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ESTIMATING SEASONAL AGRICULTURAL IRRIGATION
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ESTIMATING SEASONAL AGRICULTURAL IRRIGATION WATER USE IN MICHIGAN: FIELD-LEVEL EVALUATION OF THE MICHIGAN WATER USE REPORTER

By

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ABSTRACT

ESTIMATING SEASONAL AGRICULTURAL IRRIGATION WATER USE IN MICHIGAN: FIELD-LEVEL EVALUATION OF THE MICHIGAN WATER USE REPORTER

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The Michigan Water Use Reporter (MWUR) model is a simulation designed to estimate water use from irrigated agriculture in the state of Michigan. The model was developed by Moen (1999) but had never been evaluated against actual grower reported irrigation amounts. The evaluation of this model took place with data from the 2002 and 2003 growing season. Twenty-one fields across central and southern lower Michigan were used as study sites. Volumetric soil moisture and seasonal irrigation water depths were recorded from each site and used to test the simulation. Validation of the simulation was conducted in two stages. First, seasonal irrigation water volumes were compared, using descriptive statistics, to simulated season irrigation output. Second, simulated volumetric soil moisture were validated using field measurements from a capacitance probe. A sensitivity analysis of managerial and crop physiological parameters was conducted after validation. Depth per irrigation, irrigation trigger level, planting date, and root growth rate were analyzed. The simulation tended to overestimate both seasonal irrigation water depth and volumetric soil moisture across all crops. The sensitivity analysis found depth per irrigation and trigger level were by far the most sensitive parameters. These tests indicate the model, while demonstrating sound hydrology, does not properly characterize the methods grower use to decide when to irrigate. Better parameterization of these methods will result in a more robust simulation.

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Statement of Problem

Water use in the state of Michigan has not been of great concern until recently. The visibility of the Great Lakes and abundant groundwater supply has, in the past, given citizens of the state a sense of security regarding the availability of fresh water. In recent years, though, pressures for water use have been increasing from industry, residents and agriculture. Concerns over the export of Michigan water and legal disputes between irrigators and residents have put the issue of water availability in the limelight and the state legislature is ready to act on regulating water use within the state.

Agriculture has historically benefited from legislation that exempts the industry from many state regulations. Also, much of the agricultural water use in the state goes toward irrigation of crops during the growing season. Moen (1999) developed the Michigan Water Use Reporter (MWUR) model that estimates the amount of water applied for irrigation, at a 4 km resolution but reported at a county level, across the state on an annual basis. While the MWUR model has been written, it has not yet been validated against field reported or measured results.

This study proposes to address the outputs of the model by statistically comparing the modeled total seasonal water volume and seasonal soil volumetric water content to similar data collected at cooperator sites across the state. If a positive correlation is found, these comparisons will allow legislators to put their trust in the scientifically validated model output when making policy decisions. This model will eventually allow both the state government to monitor water use in a non-intrusive fashion and the growers to justify their reasonable water use for irrigation under current practices.

Objectives

The MWUR model, while potentially very powerful, has yet to have its output compared with data collected from actual study sites across the state. The model output includes both the total volume of water applied and volumetric soil moisture per day for a growing season at a 4 km resolution. The objectives for this study are therefore as follows:

1) Collect volumetric soil moisture and amount of water applied in irrigation for study sites across the state.

2) Run the model for the study site locations.

3) Compare the model output for volumetric soil moisture trends and total seasonal water use.

4) If the model output significantly deviates from any of the data collected from the study sites, perform a sensitivity analysis to explain why these deviations occurred and suggest possible ways they may be resolved.

Background and Literature Review

Introduction

Irrigation of agricultural crops is a vital component of food production worldwide, allowing growers to reduce production risk associated with crop water shortages and to improve commodity quality. Land under irrigation comprised approximately 22 Mha in the United States in 1997 and Michigan accounted for approximately 0.15 Mha of the total (NASS 1999). Overall, the seasonal average irrigation depth per season in the U.S. has decreased from 650 mm in the 1970's to 500 mm by 1996, indicating improved water efficiency. At the same time, the use of center pivot irrigation systems has increased to over 30 percent of all irrigation systems (Howell 2001).

In recent years, water use has moved to the forefront of public awareness in the state of Michigan. Highly publicized lawsuits involving groundwater rights have been brought against water bottlers, mining companies, and agricultural irrigators. With all of this publicity, state lawmakers have begun to take notice and are looking closely at water use issues. They have passed two pieces of legislation regulating large consumptive users of Great Lakes Basin water. PA 148 is a reporting and regulation bill and PA 177 is a conflict resolution bill.

The Council of Great Lakes Governors adopted the Great Lakes Charter in February 1985 in an agreement to outline ways to protect the water of the Great Lakes from environmental degradation and exportation of water outside the basin. The Great Lakes Basin is defined to include all bodies of water, rivers, stream, connecting channels, and groundwater within the watershed of the Great Lakes and St. Lawrence River.

Michigan is the only Charter member state of the nine U.S. states and two Canadian provinces that lies completely within the Great Lakes Basin.

The original Charter calls for, among many things, a common database of information on water withdrawals within the Basin. This database includes data such as the volume and uses of the withdrawn water. Another agreement was signed in August 2001, known as Annex 2001, to reaffirm many of the ideals of the original charter. Six directives were added to the Charter at this time. One directive calls for the establishment of a new decision-making standard for the approval process of new user withdrawals, such as large scale irrigation pumping wells. The second directive calls for the development of a decision support system to ensure the best data are available regarding the state and uses of the Basin water (COGLG 1985; COGLG 2001)

The Michigan Water Use Reporter (MWUR) model estimates the seasonal volume of irrigation water demand in the state of Michigan. The MWUR simulation upholds many of the ideals of the Charter and the directives in Annex 2001. It is designed to provide regulators with detailed information regarding water use for irrigated agriculture in Michigan and to provide quality data for the common database of knowledge called for in the Charter. It can provide science-based information for decision supports systems, as well (COGLG 2001).

While the Charter is a semi-binding agreement between the Great Lakes states and provinces, it is not a legally binding document because the federal governments of the United States or Canada have not ratified it. Therefore, the Michigan state legislature recently passed two documents, signed by Gov. Jennifer Granholm in November 2003, relating to water withdrawal reporting and regulation, and conflict resolution of water use disputes.

The reporting and regulation bill passed is PA 148, from the original Senate Bill 289. This act calls for the reporting of well data for large scale agricultural users, among others. Agricultural users must comply with reporting regulations if their well pumping capacity exceeds 100,000 gallons of water per day for a 30-day period. If the grower falls into this category, they must report the source, volume, and use of the water withdrawn. Part (2) of Section 32708 states: "The Department (of Environmental Quality) and the Department of Agriculture, in consultation with Michigan State University, shall validate and use a formula or model to estimate the consumptive use of withdrawals made for agricultural purposes consistent with the objectives of Section 32707." The MWUR model from Michigan State University is the system referred to in the bill. This simulation estimates the volume of water consumed by irrigated agriculture in Michigan, reporting at the county level.

Let us first consider the definition of beneficial use of water. Burt et al. (1997), writing for the American Society of Civil Engineers (ASCE), defines beneficial water use in agriculture as water which "supports the production of crops: food, fiber, oil, landscape, turf, ornamentals, or forage." This includes water use for crop evapotranspiration (ET), maintaining or improving soil quality (removal of salts), climate control (frost protection), and plant emergence among others. He does qualify that the top priority of water is human consumption but that agriculture is still considered a beneficial use of water to society.

Another important definition to this argument is that of consumptive use of water. Agricultural water use for irrigation fits the definition of consumptive use. Burt et al. (1997) define consumptive use as "irrigation water that ends up in the atmosphere (evaporation or ET) or in the harvested plant tissues (either as molecular water, notably in watermelon or tomatoes, or in organic compounds and is considered irrecoverable, that is, it is consumed". It is assumed by the Michigan Department of Environmental Quality (MDEQ) that if the water reaches the atmosphere through evapotranspiration, 90 percent of the original amount will be transported out of the basin, in this case the Great Lakes Basin, and is lost from the hydrologic system of the Great Lakes (R. van Til, MDEQ, personal communication).

