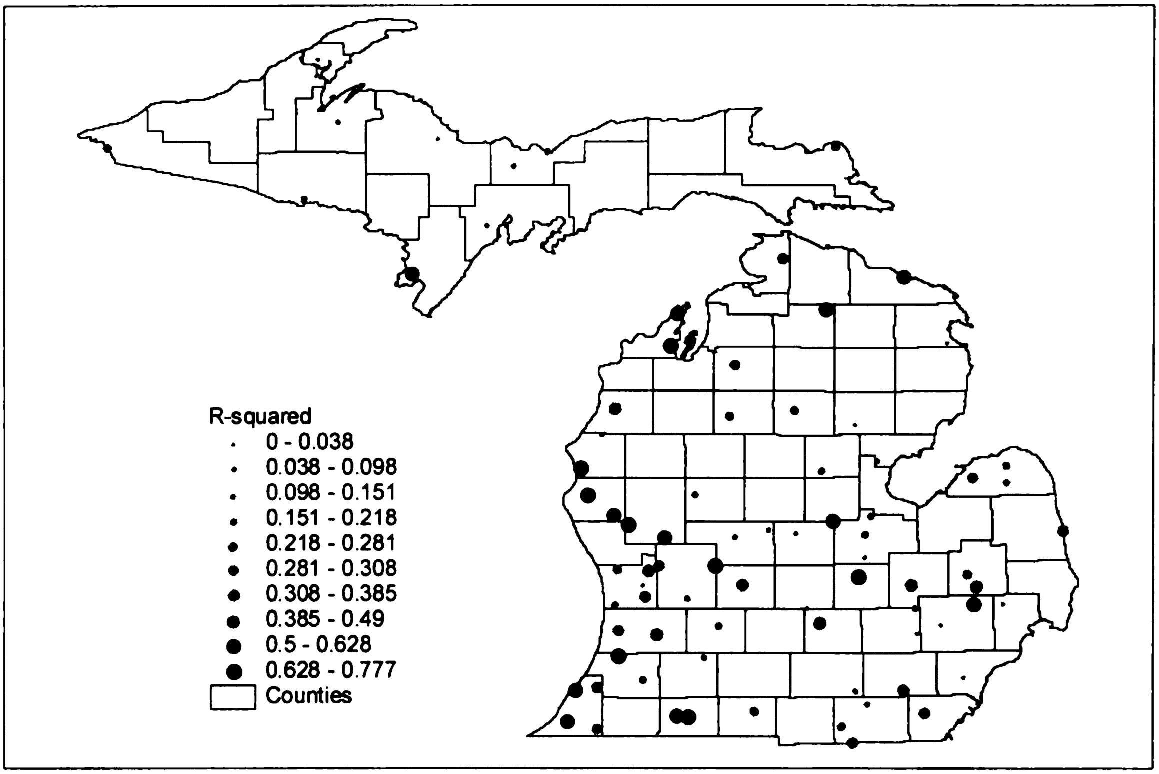

Figure 5.13c. Spatial distribution of r^2 values for correlation of weekly radar precipitation on gauge measured precipitation, 1998. (Size indicates value of r^2).

The spatial distribution of r^2 values reported in Table 5.8 is shown in Figure 5.13b. Higher values indicate better correlation, values of greater than .5 are shown as a darker color. Spatial patterns of correlation for 1997 and 1998 are not evident based on visual inspection of Figures 5.13 b and c. Stations that show a high correlation in terms of total seasonal precipitation do not in all cases show a high correlation in weekly totals. This indicates the need to assess the timing of precipitation, as well as total amounts, when comparing NEXRAD and rain gauge observations.

5.8 Irrigation Estimates using Gauge Vs. NEXRAD Preciptiation

If rain gauge observations and NEXRAD estimates are highly correlated in terms of both seasonal and weekly totals, then the potential for using rain gauge observed precipitation in the SWBM exists. Based on the above analysis, however, it can be concluded that a high degree of correlation, in terms of seasonal distribution of rainfall, does not exist between rain gauge observations and NEXRAD estimates. Assuming that systematic biases in NEXRAD data are corrected by calibration to rain gauge observations and the random error component is minimized, the use of NEXRAD data should be preferable to other sources of data because of it's ability to capture localized variations in precipitation amounts. In cases where NEXRAD data are not available, rain gauge measured precipitation data may be a suitable substitute if the gauge network is dense enough to capture regional variation in precipitation totals.

To assess the potential impact of the use of gauge data rather than NEXRAD data, three sets of simulations were run, varying only the source of precipitation data. Irrigation requirements for 100 acres of corn and 100 acres of soybeans were simulated for all NEXRAD cells in five counties. The five counties simulated were Allegan, Huron, Ionia, Grand Traverse, and St. Joseph. These counties were selected because of their potential for irrigation and location in various regions throughout Michigan. Temperature and solar radiation data were from the same data source. The three sets of precipitation data were:

1. NEXRAD data
2. Nearest rain gauge data. Precipitation values from the nearest rain gauge site.
3. Weighted average of all rain gauge sites within 48 km. (30 miles). Precipitation values from all rain gauges within 48 km. were used. Weights to each value were assigned based on the squared inverse of rain gauge distance from the NEXRAD cell. See Example 5.1.

Example 5.1. Calculation of precipitation weighted by inverse of squared distance.

In situations where more than one rain gauge was located in close proximity (<30 miles), the precipitation value was calculated as a weighted average of all nearby stations, weighted by the inverse of squared distance. For example, suppose there are three stations within 30 miles, with the following values:

Station	Distance	Precipitation
1	2	10
2	4	5
3	6	11

In step 1, the total of the squared inverse distance is calculated, in this case,

$$1/2^2 + 1/4^2 + 1/36^2 = .34$$

In step 2, estimated precipitation is calculated as a sum of the precipitation from each station times the weight for the station. This is:

$$((1/2^2)/.34) * 10) + ((1/4^2)/.34) * 5) + ((1/6^2)/.34) * 11) = 9.17.$$

In cases where no gauges existed within 30 miles, the value for the nearest gauge was used.

Results of the simulations are presented in Tables 5.11a and 5.11b for corn and soybeans, respectively. The total irrigation requirements (cm.) assume that 100 acres of corn and 100 acres of soybeans were grown in each NEXRAD cell in each county. The result of interest is the P1/R and P2/R ratios, which show the ratio of irrigation estimates using the nearest station (P1) and multiple stations (P2) to the irrigation estimate using radar (R) precipitation. For example, in Allegan County, values of .96 and .94 are shown for corn (Table 5.9a). This indicates that using the nearest gauge data for precipitation inputs, the irrigation estimates were .96 of the estimates obtained using NEXRAD data. Using a weighted average of all gauges within 48 km., the ratio was .94.

As expected, total irrigation requirements were less using rain gauge precipitation data than using NEXRAD data for all counties for both crops. This is due to the consistently lower NEXRAD precipitation values compared to rain gauge measurements, as discussed above. R/G ratios (Table 5.8) are as follows; Allegan, .8, Ionia, .8, Three Rivers (St. Joseph) .6, NWMI Hort., .6, Old Mission .7, Pigeon 1.0 and Bad Axe .6. This indicates that, on average, gauge observed precipitation is 20 – 40% higher than NEXRAD estimates in the simulated counties. Correspondingly, irrigation totals using rain gauge precipitation are lower (by 10 –15%) than totals using NEXRAD precipitation. In all but one case (Allegan), the use of multiple stations to estimate the precipitation value resulted in an improvement in the P/R ratio.

Table 5.11a. Results of the simulations using NEXRAD (R) and gauge precipitation (P) data for corn. P1 = nearest station, P2 = all stations within 48 km. Total irrigation water applied is shown (cm.) for the three data sources. Ratio of P/R is shown for both P1 and P2.

County	R (cm.)	P1 (cm.)	P2 (cm.)	P1/R	P2/R
Allegan	64680	62230	60564	0.96	0.94
Huron	55566	40474	43414	0.73	0.78
Ionia	45178	34594	35084	0.77	0.78
Grand Traverse	34888	30282	30282	0.87	0.87
St. Joseph	41454	36652	37828	0.88	0.91
Total	241766	204232	207172	0.84	0.86

Table 5.11b. Results of the simulations using NEXRAD (R) and gauge precipitation (P) data for soybeans. P1 = nearest station, P2 = all stations within 48 km. Total irrigation water applied is shown (cm.) for the three data sources. Ratio of P/R is shown for both P1 and P2.