The agriculture industry in Michigan has relied on farmer surveys in the past to estimate the amount of irrigation water used by the industry. Michigan Agricultural Statistics Service (MASS) and the National Agricultural Statistics Service (NASS) conduct these surveys and publish results once every four years. With the advent of new weather and climate monitoring technologies, a computer model was developed to provide government agencies a way of estimating irrigation water use in a less intrusive way (Moen 1999). While these estimates are not official, they do give these agencies some idea of the annual water use by irrigators.

The MWUR water use simulation employs the well-tested method of a soil water balance (Ritchie 1985; Knox et al. 1996; Ejieji and Gowing 2000; George et al. 2000). While other simulations have estimated water use across regional areas (Knox et al. 1996), none have been developed or tested for an entire state in the Great Lakes region of the United States. Estimates from initial simulation runs were found to be in agreement with state-level government estimates, although the Michigan Water Use Reporting (MWUR) model has yet to be validated with in-field data (Moen 1999). The model cannot be considered reliable until this validation takes place.

The model uses commonly measured weather data, more specifically temperature, solar radiation, and precipitation, in conjunction with available soil texture maps to estimate crop water demands through the growing season across a large area of thousands of square kilometers. The technological breakthrough making this model possible is the implementation and improvement of National Weather Service WSR-88 radar rainfall estimates, also known as the Next Generation Radar (NEXRAD). This product provides hourly growing season precipitation estimates, a key input variable, at a 4 km resolution across a continuous grid for the entire state and region.

Next Generation Radar

The National Weather Service first released its WSR-88 (NEXRAD) product in 1988. The radar beam scans the atmosphere at a small angle above horizontal and measures the reflectivity of the return beam, Z (mm^6/m^3). Algorithms then relate the reflectivity to a rainfall amount, R (mm) (Fulton et al. 1998). This relationship is dependent upon the intensity of precipitation, size of the hydrometeors, and form of precipitation (rain, sleet, snow, etc.). Biases do occur when precipitation intensities increase, when the size of the hydrometeors increase, or when the precipitation is partially or totally frozen. Atmospheric particulates also can have adverse affects on these estimations (Krajewski and Smith 2002).

Operational post-processing is utilized by the National Weather Service to aide in the reduction of errors of the precipitation estimates. Krajewski and Smith (2002) found a reduction in errors when the original estimates were corrected using rain gauge network data. The output of the second stage of processing is referred to as Stage II NEXRAD data. Unfortunately, there are errors associated with rain gauge networks as well, and care must be taken when using these products. Both Steiner et al. (1999) and Krajewski and (2002) reported poor data quality in historical rain gauge data. When high quality data were used, Steiner et al. (1999) were able to obtain a root mean square error for the radar rainfall estimation of about 10 percent.

The final post-processing stage involves overlaying Stage II estimations from nearby radar stations over one another. The possibility for error increases the further the particle is from the radar station (Fulton et al. 1998). Also, errors occur as the angle from horizontal increases (Borga 2002; Sharif et al. 2002). The mosaicing process helps to reduce both of these sources of error (Borga, 2002). The Stage III data product used in the MWUR model comes from the NWS and the Michigan Climatological Resources Program (MCRP). The NEXRAD Stage III product is only available during the warm season, as it has yet to correctly estimate frozen precipitation events. This limitation does not necessarily affect the MWUR model because it simulates crop water use during the growing season. The MCRP found the frequency in which the NEXRAD correctly sensed precipitation was on the order of 95.6 percent when using the Michigan Automated Weather Network (MAWN) as a baseline (Andresen and Aichele 2003). Mean differences between radar estimated and ground measured (MAWN) hourly precipitation was 0.01 mm, with a mean absolute difference of 0.11 mm. When these statistics are calculated using National Oceanographic and Atmospheric Administration

(NOAA) first order weather stations, the mean difference in precipitation was -0.1 mm and had a mean absolute difference of 0.61 mm.

While there are errors related with this new rainfall data product, there are also great advantages. Chief among them is a spatially continuous dataset with a resolution of 4 km (Figure 2). This allows for larger scale study areas where rain gauges may be limited. Koren et al. (1999) found these data to be useful for lumped hydrological modeling, the soil-water balance being one method tested, for the Arkansas-Red River basin. A finer resolution was preferred because of grid overlaying, but evapotranspiration was positively correlated with scale. Carpenter et al. (2001) also found the Stage III NEXRAD to be applicable and useful for hydrologic modeling of larger scale catchments.

Irrigation Scheduling and Crop Modeling

The soil water balance model used in the MWUR scheme is a well tested method that has become a standard in physical modeling of crop systems (Jensen et al. 1970; Wright and Bergsrud 1991; Knox et al. 1996; Prajamwong et al. 1997; Ejieji and Gowing 2000; Panigrahi and Panda 2003). A soil-water balance method is utilized to calculate plant available soil water, based on the work of Joe Ritchie (Ritchie 1972; Richardson and Ritchie 1973; Ritchie 1985; Ritchie 1998). A soil water balance sums water inputs and outputs from the system for a specific area:

$$\Delta S = Pe + IRR + GW - DP - ET - RO - \Delta SS$$

where the change in soil water storage, ΔS, is the sum of the effective precipitation, Pe; irrigation, IRR; ground water upward flux, GW; deep percolation, DP;

evapotranspiration, ET; surface runoff, RO; and change in surface storage, ΔSS (Prajamwong et al. 1997; Moen 1999).

The method requires commonly measured meteorological data on a daily basis and knowledge of physical soil characteristics. Meteorological data, in this model includes precipitation, maximum and minimum temperatures, and solar radiation. Temperature and radiation are used directly to calculate crop potential evapotranspiration, which will be discussed later. Soil water holding capacity, including the drained upper and lower limits, is necessary for the calculation of the net plant available water stored in the soil profile.

The profile is often broken into distinct horizontal layers and the soil water balance is calculated for each. These layers may have different characteristics based upon location and the depth of each may change with root development during the growing season (Burt et al. 1997; Prajamwong et al. 1997). Also, soil types may change through the profile, with different properties such as plant available water capacities (Mahmood and Hubbard 2003; Panigrahi and Panda 2003; Starks et al. 2003).

Within the soil profile, water may move in many directions. The greatest depletion in the rooting zone occurs as a result of evapotranspiration (ET) (Jensen et al. 1971). This is the combination of evaporation from the soil surface and transpiration of water through plants. ET may be directly measured through the use of a lysimeter or estimated indirectly from the calculation of potential evapotranspiration (ET_p) using one of many commonly-used equations. Over the years, many different methods for estimating ET_p have been developed. There are a handful of well-tested methods, each useful depending upon the regional climate and climate data available. In most cases, a reference ET is calculated for a standard well-watered canopy, usually grass or alfalfa. The estimated crop ET_p is a product of the reference ET and an empirical crop coefficient (K_c) (Jensen et al. 1990; Allen et al. 1998). The K_c value is based upon the specific crop of interest and its growth stage. A drawback to the estimation of crop ET_p is the requirement of a relatively large amount of detailed meteorological and agronomic data.

When meteorological data are limited, a number of estimation approaches are available. For monthly temperature based estimates of potential evapotranspiration (ET_p), the Thornthwaite method is reasonable. Thornthwaite (1948) developed a model based upon mean monthly temperature, day length, days per month, and a heat index derived from the sum of a 12-month index. This method has obvious shortcomings if a sub-monthly time period is used. Short-term mean temperature does not relate well with incoming radiation, and therefore leads to serious errors using this method (Rosenberg et al. 1983)

The Jensen-Haise method uses mean daily air temperature and the daily solar radiation equivalent of evaporated water to estimate ET_p. Jensen and Haise (1963) evaluated this method with lysimetric measurements in arid regions of the western United States. They found a good correlation, but only under non-advective conditions (Rosenberg et al. 1983).

Probably the most widely used method to estimate ET_p are the Penman and modified Penman-Monteith methods (Rosenberg et al. 1983; Allen et al. 1998). The Penman method is a combination of an energy component, solar radiation, wind speed and duration. No temperature component is used. The method was developed using a linear regression of evaporation rate over vapor pressure deficit versus wind speed.

Evaporation was measured from a evaporation pan, surrounded by a grass canopy, at Fort Collins, CO (Jensen et al. 1990). Monteith (1981) later modified the Penmen equation to accommodate aerodynamic and crop canopy resistance (Hatfield 1990).

For well-watered or humid conditions, the Priestly-Taylor method is a simplified and very useful form of the Penman-Monteith method (Jensen et al. 1990). It takes the form:

$$ET_p = \alpha[s/(s + \gamma)] * (R_n + S)$$

where ET_p is the potential evapotranspiration, s is the slope of the saturation vapor pressure at the mean wet bulb temperature, γ is the psychrometric constant, R_n is the flux density of net radiation, and S is the soil heat flux. The α term is considered the ratio ET_p/ET_{eq} and is an empirically derived constant. ET_{eq} is the equilibrium evapotranspiration. Stewart and Rouse (1977) found values of α varied slightly around the value 1.26 for temperature ranges of 15 to 30°C (Rosenberg et al. 1983). The equation is used in the Ritchie water balance and the MWUR simulation because of its utility under humid conditions, which best describes the growing season climate in Michigan. Also, meteorological data are more readily available for this ET_p calculation. Within MWUR, ET is calculated from the ET_p by multiplication of a crop-specific coefficient.

Other calculations in MWUR

Calculation of ET is the first major step of the soil water balance model within MWUR, followed by root growth and development. New root growth is a function of daily solar radiation and existing leaf area or days after planting, depending upon crop. Vertical root growth distribution is later used to calculate potential plant water uptake for each soil layer. Water is extracted from any layer with a root length distribution value of 0.05 or greater (Moen, 1999).

Next, volumetric soil water values are calculated. Ponding values are determined based upon hourly NEXRAD rainfall rates, irrigation events, and soil hydraulic conductivity. When rainfall intensity and volume are greater than soil infiltration rate, ponding occurs. This routine calculates the daily infiltration, runoff, and changes to depth of ponded water. Downward water movement through each layer is calculated when water is in excess of the soil drained upper limit. The potential drainage calculation relates the layer's drained upper limit (DUL), saturation level (SAT), hydraulic conductivity (K_s), and infiltration from the layer above. Finally, soil evaporation is calculated. This routine calculates upward movement of water by capillary action as well as evaporation. Evaporation is a function of leaf area index and potential evapotranspiration (Ritchie 1972; Moen 1999).

The determination of irrigation events is then based upon the ratio of extractable soil water (EWS) to the potential extractable soil water (PEWS) in the rooting zone of the soil profile. The extractable soil water and potential soil water equations take the form:

$$ESW = \Sigma(SWi - LLi)*DI \text{ for } i = 1 \ldots n$$

$$PESW = \Sigma(DULi - LLi)*DI \text{ for } i = 1 \ldots n$$

$$DI = ESW/PESW$$

Where

SWi = Current volumetric soil water content in layer i

LLi = Lower limit of volumetric soil water in layer i

DULi = Drained upper limit of volumetric soil water in layer i

DI = Drought index

n = Number of layers

The default drought index, which effectively triggers an irrigation event, is set at a value of less than or equal to 0.5, but can be altered by the user to reflect differing water management strategies (Moen 1999).

Use of GIS in Crop Modeling

A geographic information system (GIS) is a tool to store, analyze, and display spatially referenced data. It allows the user to link information stored in a database to a location in space and compute new data for that location (Maracchi et al. 2000) It also has the capability to incorporate remotely sensed data for analysis and display purposes. These data can include satellite land cover data, satellite-derived soil moisture estimates, or radar precipitation estimates. The use of GIS in hydrologic modeling has increased in recent years because of the spatial analysis capabilities of these programs (Engel et al. 1997; Knox et al. 1997; Sousa and Pereira 1999; Ogden et al. 2001; Heinemann et al. 2002; Ines et al. 2002; McKinney and Cai 2002; Martin de Santa Olalla et al. 2003; Rowshon et al. 2003; Rowshon et al. 2003). Figure 1 is a visualization of the input-layering taking place within the MWUR model.

Ogden et al. (2001) describe a number of different GIS interfaces for hydrologic watershed modeling. In his review, he notes the importance of temporal variability. Not only is there a need for spatial consistency within inputs and outputs, but also temporal consistency such as daily or annual averages of variables. He also states the need for spatially continuous data, such as the NWS NEXRAD radar precipitation estimates. The NEXRAD product is useful because the data are available in a raster grid network covering the entire state and relatively short temporal resolution (hourly). As the quality

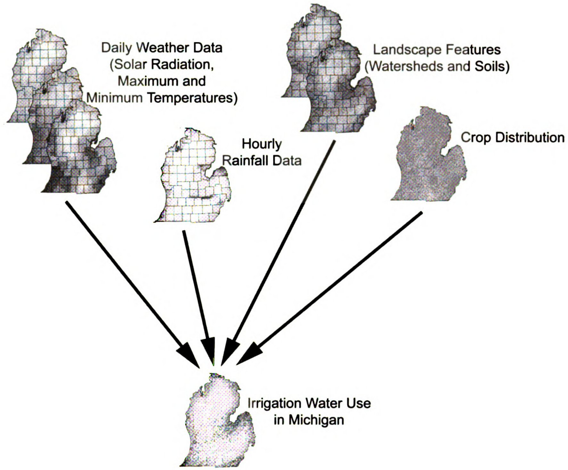


Figure 1: A visualization of the layering taking place within the MWUR simulation (courtesy of Tracy Aichele, 2002).

and availability of products such as NEXRAD precipitation estimates increase, use of hydrologic models will continue to increase within the GIS platform.

A GIS is also very capable of analyzing the water needs for agriculture. Knox et al. (1997) wrote a computer model that estimates irrigation water requirements for potatoes in England and Wales, which is very similar to the MWUR program. They were able to create maps of water use at a 5 km resolution for analysis at county and river basin scales. All necessary datasets were available in digital form from government agencies. These included regional soils maps, weather data, and land use maps. This program provided water use maps for catchment managers and planners, as well as providing politicians with a tool to more effectively litigate their water resource. Inputs and calculation methods were very similar to those used by Moen (1999), except for the precipitation data. Knox et al. used data from 11 automated weather stations instead of remotely sensed precipitation and solar radiation data. To avoid modeling many soil textures, they used three representative soils, high, medium, and low available water capacities, for the entire region instead of the numerous soils used in MWUR. Total water demand for maincrop potatoes in 1990 was determined and compared with the governmental survey estimation at a county level. The simulated water depth applied was greater than reported governmental values by about 16 percent.

Engel et al. (1997) developed a program, AEGIS/WIN, that linked the Decision Support System for Agrotechnology Transfer (DSSAT) with a GIS interface. This allowed for the creation of thematic maps of field management practices, such as final yields, irrigation requirements, and nitrogen leaching for an entire farmsted, which can be used by growers as part of a precision agriculture practice or by planners as part of a regional resource management program. Heinemann et al. (2002) had a newer version of this program, assumed it was calibrated for their region, and used it to estimate the spatial water requirements for counties in the Brazilian state of Parana. Thematic maps were developed for annual irrigation withdrawal and runoff. The authors were very satisfied with the results when such limited input data were available.