County	R (cm.)	P1 (cm.)	P2 (cm.)	P1/R	P2/R
Allegan	110642	108290	107114	0.98	0.97
Huron	153370	98000	130046	0.64	0.85
Ionia	100744	98784	102900	0.98	1.02
Grand Traverse	107800	98000	99372	0.91	0.92
St. Joseph	73402	60564	60956	0.83	0.83
Total	545958	463638	500388	0.85	0.92

The results reported in Tables 5.9a and 5.9b lend support for the potential use of daily station data from rain gauges to provide irrigation estimates consistent with estimates computed using NEXRAD data. Differences in the estimates provided can be explained by differences in NEXRAD and rain gauge precipitation estimates. In addition to assessing county totals, however, it is important to view the results at the NEXRAD cell level. Biases in estimations could be introduced, for example, as a function of distance from the weather station. Cells closer to the station should be in closer agreement than those cells located farther away. Table 5.12 shows the range of P/R values in each county for each crop simulated. In Allegan County, for example, values for corn ranged from .14 to 2 using the nearest station (P1/R), and .57 to 3 using all stations within 48 km. (P2/R). On a cell by cell basis great variation can be seen between irrigation estimates using NEXRAD precipitation and estimates made using rain gauge data. When aggregated to the county level however, individual cell variations disappear. This analysis assumes that crops are grown in all NEXRAD cells in each county, which in reality is not the case. If only a small percentage of the cells in a given county contain irrigated acreage, then the potential exists for irrigation estimates made using nearest rain gauge data versus estimates made using NEXRAD data to differ substantially.

Table 5.12. Range of P/R ratios by County and Crop.

County	Crop	Min P1/R	Max P1/R	Min P2/R	Max P2/R
Allegan	Corn	0.14	2	0.57	3
	Soybeans	0.3	3	0.73	2.5
Grand Traverse	Corn	0.71	2	0.6	1.33
	Soybeans	0.5	1.18	0.69	1.2
Huron	Corn	0.38	1.67	0.5	1
	Soybeans	0.57	1.44	0.64	1.2
Ionia	Corn	0.33	2	0	1.33
	Soybeans	0.62	6	0.8	1.57
St. Joseph	Corn	0.71	1.25	0.71	1.25
	Soybeans	0.6	1.3	0.6	1.25

Because the P1 and P2 estimates are based on the same data source (nearest station or stations), the variability seen in P/R ratios must be a function of the variability in NEXRAD precipitation estimates. This is illustrated in Figures 5.14a, 5.14b and 5.14c, which show May – August precipitation totals for St. Joseph County using a) NEXRAD data, b) nearest station (P1), and c) multiple stations (P2).

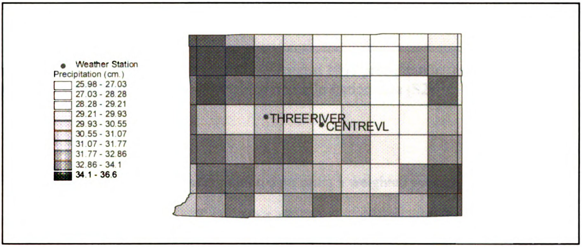

Figure 5.11a. Distribution of total May - August 1997 precipitation (cm.) in St. Joseph County by NEXRAD cell using NEXRAD data.

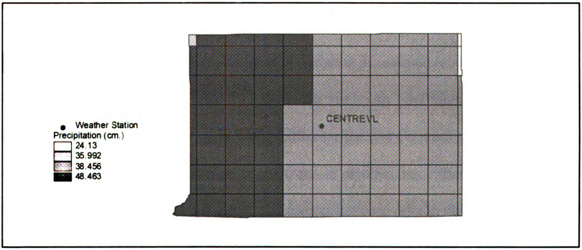

Figure 5.11b. Distribution of total May - August 1997 precipitation (cm.) in St. Joseph County by NEXRAD cell using nearest station data (S1).

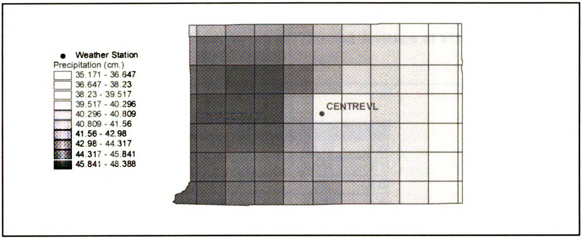

Figure 5.14c. Distribution of total May - August 1997 precipitation (cm.) in St. Joseph County by NEXRAD cell using weighted multiple station data (S2).

The effect of smoothing the precipitation data using a weighted average of multiple stations is apparent in Figures 5.14b and 5.14c. Data values from four stations are shown in Figure 5.14b, with each cell assigned a value according to the nearest station. Precipitation values are 'smoothed' when all stations within 48 km. are used to compute a precipitation estimate, as seen in Figure 5.14c. In terms of range of values, the NEXRAD data ranges from 25.98 to 36.6 cm., the S1 data ranges from 24.13 to 48.46, and S2 data ranges from 35.17 to 48.38. A high degree of variation in seasonal totals by NEXRAD cell is seen for all Counties. Table 5.12 shows the minimum, maximum, mean, and standard deviation of May – August precipitation for the five Counties simulated. The range for these five Counties is from 10 to 20 cm. of precipitation. That is, there can be a difference of 10 to 20 cm. in precipitation estimates between cells in the same county for a given season. This variation, if indeed true, can not be captured by rain gauge measurements because rain gauges are generally located many kilometers apart.

Table 5.12. Minimum, maximum, mean, and standard deviation of May – August precipitation totals for all NEXRAD cells by County.

County	Min (cm.)	Max (cm.)	Mean (cm.)	SD
Allegan	26.1	46.3	35.8	4.6
Grand Traverse	14.3	27	19.9	3.1
Huron	16.4	30.6	22	2.8
Ionia	21	35.3	26.5	3.4
St. Joseph	26.4	36.6	30.9	2.1

To conclude the precipitation data analysis, the SWBM was run using the 1997 irrigation acreage reported to MDA using the nearest rain gauge site for precipitation data. Results compared to the results obtained using NEXRAD precipitation data are shown in Table 5.13. The irrigation estimate using rain gauge data was 94% of the amount obtained using NEXRAD precipitation data. This is consistent with the findings reported in Tables 5.9 (a and b). The use of rain gauge measured data resulted in aggregate irrigation estimates that were slightly lower than those obtained using NEXRAD data, which is largely a function of the higher rainfall amounts reported by rain gauges. The difference in terms of the average depth of water applied was less than one centimeter (12.6 versus 11.8 cm.). Given the uncertainty in the measurement of site-specific driving variables (soil and weather) of the SWBM in addition to the potential variation in management practices, a difference of one centimeter of water applied is an insignificant difference. Consider that if the SWBM were to model irrigation applications within +/- one irrigation event, then the interval of estimation would be 12.6 +/- 2.5 cm. The use of daily rain gauge data, then, is a viable option for the SWBM if the scale of estimation is at the county, watershed, or state level.

Table 5.13. SWBM irrigation estimates using 1997 reported acreage with a) NEXRAD precipitation (R) and b) Nearest Rain Gauge precipitation (G) as precipitation input.

Precipitation Source	Total (Acre-Inches)	Avg. Amount (cm.)
NEXRAD	1008205	12.6
Gauge	945022	11.8

5.9 Summary, Conclusions, and Recommendations

This chapter has presented an analysis of the NEXRAD precipitation data and it's correlation with rain gauge observed precipitation amounts. As a basis for comparison, weather station data from a network of volunteer weather reporters was obtained and summarized. The spatial distribution of station data was shown for each of the three years 1996 – 1998. Statistical summaries and spatial distribution of the NEXRAD data was also presented.

Some general conclusions can be drawn from this analysis.

1. NEXRAD data for May 1996 and May 1997 appears to show some systematic bias as a function of distance from the radar site. A clear range line can be seen at the outer

range of the two radar ranges in southeast and southwest Michigan.