Other investigators have developed irrigation monitoring systems with GIS platforms. Martin de Santa Olalla et al. (2003) and Rowshon et al. (2003a) both developed reliable programs for system managers to better monitor and distribute irrigation water. Rowshon et al. monitored furrow irrigation in Malaysia, outputting weekly water needs for rice production in maps, graphs, and tables. While their irrigation scheduler underestimated water needs, they were satisfied with the weekly monitoring and map development for water use. de Santa Olalla et al. used LANDSAT satellite imagery to delineate irrigation areas and crop types in southeastern Spain. The GIS was able to link these locations, crop types, and field areas with government estimations of water use for individual crops to monitor groundwater withdrawal for irrigation in the aquifer. The system passed beta testing after successfully outputting reasonable water volume estimates compared to an exhaustive field study and is now fully operational for estimating irrigation withdrawals in the Mancha Oriental aquifer of southeastern Spain. He (1999) performed an analysis of irrigation water needs for the Saginaw Bay basin in lower Michigan. He used a GIS in conjunction with four crop growth models to overlay soil series maps, multi-station climate data, and multi-season management strategies (planting date, harvest date, etc.) to calculate the average irrigation demand for the Cass River watershed.

Sousa and Pereira (1999) validated a regional irrigation water requirement model for maincrop potatoes in northeast Portugal by first validating the simulation under local conditions, running a 19 year time series of historical weather data, and finally creating spatial water requirement maps using kriging techniques within a GIS interface. They chose the geostatistical method of kriging to overcome spatial heterogeneity problems. Soil moisture was monitored in 2 ha plots using a neutron probe, gravimetric samples, and tensiometers. Monitoring of soil moisture was utilized in the validation of their model to local conditions. The subsequent 19-year irrigation water estimation, for 106 locations, resulted in a mean depth of 290 mm of water per year. Surface maps of irrigation requirements for the entire region were later created from these 106 locations using kriging techniques.

Soil Moisture Monitoring and Calibration

Some of the above irrigation scheduling and monitoring programs were validated with measured volumes of water flowing through a monitored system (Rowshon et al. 2003) or from governmental survey estimates (Fanning et al. 2001). These methods are not common, though. The majority of irrigation models based upon the soil water balance were validated through a combination of soil moisture probes and gravimetric field samples.

One of the many methods for measuring soil moisture in the field is the time domain reflectometry (TDR) method. This method is based upon the relationship between the soil water capacitance, dependent upon water content, and the time shift of a 1 MHz signal sent by two metallic probes in the soil (Lane and Mackenzie 2001). The technology is useful because it provides a continuous output signal and can be automated with a datalogger. The academic community has until recently, mainly utilized it. Once calibrated, it can be a reliable method for continuous, *in situ* measurement of soil moisture (Jackson 2003). Many times this technique is used as a comparison for the validation of models (Starks et al. 2003), remote sensing of soil water content (Wilson et al. 2003), or comparison for other field-based measurement technologies (Tomer and Anderson 1995; Lane and MacKenzie 2001; Wilson et al. 2003). Chief among the limitations of this method is the high costs for installation to achieve the desired spatial coverage. Also, TDR probes are not portable and each must be buried to the desired depth. Finally, the sphere of influence that the TDR measures is based upon the length of metallic probe, which can vary between units (Starks et al. 2003).

The neutron scattering probe was used to validate models of Knox et al. (1996), Sousa and Pereira (1999), George et al. (2000), and Panigrahi et al. (2003). Each set up a sampling scheme for their respective studies and sampled soil moisture on a routine basis. The neutron probe requires aluminum access tubes installed within the field. Readings are taken at a soil depth as to give an average of soil moisture for each soil layer, usually about 15-cm in depth. Measurement frequency ranged from twice per day (George et al. 2000), to daily (Panigrahi and Panda 2003), and finally weekly (Sousa and Pereira 1999). These soil moisture values were used to compare soil water balance output from their respective irrigation models to physically measured root zone water content.

Portability and depth of measurement are two of the main reasons to use this technology. Measurements can also be taken relatively quickly. There are limitations to the neutron scattering method of measuring soil moisture, though. First, the neutron probe does use radioactive material and requires special licensing and safety equipment to use. Second, the resolution of soil moisture is coarser for this method than some others due to averaging of a greater soil area.

Gaze et al. (2002) performed a study to assess the accuracy and utility of the neutron probe for measuring changes in soil moisture in a potato field. They placed aluminum access tubes on the ridge, side, and furrow of a potato field to a depth of 100-cm. The probe was calibrated against gravimetric soil samples for each reading depth of each tube under bare soil conditions. Sample readings were taken prior to and 2-4 hours after an irrigation event. There were a total of nine irrigation events spread over three plots. Another test was set up in the laboratory in which an access tube was placed in a vat of soil, with measurements taken prior to and after watering events. In both the field and lab studies, they found the neutron probe underestimated soil moisture immediately after a wetting event, but was reasonable during soil drying from field capacity. They also applied equal amounts of water to dry and wet soils in the field and the probe could account for more of the applied water when soil was initially drier. There was also no difference in general trends between tube locations. They concluded that the neutron probe has difficulty measuring water present near the soil-atmosphere interface and that the device is inconsistent in its measurement of soil water storage under large water input settings. Therefore, its reliability and utility for the measurement of soil water deficits with large irrigation amounts must be questioned.

While there are both positive and negative studies regarding the utility of the neutron probe, other technologies are available. In particular, capacitance-type probes use similar construction and principals of soil water content measurement to the neutron probe and TDR, respectively. An electrical field signal is generated between 2 annular electrodes placed in the soil profile (Lane and Mackenzie 2001). This signal penetrates the surrounding soil profile, which returns a signal at a similar frequency. Some of the energy is trapped in the water present and the probe then measures the shift in return frequency (Tomer and Anderson 1995).

Tomer and Anderson (1995) conducted a field evaluation of a capacitance type soil moisture probe against neutron and TDR technologies in sandy textured soils. They chose the Troxler Sentry 200-AP frequency domain reflectometer, the same probe used for the validation of the MWUR model. Soil cores were taken for calibration purposes of the neutron, capacitance, and TDR probes. A linear regression equation was fit to the frequency shift values vs. calculated volumetric water content. The calibration resulted in a good correlation, particularly at depths greater than 1.0-m. The capacitance probe tended to sense water near the surface, which the neutron probe could not. But they also reported the capacitance probe had difficulty detecting frequency shifts in dry, coarse soil. They believe this bias is accentuated when air pockets result from poor soil-to-tube interface occurs. These air pockets are important because of the large difference between the dielectric constant of water (80) and air (1). The authors concluded the probe was satisfactory for relative measurements of soil moisture, but cautioned the user about the need to be deliberate in tube installation. In a similar experiment, Ould Mohamed et al. (1997) and Khosla and Persaud (1997) were in agreement with Tomer and Anderson (1995) and found the calibration and use of a capacitance probe suitable for *in situ* soil moisture measurement. The soils tested were different textural classes, silt clay loam (Ould Mohamed et al. 1997) and loamy sand (Khosla and Persaud 1997), but similar conclusions were found. Both agreed with the utility of this method but report the probe has difficulty properly measuring soil moisture under dry soil moisture conditions and cautioned users about tube installation. Khosla and Persaud (1997) used a Marquard family of equations to find a regression equation for each site tested.

Work has continued in testing of the capacitance method for measuring and monitoring *in situ* soil moisture. Wu (1998) calibrated a probe for heterogeneous soil profiles in Nepal and demonstrated a single regression curve could be calculated for each field. By far the most reported problem with this technology is the need for deliberate installation of the access tube. de Rosny et al. (2001) and Lane and MacKenzie (2001) both reported the introduction of errors in frequency shifts due to air gaps between the soil and access tube. Lane and MacKenzie concluded the utility of capacitance probe technology was questionable because of these installation problems. Also, errors in probe measurements increased as volumetric soil moisture rose above 35 percent. Chanzy et al. (1998) concluded soil moisture could be accurately monitored, after calibration, in a field using one to three access tubes. This method was chosen to validate the MWUR because of its consistent volume of aggregation, safety, and speed of measurement.

Regional Modeling and Consideration of Scale

The scale of inputs and outputs must be considered whenever modeling any plant-soil-atmosphere system, as errors can be introduced when aggregating or disaggregating variables or inputs to fit the desired scale. Hansen and Jones (2000) and Anderson et al. (2003) both discuss the problems and common pitfalls of upscaling or downscaling crop and crop/climate models. Errors are often introduced when trying to aggregate or weigh heterogeneity within an input pixel. Using linear areal averages can be problematic if the inputs are related in a nonlinear fashion. Also, the model-driving inputs may change as the scale of the model increases. Anderson et al. (2003) reports an example of this for the calculation of ET. As the model scale moves from canopy to landscape, ET becomes more dependent on feedbacks from the atmospheric boundary layer than net radiation receipt. Hansen and Jones (2000) describe the phenomena as a shift from high-frequency disturbance sensitivity to low frequency disturbance sensitivity.

Hansen and Jones also suggest input sampling when aggregating data. This involves "repeatedly using different sets of inputs sampled in a manner that captures enough heterogeneity to reduce aggregation errors to an acceptable level". This is currently being done for the MWUR NEXRAD Stage III precipitation estimates at the Michigan Climatological Resources Program at Michigan State University. A GIS is a suitable tool for this sort of task because of the ability to analyze data in different input layers and at various scales. Raster data are already in evenly sectioned grid cells, while vector data can take the form of odd shaped and sized polygons. These layers can be overlayed and aggregation algorithms calculate outputs (Figure 1). Hansen and Jones note a GIS is also a good tool for the data processing stage for similar reasons. The meteorological and soil data available for the MUWR model are at similar scales and extents. Figure 2 is the statewide NEXRAD grid network spatial distribution, which is the same as the MWUR output. All have sub-county resolution and regional extent (Figure 3). In the validation phase of this study, soil moisture and water use reports are at a much smaller scale. The area of a NEXRAD grid is 16 km^2, while a typical study field is 0.32 to 0.64 km^2 (Figure 4). Plus, soil heterogeneity within a single field can be large (Basso et al. 2001).

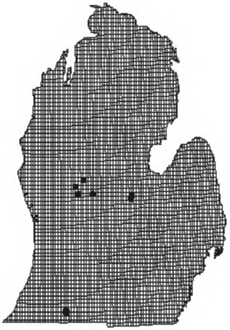


Figure 2: The NEXRAD 4 km grid network across lower Michigan with point locations of study sites.

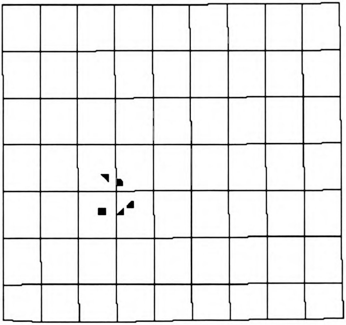


Figure 3: The NEXRAD 4 km grid network at the county size, with field sizes delineated.

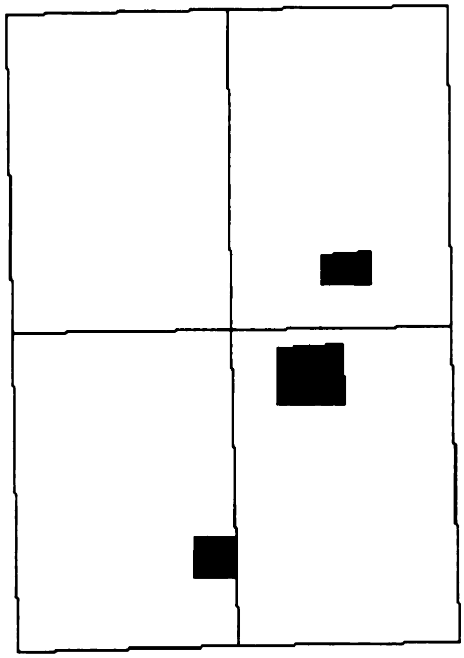


Figure 4: Four NEXRAD 4 km grid cells and three study fields (in black).

Soil moisture is probably the most highly variable parameter for a model such as MWUR, and one of the most important to characterize. It is highly variable both spatially and temporally and has non-linear influences on many environmental processes (Western et al. 2002). Western et al. review many works regarding the scaling techniques of soil moisture. Soil texture, topography, and vegetation all have effects on the spatial distribution of soil moisture at the local scale, while variations in rainfall or even climate may affect moisture at the regional scale (Paz et al. 2001; Batchelor et al. 2002). Therefore, it is not necessarily desirable to quantify the spatial pattern of soil moisture, but rather to quantify the spatial statistical structure. Western and Bloschl (1999) were able to capture the switch in process as scale was increased from vertical water movement at smaller scales to lateral movement at larger scales by representing the overall effects of soil moisture processes through spatial continuity.

Western et al. (2002) give two examples of interpretation of soil moisture measurements with small support, or area of aggregation, and large spacing. The first method relies on a dense sampling structure with a high resolution of data points. The second method is the development of a relationship between point measurements and areal soil moisture. The limitation to this method is the need for a time-stable relationship between point measured soil moisture and the spatial mean.

One must be keep in mind the different environmental variables that drive physical processes at different scales when validating soil moisture. The processes most influential at the field scale are not necessarily the same at larger ones. In the MWUR simulation, variability lies in larger processes such as precipitation and crop water demands over a multi-field area. The point measurements used to validate this simulation can quantify variability within a single field. The upscaling of the measurements to that of the model is necessary and still has relevance. Field scale measurements have been used previously to validate regional models (Knox et al. 1996; Sousa and Pereira 1999).

Two schools of thought dominate in the argument of the complexity of models as scale is increased. One argues for simpler models, hence reducing the number of inputs and the potential for effects of bias in the data. The second group believes larger scale models are built upon the smaller scale models, just with more complexity. While input data can become arduous, more real world functions are taken into account (Hansen and Jones 2000). However, input data may also be error prone. Soil maps at a regional scale, such as STATSGO, are aggregated to a map unit that may lose individual, field level soil characteristics. Hansen and Jones report the median CV of plant available water within soil associations in the STATSGO data set range from 40-60%. This can have dramatic effects on potential ET and plant water uptake, with reports of a 16% underprediction of ET and a 17% underprediction of mean production (yield) in the Hansen and Jones simulation. It must be noted, though, that increasing the detail in datasets does not necessarily mean perfect data. The SSURGO data set, a newer and more detailed soil survey, is not available for all areas and can still result in limited detail at the field level (Hansen and Jones 2000).

Weather data can be problematic as well. Interpolation between rain gauges may not describe the variability of amount or intensity over short distances (Hansen and Jones 2000). The NEXRAD Stage III radar precipitation estimates, with a spatial resolution of 4 km (Fulton et al. 1998), are better suited to sense differences in rainfall amount over smaller distances than a rain gauge network of typical density within the United States.

The MWUR simulation requires a daily precipitation estimate, which is the sum of hourly NEXRAD estimates, reducing the effect of rainfall intensity on the landscape.

Management decisions are also difficult variables to parameterize. Decisions like crop cultivar and planting date may have impacts on model outputs (Hansen and Jones 2000). Crop cultivar is not considered at all in the MWUR simulation, but planting date is set for a single date across the state for each crop. Distribution of crop acreages across the state is also necessary.

The issue of scale is a difficult aspect of modeling and model validation. It is important to characterize the level of detail required to adequately describe the desired process. Data availability, processing capabilities, and spatial and temporal extent all must be considered when making the modeling decisions. Weather data (particularly precipitation), soils data, and crop physiology are inputs of the greatest concern for MWUR. Characterizing the sensitivity of the model to these inputs is of great interest because it describes the driving parameters at the regional scale and the level of aggregation for output optimization.