2. In comparison to rain gauge data, NEXRAD estimates were consistently lower for all three years (1996 – 1998). There is also a spatial pattern to this bias. NEXRAD estimates for the Upper Peninsula and northern lower Michigan are much lower compared to rain gauge estimates than the same ratio for southern and central Michigan sites. The gauge to NEXRAD ratio averaged 1.4 for 1997, with most of the southern and central Michigan stations range from 1.2 to 1.3. This indicates a 20 to 30% higher precipitation measurement by rain gauges as compared to NEXRAD values.

3. Five counties were simulated to assess the potential for the use of station data as a source of precipitation data for the SWBM. At the county total level, results showed good agreement estimates made using NEXRAD estimates. The slightly lower estimates obtained using station data are a function of the higher precipitation estimates from stations compared to NEXRAD. If station data and NEXRAD totals are similar in value, then irrigation estimates should also be very similar between the two data sources.

4. A data smoothing procedure was used to assess the impact of using multiple stations for precipitation estimation, rather than the nearest station. Results (compared to NEXRAD estimates) were better using smoothed data than simply using the precipitation from the nearest station.

5. For county or larger scale estimates, the use of daily rain gauge data from the nearest rain gauge will provide irrigation estimates similar to NEXRAD data. Results may be slightly improved if a kriging procedure is used to incorporate data from multiple stations. Given a reasonably dense rain gauge network, however, adequate results can be obtained using the nearest rain gauge as the precipitation source. This is a viable option for states or regions that do not have access to NEXRAD data or technical capabilities for processing and storing this data.

6. If estimates are to be done at the sub-county level, the only logical source of precipitation data is NEXRAD, due to the potentially high variations in seasonal totals seen in distances of only a few kilometers. Further analysis is recommended, however, to evaluate the accuracy of the NEXRAD data in terms of quantity estimates and the spatial distribution of these estimates. The high spatial and temporal resolution of this data source makes comprehensive 'validation' a difficult task. Because of the many potential uses for this data, however, continued assessment and improvement is expected as the NEXRAD product is further developed.

CHAPTER VI

SUMMARY AND FINAL ANALYSIS

In this concluding chapter, section 6.1 presents a brief review of the research objectives. Section 6.2 summarizes the soil data analysis and section 6.3 summarizes the precipitation data analysis. Section 6.4 presents an analysis relating to model sensitivity to management parameters. Section 6.5 discusses total water requirement as a means of assessing irrigation need. Section 6.6 presents results relating to the correlation of irrigation amount and precipitation levels. Section 6.7 discusses the advantages and disadvantages of various water use estimation methods. Study limitations are discussed in section 6.8, and issues for further research are discussed in section 6.9. Section 6.10 presents final comments.

6.1 Research Objectives

Michigan's water use reporting law currently requires that irrigation water use by agriculture is monitored and reported at county, watershed, and statewide levels. The Michigan Department of Environmental Quality (MDEQ) administers the water use reporting program. Under the law, water users who have the capacity to withdraw over

100,000 gallons per day averaged over any 30-day period during a year to report their water use to the MDEQ.

In 1994 and 1995, water use information was collected by surveying all to irrigators in the state. This process was time-consuming, and the survey response rate was less than desired. With the availability of high-resolution precipitation data from the NEXRAD radar system of the National Weather Service in 1996, MDEQ decided to pursue a different approach to water use estimation for agricultural irrigation. The use of a soil water balance model (Ritchie, 1972, 1986, and 1998) to model water use requirements was proposed. It was hypothesized that NEXRAD precipitation data, combined with other spatially referenced input data, could be used to run the soil water balance model to simulate soil water conditions and irrigation requirements over the course of a growing season. Using the revised method, irrigators are required to report only the crops grown and the acreage of each crop for each year. This greatly lessens the reporting requirements, and makes it possible to collect acreage data during the current growing season, rather than at the end of each agricultural year.

As an initial test, the SWBM method was used to estimate irrigation water for the partial set of irrigator forms that were returned for the 1997 season. A number of questions arose during the development and implementation of the SWBM method. While the SWBM method offers great potential in terms of efficiency and accuracy improvements, it also requires detailed input data from multiple sources. Detailed soil and precipitation may not be available for other U.S. states that could potentially use the SWBM method for water use estimation. The primary objective of this research was to assess the potential for using 'simplified' input data for soil and precipitation to run the SWBM. This analysis concentrated on assessing the sensitivity of individual soil map units to irrigation requirements and the use of readily available rain gauge data for precipitation estimates. The result of this analysis, it was felt, would be useful to current users of the SWBM as well as for resource managers in other states or regions who are responsible for water resource management and analysis and could potentially use the SWBM for their state or region. A secondary objective of this research was to assess the degree of correlation between NEXRAD estimated precipitation amounts and rain gauge observations.

6.2 Soil Data Analysis

Chapter IV discussed the soil data analysis. The STATSGO database (NRCS, USDA, 1994) provided a data set of spatially referenced soil information on a statewide basis. A number of data fields required by the SWBM were derived from the STATSGO database, as discussed in chapter 3. To assess the variability of each soil map unit in terms of irrigation requirements, a 30 year data set of historical weather was used to simulate irrigation requirements for 4 crops for each of the 190 soil map units in Michigan. Tests for non-different results of the paired time series data were carried out to identify map units showing insignificant differences in irrigation requirements.

The simulation results showed that for a given crop, irrigation requirements were similar for many map units. Four or five soil groupings could be created that would include about 95% of the land area in Michigan, with most soils (about 90%) in the major group. Groupings differed by crop, however, meaning that, in an operational setting, it would be necessary to maintain soil groups for each crop or crop type. The need to maintain soil groupings by crop type is inconsistent with the original goal of simplifying the soil data parameters, and therefore it was recommended that major soil groupings only be used in situations where more detailed soil data is not available.

6.3 Precipitation Data Analysis

The main objective of the precipitation data analysis in chapter V was to compare precipitation data obtained from NEXRAD radar with rain gauge observations from a network of reporting weather stations around the state. Temperature and solar radiation data, because of their general availability and reliability, were not explicitly considered in this research. Because of the various technical, storage, and availability issues regarding the NEXRAD data, the investigation of the use of a surrogate data set for precipitation data (gauge data) was considered pertinent to this research. In addition to it's potential as a data source, the rain gauge data also provided a means of testing the NEXRAD data for systematic biases.

Statistical summaries of the station and NEXRAD data were presented. Maps showing the spatial distribution of rain gauge data were produced for comparison to the NEXRAD data. To assess the spatial variability and correlation of weekly rainfall, the coefficient of determination (r^2) for each gauge in relation to all other gauges was calculated and assessed. Comparison of the NEXRAD data to rain gauge data revealed a generally lower level of precipitation estimated in the NEXRAD data compared to the observed rain gauge levels. The bias was more pronounced in northern lower Michigan and the Upper Peninsula of Michigan (Figure 5.11b). Although most stations reported more rainfall than NEXRAD, some reported less, so the bias was not evident for all rain gauge sites. Spatial bias was evident for the three years examined, but the extent and pattern of spatial biases differed in each year.

Within a defined region, such as a county, a high degree of variability in seasonal totals of precipitation was reported by NEXRAD (Table 5.12). Although not yet validated, if this variability is indicative of reality, then there is a definite need for high-resolution precipitation data such as NEXRAD for detailed modeling efforts. Such variability is expected on a daily basis, due to the predominance of rainfall from isolated thunderstorms, but was not expected by the researcher for seasonal totals. As the time frame of analysis is increased, it was thought that values of adjacent or nearby cells should be closer together assuming that the occurrence of rain in any one cell is a random event for small storms or a related event for larger storms. Further research is necessary to investigate the variance of precipitation over small areas to determine the true nature of this phenomenon.

SWBM simulations using rain gauge precipitation data were run for five counties and results compared to the estimates using NEXRAD precipitation data. It was found that the irrigation estimates for county level totals were quite close to results obtained using NEXRAD precipitation estimates. Differences were largely a function of the differences in rainfall estimates between the two data sources. A smoothing technique that used precipitation data from all nearby stations to compute a weighted average precipitation value was found to provide better results than using the nearest station data. At the County and watershed levels, it was concluded that the use of daily precipitation data from a well-designed network of weather stations would provide irrigation estimates very similar in value to those provided using NEXRAD data. Because of the variability in precipitation at the 4 km. scale, however, station data should only be used for large-scale (county, watershed, or state) estimates.