Conclusion and Summary

The simulation of environmental physical processes is continuing to better characterize the 'real world' for growers, regulators, and decision makers. This thesis on modeling crop water use from irrigation is concerned with just one of the many important physical processes in agricultural production. While it does not take many cultural or societal issues into account, the model does have the potential to complement a suite of models that do better characterize this social aspect.

Bland (1999) discusses the need for agricultural modelers to begin working on integrated assessment, and specifically the integrated assessment models. The goal of integrated assessment is to produce scientifically-based information for environmental debates introduced in public and governmental forums, while respecting the human value. He proposes this modeling work focus on creating a system of diverse models interacting with one another so interaction between systems not usually considered together can be assessed. Specifically, models with a predictive capability are needed. System models, composed of small physical models describing farm-level functions, can be aggregated to describe and predict farming operations, and the broader agricultural system, depending upon various social choices. Bland calls this new paradigm "Agrarian Systems Modeling". This term describes the construction of ISMs for food-production systems. His example of the SIVI model for the potato and vegetable industry in central Wisconsin links agronomic practices, spatial distribution of fields, groundwater flow, crop yield and value, income derived from that yield, and linkages between the industry and public infrastructure. The goal of this model is to inform the public about the environmental and economic impacts the industry has on the region.

I believe, with further work, the MWUR model could become an integral part of a similar simulation for the state of Michigan, and perhaps the Upper Great Lakes Region. When integrated with a suite of models, MWUR could give important contextual information on the volume and distribution of irrigation water use.

Methods

Overview

The validity and sensitivity of the Michigan Water Use Reporting model, developed at Michigan State University (Moen 1999) was tested. The model estimates seasonal water use at a 4 km resolution for irrigated agriculture across the state. Farm locations and crop acreages are the necessary inputs into the simulation. While the resolution of the model is 4 km, the results must be aggregated to county level because of privacy issues.

Validation involved calculation of mean differences and mean absolute differences between simulated results and data collected from cooperating growers across lower Michigan. Data collection included recording volumetric soil moisture and grower reports of irrigation volume applied to each crop during the 2002 and 2003 growing seasons. The crops studied are the largest irrigated crops by acreage and volume of water applied. They include corn, potatoes, and soybeans, along with specialty crops. The farm locations were located in counties with large acreages under center pivot irrigation. This type of irrigation sprinkles water from above the crop canopy through a boom fixed at one end and free at the other, giving it the ability to rotate across the field. This was the most widespread irrigation delivery system in the state in 1997 (MASS 1998).

Monitoring soil moisture involved contacting potential cooperators, choosing field locations, installing observation tubes, and taking bi-weekly measurements of volumetric soil moisture values with a capacitance probe. Potentially willing growers were contacted regarding cooperation with the study. Of those willing, field level sites were chosen based upon location within the state, crop type, and distribution of crops in the area (Figure 3). An effort was made to be as comprehensive as possible in the selection of crop type and distribution in the major irrigated areas of the state. Field level spatial resolution was chosen because of data availability from the growers and the soil moisture measurement device. Attempts were made to monitor the same fields in both seasons of the study (years 2002 and 2003), but some compromises had to be made to ensure a more representative crop distribution.

Field sampling involved physically carrying the FDR unit to each access tube, lowering the probe to the proper depth, and taking a reading with the aid of a datalogger. A number of considerations were taken into account before final field selections were made. First, a number of irrigation delivery systems are utilized in Michigan. Center pivot systems are associated with the greatest irrigated area and volume of water applied in the state in 1997 (NASS 1999). Therefore, these systems were the focus of this study. Drip, furrow, and subsurface irrigation, among others, account for a small percentage of the total volume of irrigation water.

General farm locations were considered based upon the amount of center pivot irrigation taking place in their region. Two of the counties chosen, St. Joseph and Montcalm, were the largest irrigating counties in the state by acreage in 1997. These counties account for approximately 19 percent of the irrigated acreage of the state. Saginaw County, in eastern Lower Peninsula, has been the location of past residents vs. grower disputes. The three counties mentioned, plus Mecosta County, account for roughly 21.3 percent of the irrigated acreage in the state in 1997 (MASS 1998). St. Joseph County is located in the southwest portion of the Lower Peninsula of Michigan, while Montcalm and Mecosta Counties are all located in the west-central part of the

Lower Peninsula. Figure 2 shows the relative location within the state of the study sites. Agricultural soils in all three counties tend to be loamy sand to sandy and have high infiltration rates. Saginaw County soils tend to be higher in clay content with poor to very poor infiltration and drainage (Survey 1960; Survey 1983; Survey 1984; Survey 1994).

Simulation runs occurred after all the seasonal weather data was made available. Temperature, solar radiation, and radar precipitation estimates were the meteorological data used to drive the model. These variables are available as raster data sets. Temperature and solar radiation data are at a 20 km resolution, while radar rainfall estimates are at 4 km resolution. The model calculates water use at the 4 km resolution. Figure 2, Figure 3, and Figure 4 show the relative size of the fields at the state, county, and local scales, repectively, to the NEXRAD grid network. Other inputs include a statewide soil texture data set, the STATSGO data set, crop acreages, and farm locations.

Measurement of Soil Moisture

Soil moisture was monitored in the field using a Troxler Sentry 200-AP capacitance probe (Irrigation Scheduling Methods, Inc. (ISM), Malaga, WA). This probe relates oscillation frequency to soil water content, based upon the capacitance, in relation to the dielectric constant, of the surrounding material (Robinson et al. 1998). Water has a much greater dielectric constant air (Wu 1998). The probe requires calibration for each soil type being measured (Tomer and Anderson 1995; Khosla and Persaud 1997; Ould Mohamed et al. 1997; Chanzy et al. 1998; Wu 1998; Lane and Mackenzie 2001; Mandal et al. 2002) because soil is not a perfect dielectric. The soil and material surrounding a tube is an electrical conductor (Robinson et al. 1998). The probe readings are an integration of a cylinder of soil 30 cm high and 10 cm radius from the wall of the tube (Wu 1998; de Rosny et al. 2001).

Calibration of the capacitance probe began with the installation of access tubes in the field. These tubes are 5 cm Schedule 40 polyvinyl chloride (PVC) pipe. Installation began when the 1.7 m tubes were pounded vertically into the ground using a sand filled mallet. Soil was then augered out of the middle of the tube. Care must be taken to ensure a tight soil-tube interface. The tubes were driven to a maximum depth of 1.5 m, but many times obstacles in the soil profile, like stones, prevented installation to the maximum depth. A minimum depth of 0.9 m was achieved in all fields. This depth is satisfactory because it encompasses most of the rooting zone for all crops considered in this study. The excess PVC above ground was clipped to a height of 0.15 m. Sample probe readings were taken at 0.3 m intervals when installation was complete (ISM1996). Three access tubes were placed in transect across each field, about 75 m apart. The three tubes were installed per field (Chanzy et al. 1998), totaling 39 tubes per season for the entire study. Care was taken to try and line the access tubes with the irrigation pivot in a radial line to reduce the delay in the time between which individual tubes saw irrigation events.

Immediately after installation, bulk density cores were taken near the access tube at the median depth of the probe readings in the soil profile because the probe integrates an entire 0.3 m section. These samples were placed in tins and sealed in plastic bags to minimize evaporative loss. The procedure was repeated for each tube installed. Approximately once every two weeks, bulk density samples were again taken for each depth, near one tube. As many samples were taken as time permitted for each field through the season.