In summary, systematic biases were found in the NEXRAD precipitation data compared to rain gauge precipitation amounts. More research is necessary to assess the NEXRAD estimates both in terms of amount (cm. of rain) and in terms of the spatial distribution of the precipitation. The decision to use NEXRAD or station data for precipitation input to the SWBM should be a function of many factors. The availability of NEXRAD data is the first major factor. If NEXRAD data are available, then the cost and effort involved in processing, storing, and maintaining the NEXRAD data are factors to consider. If spatial and temporal accuracy at sub-county levels is desired, then NEXRAD data are the only viable option if the spatial variability in precipitation amounts suggested by the

NEXRAD data is true, and if this variability is reflected in differences in irrigation amounts between irrigators. If estimates are to be made at the county or greater level on a seasonal basis, then the use of precipitation data from a well-designed rain gauge network is a viable option. An important consideration is the level of accuracy that can be associated with the NEXRAD precipitation estimates. Comparison with rain gauge data would indicate that a high level of accuracy of NEXRAD data should not be assumed, but rather be the subject of further investigation.

6.4 Model Sensitivity to Management Parameters

Differences in management strategy may also impact the total irrigation water applied to a crop. Aversion to risk, labor availability, and economic factors impact an irrigator's decision of when and how much to irrigate a crop. Swaney et al. (1983) evaluated irrigation strategies for soybeans with the goal of profit maximization. Maximum profit was found at an irrigation threshold of 70% and 1 cm. irrigation per application. Near-optimal results were found with an irrigation threshold of 60% and 3 cm. applications. The irrigation threshold and amount of water applied are management parameters that are defined for each crop in the SWBM. The default values used in this research are listed in Appendix B. In the default settings, the irrigation threshold is 50% for all crops and the irrigation amount varies from 1.5 to 2.5 cm. per application. To examine the sensitivity of the SWBM to changes in these management parameters, simulations were run for the 1997 data set using the two irrigation strategies defined above (70% and 1cm. and 60%

and 3 cm.). The results of these simulations were compared to the results obtained using the default values (Table 6.1).

The sensitivity of irrigation estimates to different management strategies can be seen in the results shown in Table 6.1. The default strategy is the most conservative in terms of water use. Strategies II and III represent the strategies found by Swaney et al. (1983) to be optimal for soybeans. Increasing the irrigation threshold from 50% to 60%, with a fixed application rate of 3 cm. resulted in a 23% increase in irrigation amount. Strategy III shows a 45% increase in irrigation amounts compared to the default strategy. While results obtained by researchers for soybeans on a sandy soil in Florida are not directly applicable to all Michigan crops and soils, these results show the potential differences in irrigation amount estimations based on changes in irrigation management strategies. The yield response to different water management strategies must be known in order to determine economically optimal management strategies. In terms of implementation of the SWBM method, these results indicate the importance of knowing the management strategies employed by irrigators in the region being modeled.

Table 6.1. Total irrigation requirements under different management strategies using 1997 irrigator records and NEXRAD precipitation data.

Strategy	Threshold (%)	Amount (cm.)	Irrigation (cm.)	Ratio
I (Default)	50	Variable	1108026	1.00
II	60	3	1358467	1.23
III	70	1	1605303	1.45

6.5 Total Water Requirements

If the timing of precipitation during the course of a growing season is not a critical factor in determining irrigation requirements, then it could be hypothesized that the total water requirements of a particular crop/soil combination would be relatively constant on an annual basis. That is, in dry years, more irrigation would generally be required than in wet years, but the total water applied (precipitation + irrigation) would be approximately the same. If the timing of precipitation is a critical factor, however, we would expect to see variation in irrigation amounts, even in years with similar precipitation levels. Figure 6.1 shows the total water requirements for corn on soil MI001 for the 30 years of weather data from the Lansing station (1961 – 1990). The yearly data is sorted in ascending order of total seasonal (May – August) precipitation. Total seasonal precipitation and total irrigation water applied, as simulated by the SWBM is shown.

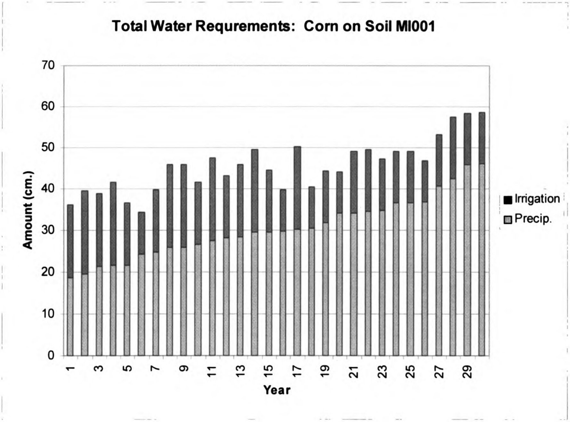

Figure 6.1. Total water requirements for corn on soil MI001 for the 30 year simulations using weather data from the Lansing, MI station 1961 – 1990. Year is sorted in ascending order of precipitation amount. Precipitation is May - August precipitation.

Most of the irrigation of corn in Michigan occurs in the months of July and August, when potential evaporation and transpiration are high and rainfall can be sporadic. Irrigation amounts, therefore, should be more highly correlated with July and August precipitation totals than with total seasonal (May – August) totals. Figure 6.2 shows July and August precipitation in ascending order on the x axis and total irrigation for each of the 30 years simulated.

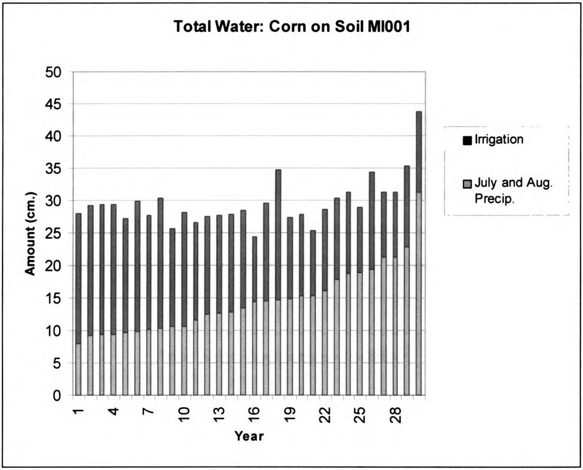

Figure 6.2. Total water requirements for corn on soil MI001 for the 30 year simulations using weather data from the Lansing, MI station 1961 – 1990. Year is sorted in ascending order of precipitation amount. Precipitation is July and August precipitation.

The results shown in Figures 6.1 and 6.2 illustrate the generally negative relationship between precipitation totals and irrigation amount resulting in a somewhat constant total water requirement, with slightly higher amounts for wetter than average years. In Figure 6.2, for example, it can be seen that July and August precipitation plus irrigation generally ranges from 25 – 30 cm for corn on soil MI001. There are exceptions to every general rule, however. Year 18 in Figure 6.2 shows greater irrigation amounts than other years with similar precipitation amounts. The results shown in Figures 6.1 and 6.2 apply only for a specific crop (corn) on a particular soil group (MI001). To show the potential differences between crops, Figure 6.3 shows the same results for soybeans on soil (MI001) using July and August precipitation. The shallower rooting soybeans extract more water from the upper soil layers than corn, and therefore total water irrigation water requirements, as simulated by the SWBM, are higher. Less variability in total water requirements is seen for soybeans as compared to corn. Variations in irrigation water applied of 5 cm. for similar precipitation levels are common however

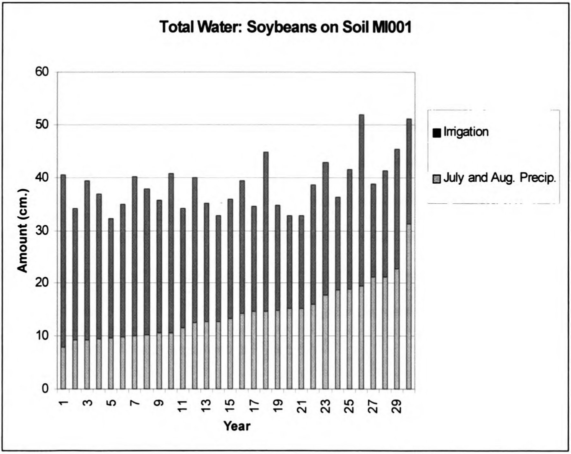

Figure 6.3. Total water requirements for soybeans on soil MI001 for the 30 year simulations using weather data from the Lansing, MI station 1961 – 1990. Year is sorted in ascending order of precipitation amount. Precipitation is July and August totals.

The variations in irrigation levels seen in years that experienced similar precipitation levels illustrates the potential advantages of a dynamic, physically-based soil water balance model for accurate assessment of irrigation water requirements. Simplified empirical approaches may provide reasonable results, but unless the empirical model was properly and completely specified, estimates could be incorrect in outlier years with irregular precipitation patterns.

6.6 Irrigation Amount Versus Precipitation

The discussion in the previous section showed the generally negative correlation between seasonal precipitation totals and irrigation water requirements for a given crop/soil combination. To assess the impact of consistent systematic bias in the NEXRAD precipitation data and it's impact on irrigation water use estimation a series of simulation were run in which the NEXRAD precipitation estimated were multiplied by a scalar. The scalar used was .5, .7, 1, 1.3, 1.5, and 2.0. The irrigation acreage used was the 1997 irrigator data set. Results are shown in Figure 6.4.

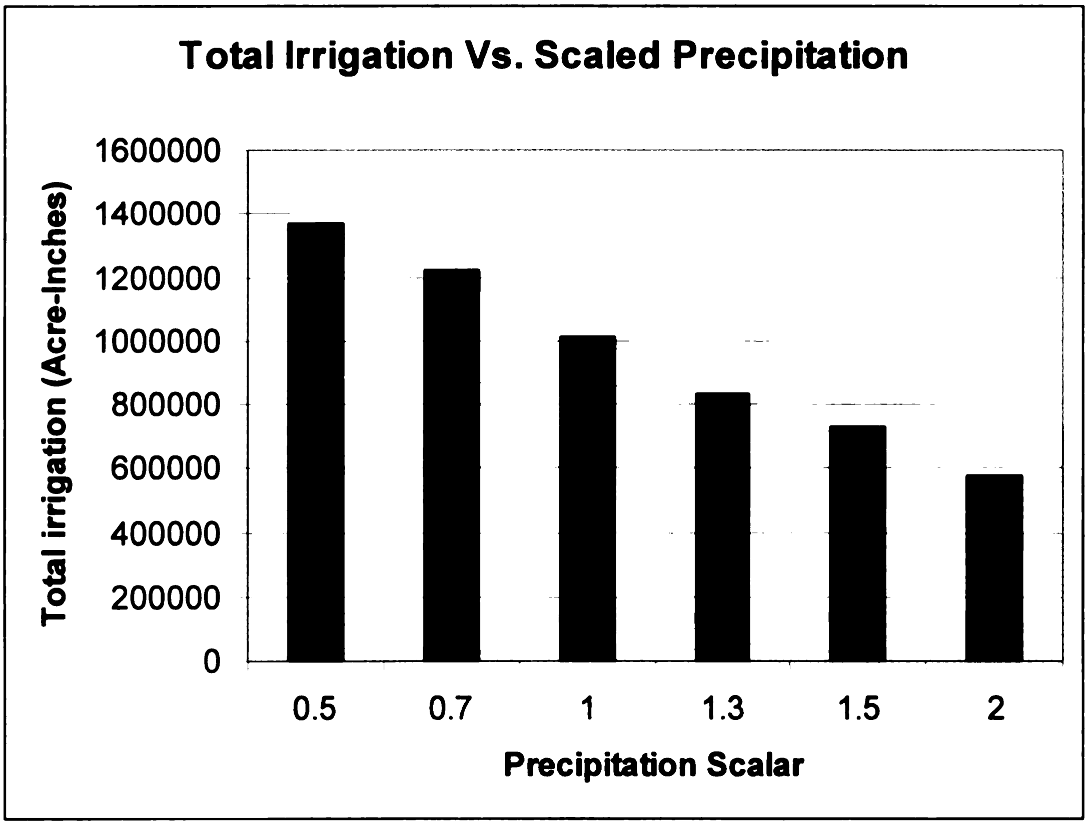

Figure 6.4. Total simulated irrigation (acre-inches) versus scaled NEXRAD precipitation with scalar applied of .5, .7, 1.0, 1.3, 1.5 and 2.0.

As expected, total simulated irrigation requirements decrease as precipitation amounts are increased, but not in direct proportion to the change in precipitation. A 30% increase in precipitation, for example, resulted in an 18% increase in total irrigation amount. A 50% increase in precipitation resulted in a 27% decrease in total irrigation. Conversely, a 50% decrease in precipitation resulted in a 36% increase in irrigation, and a 30% decrease in precipitation resulted in a 21% increase in irrigation. Total irrigation estimates then, are inelastic and negatively correlated with respect to changes in precipitation amounts.

Results in the preceding paragraph should not be taken to imply that a simple relationship exists between SWBM irrigation estimates and precipitation amounts. A scalar applied to all NEXRAD cells as in the previous paragraph does not alter the timing of precipitation, another important factor in determining irrigation amounts. In addition, analysis of aggregated irrigation amounts masks the variation in irrigation due to differences in soil characteristics.

To examine the impact of precipitation timing and differences in soil characteristics on the relationship between irrigation estimates and precipitation amounts, scatter plots of 1997 irrigation requirements versus precipitation at the NEXRAD cell level were prepared for field corn. Results are shown for May to August precipitation totals (Figure 6.5) and July and August precipitation (Figure 6.6). In these figures, each point represents the amount of irrigation (cm.) applied for the given crop in a NEXRAD cell. At the NEXRAD cell level, differences in the timing of precipitation and differences in soil characteristics are isolated. To a lesser extent, differences in temperature and solar radiation also impact the simulated irrigation requirement.