Once in the lab, bulk density cores were weighed, dried in a 105-degree C oven, for 24 hours, and re-weighed. Volumetric soil moisture and bulk density were calculated and recorded. A regression curve was fitted to find an equation relating the oscillation frequency shift probe values, or "raw values", to the volumetric soil moisture values. Marquard's non-linear least squares algorithm was used in statistical software to calculate the equation values (Khosla et al. 1997). They calibrated the same Troxler 200-AP probe and found favorable results with this type of equation. The equation takes the form of:

$$D = x_1 e^{M * x_2} + x_3 \quad (1)$$

Where D is the frequency shift reading from the probe, M is the volumetric soil moisture, and x_1, x_2, and x_3 are constants (Khosla and Persaud 1997; ISM 1999). For calibration purposes, the volumetric soil samples from bulk density cores were used as the independent variable, M. The probe readings taken immediately after a bulk density sample were the dependent variable, D. The statistical program calculated constants x_1, x_2, and x_3. These constants were then used to calculate volumetric soil moisture for each field observation through the season by rearranging equation 1 and solving for M.

$$M = (\mathrm{Ln}\ \{\})/x_2 \quad (2)$$

Tomer and Anderson (1995) attempted to use a linear regression equation to calibrate a Troxler 200-AP. The volumetric soil samples provide a second method of calculating soil moisture and were meant for the development of field level soil moisture equations for use with the capacitance probe. This method resulted in very poor r^2 values for fields in which convergence could not be attained using the Marquard family equation.

The results of the curve fitting exercise were not positive. In some cases, convergence requirements were not met after 100 iterations of the regression. Even in cases where convergence requirements were met, the equations would result in unfeasible soil moisture values for bi-weekly field observations. Table 2 is an example of erroneous field observed soil moisture. Some values are negative (volumetric soil moisture) and some result in numbers approaching infinity. Table 1 is an example of reasonable results from the calibration process for another field observed soil moisture. Unfortunately, this was only successful for 5 out of 13 fields, three in Saginaw County and two in Mecosta County. This trouble in the development of some field equations altered the use of the oven dried volumetric soil sample data. The large amounts of soil texture heterogeneity and lack of data points, too few bulk density samples per field, are most likely to blame for these problems. Instead, the data were utilized as a check of the capacitance probe data calibrated using the manufacturer's pre-developed equations.

Basso et al. (2001) reported soil moisture is a function of both soil depth and texture. They also found that soil texture was highly variable in a 7 ha field near Durand, MI, within the study area of this research. Sand content was reported to vary from 40 to 80 percent and clay content 8 to 25 percent across the field. Soil water was reported in terms of potential extractable soil water and the range of values was 140mm, in low areas, to 70 mm, in high areas. A correlation was found between topography and soil texture. Clay content was highest in lower elevations, and sand content greater in higher elevations.

ISM offers calibration software as part of the probe package. The software requires an initial soil textural classification (i.e. sand, loamy sand, etc.) and initial water

		Capacitance Probe Volumetric Soil Moisture (cm^3/cm^3)						
		6/24/2003	7/4/2003	7/8/2003	7/10/2003	7/14/2003	7/17/2003	7/24/2003
Tube 1	0-30 cm	8.45	11.37	11.03	18.43	11.60	8.01	8.90
	30-60 cm	16.57	15.72	15.30	19.45	19.75	17.00	20.33
	60-90 cm	32.93	34.65	36.71	37.51	39.99	35.16	35.16
Tube 2	0-30 cm	6.08	8.84	7.81	12.63	13.49	7.30	8.53
	30-60 cm	15.06	15.06	14.08	16.31	16.18	15.44	16.68
	60-90 cm	32.19	33.35	32.96	33.94	35.75	34.34	35.34
Tube 3	0-30 cm	2.84	6.26	5.94	11.14	7.66	5.94	7.01
	30-60 cm	15.30	12.94	12.12	14.88	14.05	13.35	14.88
	60-90 cm	29.14	28.37	27.23	28.18	31.11	30.91	31.71

Table 1: Volumetric soil moisture calculated with regression equation developed from field soil cores, Saginaw Co. 2003.

		Capacitance Probe Volumetric Soil Moisture (cm^3/cm^3)						
		6/10/2003	6/24/2003	7/4/2003	7/7/2003	7/10/2003	7/14/2003	7/17/2003
Tube 1	0-30 cm	-2.16	10.38	13.06	13.38	28.21	17.39	13.69
	30-60 cm	-1.69	14.26	17.36	16.60	16.79	20.61	18.33
	60-90 cm	21.49	∞	∞	∞	∞	∞	∞
Tube 2	0-30 cm	-3.95	2.30	4.43	7.92	17.68	9.98	9.83
	30-60 cm	-1.52	12.45	15.65	15.32	15.65	18.48	17.39
	60-90 cm	3.46	35.40	∞	46.77	∞	54.35	54.35
Tube 3	0-30 cm	-3.95	11.36	13.74	14.90	31.02	15.24	13.09
	30-60 cm	-1.63	12.17	15.31	15.14	14.97	18.59	16.73
	60-90 cm	-4.37	3.52	5.90	5.49	5.09	7.84	6.44

Table 2: Volumetric soil moisture calculated with regression equation developed from field soil cores, Montcalm Co. 2003.

content as a percent of field capacity. The initial water content was determined with litmus paper and color chart provided with the installation package. With soil texture, initial water content, and initial frequency shift, or "raw value" from the capacitance probe, the software determines the calibration equation for each layer. Each calibration equation has an associated letter code, which the software outputs for each layer of each tube. The letter output by the software was programmed into the datalogger for the associated tube and soil profile depth. Each letter has its corresponding equation pre-programmed in the datalogger. These pre-determined "equations" are nothing more than equation 1 with each letter code having been solved for the set of constants, x_1, x_2, and x_3. See Table 3.

Mean differences between the factory calibration and volumetric calibration show an increase in soil moisture using the volumetric calibration method (Table 3). The increase in mean difference of water content also increases by depth and was greatest at the third layer (60-90 cm). The factory calibration method gives each layer a predetermined equation, based upon soil texture and antecedent water content. In Table 4, the mean differences between probe measured and volumetrically determined soil moisture is small through the profile. With this evidence, along with the lack of data points to determine equations for individual fields, it was decided to use the manufacturer's calibration methods and codes.

Observation tube installation began in early June for 2002 and early May for 2003. The late start in 2002 was due to shipping delays from the soil moisture monitoring

	A	B	FAC	C	D	E	F	G	H	I	J
x_1	-1672	-1593	-1494	-1388	-1238	-1151	-1058	-960	-862	-863	-829
x_2	-0.0525	-0.0452	-0.0387	-0.0408	-0.0436	-0.0505	-0.0516	-0.0533	-0.0589	-0.0486	-0.0549
x_3	4130	4240	4329	4344	4329	4315	4345	4360	4383.02	4515.814	4532.653

Table 3: Factory calibration curve values by code letter. Constants are pre-loaded into the probe datalogger and automatically calculate volumetric soil moisture from raw probe readings. (ISM, 1999)

	Mean Difference (cm^3/cm^3)	Mean Absolute Difference (cm^3/cm^3)
0-30 cm	-0.004	0.035
30-60 cm	-0.005	0.051
60-90 cm	0.003	0.066
All Depths	-0.003	0.049

Table 4: Mean and mean absolute difference between factory calibrated capacitance probe and volumetric soil core measurements of volumetric soil moisture (cm^3/cm^3) by depth for all fields, 2003.

equipment distributor. Installations in 2003 began shortly after planting. Work started in the southern most county, St. Joseph, and was concluded in Mecosta County to the north three weeks later. Installation of the tubes was completed in early July for 2002 and early June for 2003. Afterwards, each field was visited twice per week for sampling. Fields in Montcalm, Mecosta, and Saginaw counties were visited on the same days (Monday and Thursday) while sites in St. Joseph County were visited separately (Tuesday and Friday). Observations continued through the growing season until either the crop was harvested, in the case of some potato fields, or irrigation was stopped for grain dry-down just prior to harvest. The tubes were removed from each field immediately prior to harvest so no damage would be caused to any harvest equipment.