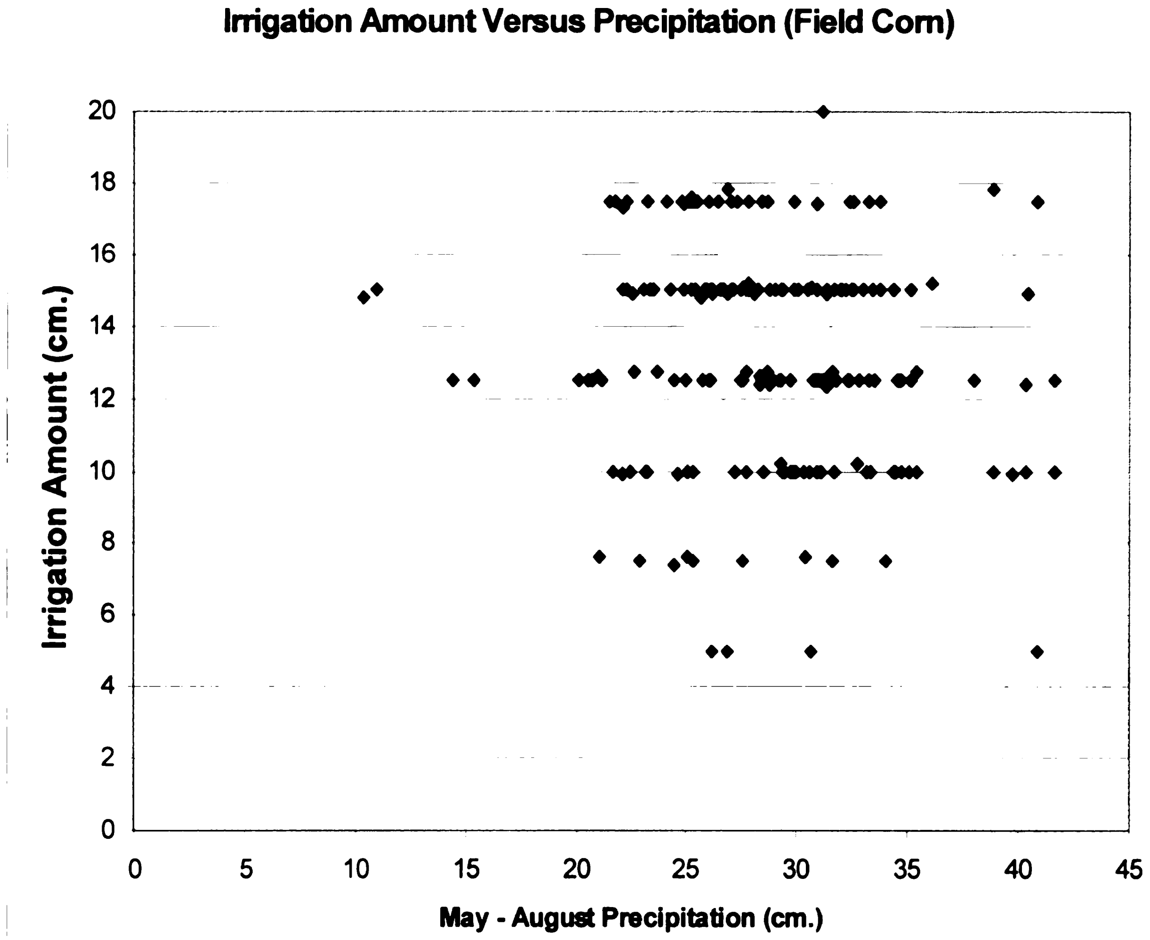

Figure 6.5. Irrigation applied (cm.) versus NEXRAD precipitation for field corn, 1997. Each point represents a NEXRAD cell. Precipitation is May to August seasonal total.

Visual inspection of Figure 6.5 reveals that there is not a discernable negative correlation between simulated irrigation amount and May-August precipitation totals at the NEXRAD cell level. A strong negative correlation is seen, however, when irrigation amount is plotted against July and August precipitation totals (Figure 6.6).

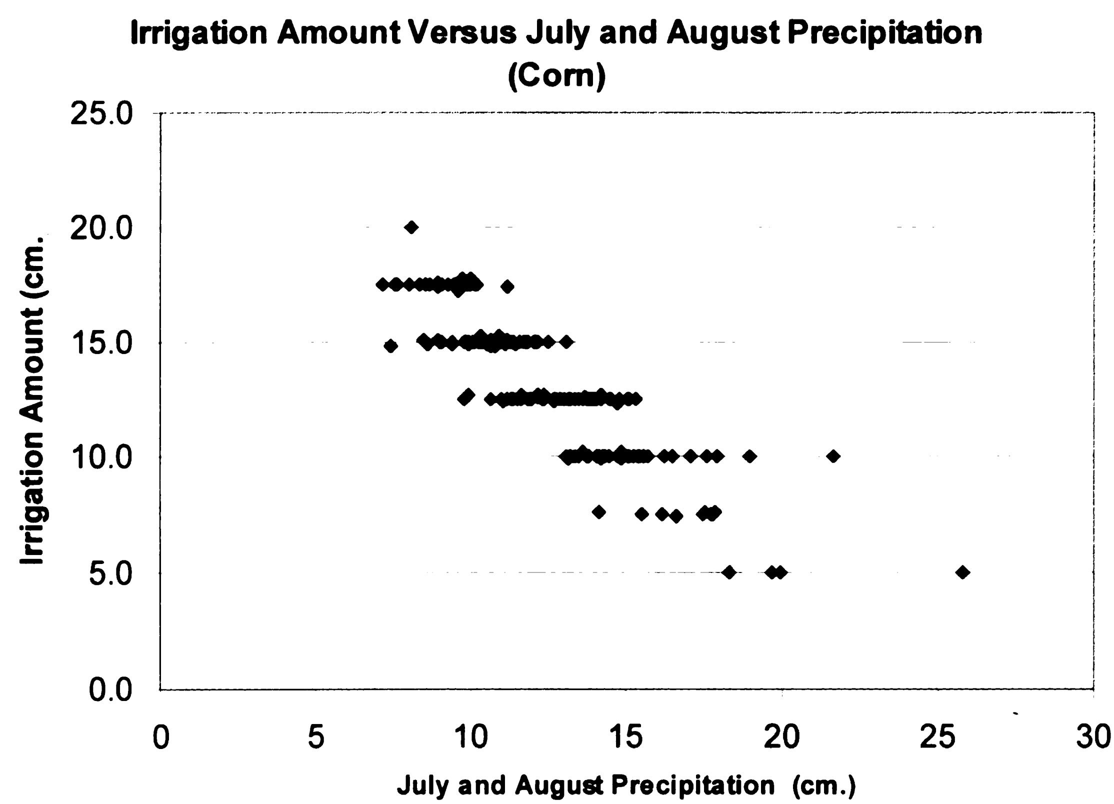

Figure 6.6. Irrigation applied (cm.) versus NEXRAD precipitation for field corn, 1997. Each point represents a NEXRAD cell. Precipitation is July and August totals.

As seen in Figure 6.6, a considerable range of precipitation levels can apply to a given irrigation level. For example, irrigation of 10 cm. was applied over a range of precipitation from 12 to 22 cm. These results show the impact of local differences in the timing of precipitation, other climate factors, and soil characteristics on the estimation of irrigation water requirements. The impact of a scalar applied to precipitation on these results would be to shift the locus of points on the scatter plot in a horizontal direction. These results again underscore the potential advantages of the use of a detailed and dynamic modeling approach for the estimation of irrigation water requirements. A more simplified empirical approach would not be able to incorporate the many local factors affecting irrigation water needs.

6.7 Options for the Estimation of Irrigation Water Use by Agriculture

Four clear options exist for the estimation of agricultural irrigation water use in Michigan. These options are:

I. Direct survey of all irrigators, as done in 1994 and 1995.
II. Reporting of county level irrigation levels by MDA/Extension agents.
III. Detailed modeling using the SWBM
IV. Simplified empirical approach using multi-year SWBM results.

Of these options, the first two are 'low-technology' approaches and the third and fourth are 'high-technology' approaches. Option II is introduced here as an alternative to the labor-intensive and bias-prone direct survey method. In option II, field personnel of the Michigan Department of Agriculture or County extension agents would be responsible for reporting to MDEQ estimates of irrigation levels in their respective regions. These estimates would be based on the local knowledge of field personnel and their interactions with irrigators in the region. This is a viable option if field personnel are intimately familiar with irrigation practices in their local area and prepare the estimation of irrigation amounts for each crop in a serious manner with due regard for accuracy. A positive feature of option II is that it is much less labor-intensive and less invasive an approach than option I. Mailing of surveys to irrigators is not necessary under option II, rather, a survey form would be sent to each responsible field personnel. Administratively, option II is much preferable to option I. From the standpoint of estimate accuracy, option II is also preferable <u>if</u> field personnel strive to prepare unbiased and accurate estimates for all crops irrigated in their region. For these reasons, option II is recommended over option I as a low-technology method.

In terms of simplified approaches (option IV), the use of simplified soil data groups was discussed in chapter IV, the use of rain gauge observed precipitation was discussed in chapter V, and the suggestion of an empirical approach using total water requirements was made earlier in this chapter. As discussed in previous sections, however, any attempt to simplify data inputs or the water use model will result in potentially less accurate estimates than a detailed modeling approach. This discussion assumes that the simpler empirical methods would be based on results of multi-year runs of the detailed SWBM and that 'detailed' data is more accurate than 'simplified' data. Any simpler empirical method (option IV) would be less accurate than the use of a detailed model (option III) because of the potential for the detailed model to handle variable weather and soil conditions more accurately. In addition, from a scientific standpoint, the continued development of a sound functional model is much preferable to the development of empirical (regression-based) models of water use. Therefore, option III (detailed modeling) is recommended as a high-technology approach.

In comparing the recommended low-technology approach (option II) versus the recommended high-technology approach (option III) it is fair to say that both methods could be used to provide 'reasonable' estimates of agricultural irrigation water use on a county and watershed level. The continued development of a modeling approach (option III), however, potentially offers many more benefits than survey approaches (option II). Irrigation estimates are possible at a 4 km. resolution using option III, but limited to county and watershed level resolution using option II. In addition, estimates can be made during the course of a growing season using option III, while option II is limited to year-end estimates. Option III, therefore, has far greater potential for use as a monitoring and management support tool than other options. Derivative benefits exist for option III as well. Consider, for example, the use of the SWBM to estimate the potential for nitrate leaching. While survey approaches are possible in the case of irrigation water use, it certainly is not feasible in the case of the estimation of nitrate leaching. Irrigation water use is only one of many potential products of a detailed modeling approach.

An additional and important feature of a detailed modeling approach (option III) is that such an approach provides a documented and defensible scientific methodology for the estimation of irrigation water use. This makes possible the use of the scientific method for the improvement of the model, in which hypotheses can be tested against observable evidence in a disciplined manner, with each step in the process made explicit. Future advancements of the theoretical knowledge base through basic research coupled with the knowledge and experience of applied practitioners will serve to improve the accuracy and precision of the SWBM irrigation water estimates. In addition to advancement in scientific theory, the continued development and enhancement of new technology will increase the availability of high-resolution data. Availability of such data will allow for the testing and validation of models over a broader range of conditions. As mentioned above, it will be possible in the future to run the SWBM throughout the growing season with near real-time data acquisition, allowing for a more thorough validation of this approach, and ultimately better monitoring of water use and more responsive water management.

Of the four options presented, option III (detailed modeling using the SWBM) is the recommended approach. This approach, however, requires a long-term commitment to the continued development and use of technology for resource management by the participating organizations. The potential benefits of this approach are many if such a commitment is made. In the absence of support or funding for a high-technology approach, option II (modified survey) is recommended as a viable low-technology alternative.

6.8 Study Limitations

The processes being modeled in the SWBM are very complex and highly dependent on soil and weather conditions that are also highly variable over time and space. The researcher must segment these continuous processes into discrete units in time and over space. In some cases, such as the soil data in this study, the segmentation scale is defined by available data. As discussed in chapter II, the characteristic scale of the processes being modeled is an important consideration when designing and developing models. The physical laws that govern natural systems, such as the force of gravity on water flow, make it possible to build mathematical models that closely approximate 'reality'. It must be recognized, however, that, any model, by definition, is a simplification of reality. Simplification occurs in the mathematics of the model itself and in the values of independent variables used by the model.

In the case of this study, the soil water balance model used has been shown to produce good results in a number of experimental settings. Accurate results of the SWBM model are dependent on accuracy of the data inputs to the model, especially pertaining to soil characteristics and precipitation amounts. STATSGO soil data and NEXRAD precipitation data, despite their relatively high resolution when compared to a county or watershed, do not capture data at the resolution of the individual irrigator (the field level). Accordingly, differences will exist between individual irrigators and model results, simply due to differences in the measurement scale of input data. A direct comparison of the SWBM method results with individual irrigator results is therefore not possible, due to these differences. Because of the scale of the data inputs, the results of the SWBM method in terms of irrigation requirements are not meant for site specific management. Levels of irrigation applied should be interpreted as estimates based on the best sources of input data available, but are not meant to imply recommended irrigation amounts for a particular crop or county.

Integrated modeling such as performed in this research is by nature a multi-disciplinary effort. It is not possible to assess, in great detail, the many factors and research issues associated with each component of this study. Because of the statewide scale and many variations in crop and soil types, 'conclusions' of this research are often limited to statements that identify general patterns and relationships in the data and model results. The issues raised in this research, however, should provide a basis for further research in many areas.

6.9 Issues for Further Research

Because of the pre-operational status of the SWBM method, comparison of SWBM estimates with actual irrigator records on a county level was not possible during this research. To better assess the SWBM results, it is recommended that voluntary submissions of irrigation records be obtained from irrigators who maintain accurate records during the first three years of implementation. As discussed above, SWBM results can vary significantly based on variations in management strategies. Comparison of SWBM results with irrigator records is necessary to determine if there is any systematic bias in the SWBM estimates. If so, adjustment of the management parameters to more closely reflect those of irrigators may be necessary. When assessing the accuracy of the SWBM, the discontinuous nature of irrigation application must be kept in mind. If, for example, irrigation is applied in amounts of 2.5 cm. with each application, then if irrigation counts are modeled to +/- 1, irrigation amounts are modeled to +/- 2.5 cm., a range of 5 cm.

In the absence of site-specific data for a more detailed validation, results of the SWBM method should be monitored and compared to estimates of irrigation amounts obtained from other sources. County extension agents involved with irrigation, for example, can provide assessments of the model results in relation to their knowledge of local operations. On a statewide basis for 1997, the average irrigation amount estimated by the SWBM for corn was 13.5 cm. (5.3 inches) with a range of 6.8 to 17.8 cm. at the county level. For soybeans in 1997, the average amount of irrigation was 17.5 cm. (6.9 inches) with a range of 9.6 – 20.3 cm at the county level. Aggregated numbers such as these can be used as a partial validation of the SWBM method on an on-going basis.

Continued assessment of the accuracy of NEXRAD precipitation data should be an important topic of research that would benefit not only this research effort but all that use NEXRAD data. Verification of the high degree of variability in precipitation estimates between adjacent or nearby cells would provide conclusive evidence for the need to use NEXRAD data in any modeling effort that attempts to accurately estimate at a sub-county spatial resolution. The systematic bias in NEXRAD data and discrepancies between NEXRAD and rain gauge precipitation levels, as discussed in chapter V, should also be a topic of further investigation.

In terms of the SWBM model itself, the current implementation uses a simplified approach for the estimation of leaf area index (LAI). Because of the importance of LAI in determining potential evaporation, the enhancement of this portion of the SWBM would potentially lead to more accurate results. The use of remotely-sensed or field-measured LAI values and the calibration of the SWBM to these values over the course of a growing season is a possible method of improving LAI estimation.

6.10 Final Comments

The implementation of the SWBM in an integrated modeling environment represents an effort to utilize a field-scale soil water balance model for large-scale water use estimates using the most detailed data available as model inputs. In this research, the SWBM is run at the finest resolution allowable by the data (4 km.) with larger scale estimates (county and watershed) made by aggregating results obtained at the finer scale. Accuracy is a function of two main factors; the ability of the model to estimate changes in dependent variables using all relevant factors (i.e. correct specification of the model), and the measurement precision and accuracy of the independent variables. Given a theoretically sound underlying model, the accuracy of data inputs plays the major role in determining the accuracy of the modeling effort. The state-wide scale of this research project made it necessary to substitute 4 km. resolution NEXRAD precipitation data, 1:250,000 scale soils data, and general assumptions regarding management practices for variables and processes that, in reality, differ at the field or sub-field scale. Results of the SWBM should therefore be viewed in the context of the precision with which the independent variables can be measured.

The 'information age' of the 21^{st} century will offer many new opportunities for resource managers and researchers. The ability to monitor, analyze, and model natural resources at high resolutions over large spatial areas will be greatly enhanced as we develop and utilize these new technologies. The integrated modeling environment and research described in this dissertation is a small, but hopefully positive step towards the development of greater capabilities for resource monitoring, modeling, and management. There are many challenges facing resource managers and researchers, but each challenge should offer an opportunity… an opportunity to more fully understand and better manage, conserve, and protect the earth's natural resources.

APPENDICES

APPENDIX A

APPENDIX A

THE RITCHIE SOIL WATER BALANCE MODEL

The core of the irrigation modeling component of this research is a soil water balance model (SWBM). References pertaining to the development and validation of the SWBM were cited in chapter 2 (Ritchie, 1972, Richardson and Ritchie, 1973, Ritchie, 1985, and Ritchie, 1998). Mathematical documentation of the SWBM is given in this Appendix. Additional details of the SWBM are given in Ritchie (1972), Ritchie (1985), and Gerakis and Ritchie (1998).

The SWBM is a multiple layer model that allows calculation of the vertical distribution of soil water as well as the total soil water content. The routines involved in the soil water balance simulation are described below in the order in which they are performed.

Step 1. Calculate potential evaporation and soil evaporation.

Potential evaporation (EO) is a function of the air temperature during daylight hours and solar radiation levels. Air temperature during daylight hours (T_D) is approximated by a weighted mean of daily minimum (T_{Min}) and maximum (T_{Max}) air temperatures (°C)

$T_D = (T_{Max} * 0.7) + (T_{Min} * 0.3)$ (A1-1)

EO is calculated as a function of two components, a radiation component and an aerodynamic component:

RadCom = (1 - GODPG) * Net24 / LatHeat (A1-2)

AeroCom = (2.8 * vpd + 3 * vpd ^ 2) * GODPG

EO = (RadCom + AeroCom) / 10

Where

RadCom = Radiation component

AeroCom = Aerodynamic component

EO = potiential soil and plant evaporation (cm day^{-1})

SR = Solar radiation (MJ m^{-2} day^{-1})

T_{DewC} = 44 'Dew point temperature constant

Net24 = SR * 0.61 - 1.5

LatHeat = 2.501 - T_D / 423 'Latent heat

T_{DewE} = 20.5 - 0.01184 * (T_{Min} - T_{DewC}) ^ 2 'Estimated dew pt. temp

vpday = 0.1 * $e^{(18.7209 - 3806 / (T_D + 273) - 222153 / (T_D + 273) ^ 2)}$

vpe = 0.1 * $e^{(18.7209 - 3806 / (T_{DewE} + 273) - 222153 / (T_{DewE} + 273) ^ 2)}$

vpd = vpday – vpe

Press = 97.8

$$GODPG = (0.598 - 0.00003 * Press) - 0.017 * T_D + 0.000149 * T_D \wedge 2$$

Potential soil evaporation (EO_S) is a function of EO and the current leaf area index (LAI).

$$EO_S = EO * e^{(-.4 * LAI)} \quad (A1\text{-}3)$$

Where

LAI = leaf area index

Step 2. Calculate root growth for the day.

Root mass and distribution are important parameters for the estimation of the amount of water taken up by the roots. In this version of the SWBM, new root growth (NRG, grams m^{-2} day^{-1}) is estimated as a function of solar radiation (SR) and the current leaf area index (LAI):

$$NRG = (SR * 0.21) * (1 - e^{(-0.6 * LAI)}) \quad (A1\text{-}4)$$

The root length distribution is calculated for each soil layer as a function of the new root growth, layer water content and a root water uptake coefficient (RWUCON). Root length distribution is used later in the calculation of water uptake (see step 7).

Step 3. Calculate ponding amount.

Ponding refers to the accumulation of standing water on the soil surface. If precipitation occurs or the current ponding depth is greater than zero, this routine is called. The ponding routine calculates ponding based on the rainfall intensity and a function for hydraulic conductivity. It calculates the daily amounts of infiltration, runoff, and changes to the height of the ponded water. The ponding routine also calls a routine for soil compaction due to rainfall action. The NEXRAD hourly rainfall rates are used on this routine to determine the maximum rainfall intensity during the precipitation event. This is the only routine in which hourly values are used, in all others, the time step is daily. The result of the ponding routine is a distribution of incoming precipitation to runoff, infiltration, or additional ponding. If irrigation occurs for the day, the irrigation amount is added to infiltration.

Step 4. Calculate the downward flow of water.

Based on the soil water content at each layer in relation to the layers drained upper limit (DUL), saturation level (SAT), and hydraulic conductivity (KsMatrix), this routine calculates the amount of water infiltrating to each soil layer from layers above.

Step 5. Calculate soil evaporation and upward water flow.

This routine uses the available energy for soil evaporation (EO_s) to estimate the amount of water moving upward and the amount evaporated from the surface layer.

Step 6. Calculate root water uptake.

The amount of water taken up by the roots is a function of the potential plant evaporation and transpiration for the day, bounded by potential evaporation minus soil evaporation (see step 1). Potential plant evaporation (EO_P) is a function of the potential evaporation and the leaf area index:

$$(EO_P) = .4 * EO * LAI \qquad \text{(A1-5)}$$

Water is removed from each soil layer as a function of the soil water content, the layer lower limit (LL), the root length distribution of the layer (step 2), and the root uptake coefficient (RWUCON). The total amount of water taken up by roots is equal to EO_P if the plant can transpire at potential levels. Otherwise the total amount of water taken up by the roots is equal to $EO - EO_S$, the potential evaporation minus soil evaporation.

Step 7. Determination of irrigation amounts.

The decision of whether or not to apply irrigation water is based on the ratio of extractable soil water to the potential extractable soil water, calculated as:

$$ESW = \sum (SW_i - LL_i) * Di \text{ for } i = 1 \ldots n. \qquad (A1\text{-}6)$$

$$PESW = \sum (DUL_i - LL_i) * Di \text{ for } i = 1 \ldots n.$$

$$DI = ESW/PSW$$

Where

SW_i	= Current volumetric soil water content, layer i
DUL_i	= Drained upper limit, volumetric soil water, layer i
LL_i	= Lower limit, volumetric soil water, layer i
DI	= Drought Index
n	= the total number of layers tested (see below).

The current soil water content is the current value for the day being simulated. The drained upper limit (DUL) is the highest field-measured water content of a soil after thorough wetting and draining until drainage becomes negligible. The DUL corresponds to water content at 'field capacity'. The lower limit is the lowest, field-measured volumetric water content of a soil after plants stop extracting water due to premature death or dormancy as a result of water deficit. The LL corresponds to the 'permanent wilting point'.

The number of layers tested (n) in Equation A1-6 is a variable that can be set by the operator. The default value is 6 (depth = 57 cm.). Any soil layer with a value for root length distribution of greater than or equal to .05 is included however. The Drought Index (DI) is the variable used to test for the irrigation threshold value (T_c). The default value for T_c is .5. That is, if DI is less than or equal to .5, then an irrigation event is triggered. The irrigation amount is a specified value that differs by crop, see Appendix b for a complete listing. A typical value is 2.5 cm. for each irrigation event. Both the threshold value (T_c) and the irrigation amount are management parameters.

APPENDIX B

APPENDIX B

CROPS AND DEFAULT MANAGEMENT PARAMETERS

Default settings for management parameters used in the SWBM are listed below for each crop.

ID	Crop	Planting DOY	MaxRootDepth (cm)	ThetaC	IrrAmount (mm.)
1	Seed Corn	135	100	50	25
2	Commercial Corn	135	100	50	25
3	Popcorn	135	100	50	25
4	Sweet Corn	135	100	50	25
5	Dry Beans	135	75	50	25
6	Green (Snap) Beans	135	75	50	25
7	Navy/Kidney Beans	135	75	50	25
8	Navy Beans	135	75	50	25
9	Soybeans	135	75	50	25
10	Barley	121	100	50	25
11	Oats	121	100	50	25
12	Potatoes	135	50	50	25
13	Rye	121	100	50	25
14	Sorghum	135	100	50	25
15	Hay/Alfalfa	121	100	50	25
16	Wheat	121	100	50	25
17	Asparagus	150	100	50	25
18	Broccoli	150	35	50	20
19	Cabbage	150	35	50	20
20	Cauliflower	150	35	50	20
21	Celery	150	60	50	25
22	Carrots	150	60	50	25
23	Cucumbers	150	25	50	15
24	Eggplant	150	50	50	25
25	Gourds	150	60	50	25
26	Lettuce	150	25	50	15
27	Melons	150	25	50	15
28	Onions	150	50	50	25
29	Peas	150	40	50	22
30	Peppers	150	40	50	22

Appendix B (cont'd)

ID	Crop	Planting DOY	MaxRootDepth (cm)	ThetaC	IrrAmount (mm.)
31	Pumpkins	150	50	50	25
32	Radishes	150	25	50	15
33	Rhubarb	150	100	50	25
34	Squash	150	70	50	25
35	Tomatoes	150	50	50	25
36	Turnips	150	25	50	15
37	Zucchini	150	50	50	25
38	Apples	135	100	50	25
39	Grapes	135	100	50	25
40	Peaches	135	100	50	25
41	Pears	135	100	50	25
42	Plumbs/Prunes	135	100	50	25
43	Sweet/Tart Cherries	135	100	50	25
44	Tart Cherries	135	100	50	25
45	Chestnuts	135	100	50	25
46	Blackberries	135	100	50	25
47	Blueberries	135	100	50	25
48	Cranberries	135	100	50	25
49	Raspberries	135	100	50	25
50	Strawberries	135	35	50	20
51	Sod	121	25	50	15
52	Nursery/Floral	135	25	50	15
53	Trees/Shrubs	121	100	50	25
54	Mint	121	100	50	25
55	Parsley	125	60	50	25
56	Mustard	125	25	50	15
57	Currents	135	100	50	25
58	Vegetable Group 1	135	30	50	18
59	Vegetable Group 2	135	50	50	20
60	Vegetable Group 3	135	50	50	20
63	Sugar Beets	135	100	50	25

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