Probe readings are an integration of the volumetric soil moisture for a 0.3 m depth of soil (Tomer and Anderson 1995; ISM 1996; Khosla and Persaud 1997). Soil moisture data were analyzed for depths to 0.9 m because all tubes were driven to a minimum of this depth and for consistency across all study areas. The 0.9 m tube depths resulted in three 0.3 m volumetric soil moisture values for each tube. The capacitance probe was lowered to the proper depth, a measurement was taken, the reading was saved to a file, and the probe was lowered to the next depth until all depths had been measured. Each of these depth measurements were made at all three tubes in an individual field and each field was visited twice per week. Before a field was re-visited, data was downloaded to a PC in the laboratory. While all the individual fields could fit in the memory, only one visit per field could be stored on the datalogger. A RS-232 connection linked the datalogger to a PC running the download program (ISM). Data was later compiled and analyzed using spreadsheet software. The volumetric soil moisture observations were taken to validate the MWUR simulation volumetric soil moisture results and were also saved in the spreadsheets. MWUR model runs began when the temperature/solar radiation data grids and NEXRAD radar precipitation estimates for the year were made available from NWS and the Michigan State Climatological Resources Program.

Model Validation

The goal of this portion of the study was to assess the validity of soil moisture and irrigation water volume applications of the MWUR model when compared to field level data. The model was validated in two parts. First, the simulated volumetric soil moisture output was compared to volumetric soil moisture measured in test fields around the state of Michigan. Second, growers supplied the values of irrigation water volume applied on test fields. The reported volumes were compared to the irrigation water volume output by the model for the grid cells encompassing each test field.

The robustness of the model was evaluated through calculation of mean differences between MWUR irrigation water volume application estimates and values of irrigation water for individual study fields from cooperators. Descriptive statistics, such and mean difference and mean absolute difference, averaged by crop and by grower, were used to describe the relationships because of the desire to find the degree to which the two datasets are different and to find any bias between them (Ould Mohamed et al. 1997; Chanzy et al. 1998; Sousa and Pereira 1999; Basso et al. 2001). Given the limited number of data points available, a maximum of 26 fields for the two years, descriptive statistics best describe the relationships than other tests. Unfortunately, some cooperators failed to provide seasonal irrigation records for certain fields. These fields were not included in any part of the statistical analysis. Records submitted left 21 of the 26 fields with complete records. Paired t-tests were utilized to test the null hypothesis that states the simulated and observed volumetric soil moisture and irrigation depths have the same mean. Biases due to within field and regional soil heterogeneity were overcome by plotting simulated values as a percent of observed over time. Discrepancies between model irrigation amounts and observed irrigation amounts applied were described by plotting the difference between the irrigation amounts against potential drainage.

To begin, model outputs were compared to both field measured and grower supplied data. Calibrated probe volumetric soil moisture data for each field were first entered into a spreadsheet program. Measured soil moisture values for each depth on each date were averaged to lessen the effects of within-field heterogeneity. The model was run for each field based upon field location in relation to the NEXRAD grid network for years 2002 and 2003. Model parameters were initially set to default values (Moen 1999). The results for seasonal irrigation depth, irrigation dates, and daily volumetric soil moisture were written to a database and, after simulation executions, individual locations were queried and the resultant outputs saved in a spreadsheet. Queries by crop were also saved. Simulated soil moisture is calculated in layers through the soil profile to a depth of 160 cm. There are 10 layers, consisting of 2, 5, 8, 11, 14, 20, 23, 25, 25, and 25 cm depths below the surface, respectively (Figure 5). These values for each layer must be aggregated to layers of 30.48-cm in size, corresponding to the layer depth of the capacitance probe measurements. A weighted average of these values was taken to convert to layer depths of the capacitance probe.

After the daily values of soil moisture were calculated at each depth for the growing season, another filter was applied to match dates of measurement with calculated

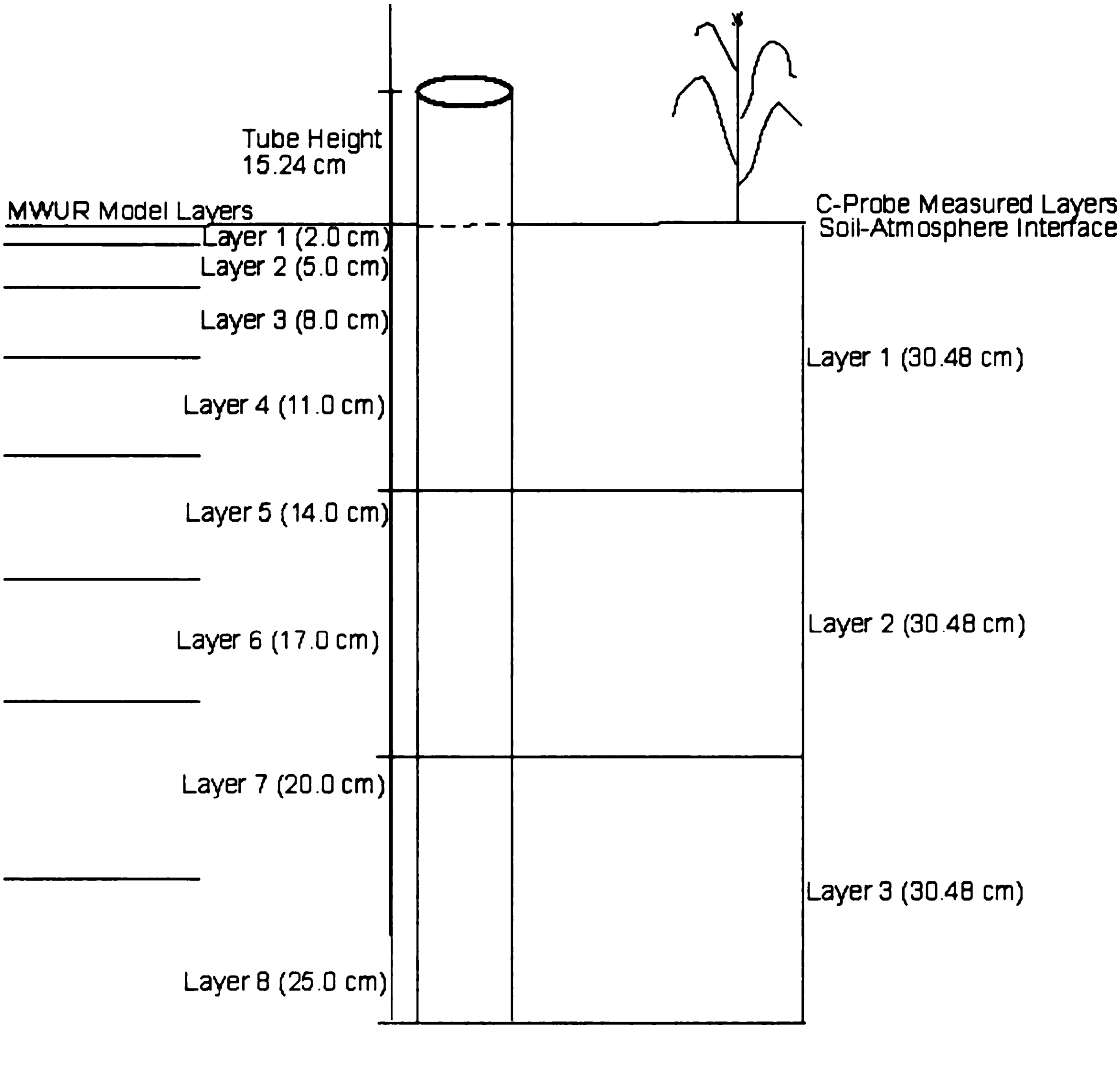


Figure 5: Visualization of model layer depths (left) and capacitance probe measurement layer depths (right) with tube placement in soil profile.

dates. Mean differences and mean absolute differences were calculated for each crop, by layer and for years 2002, 2003, and the two years combined. Paired t-tests were run by crop for the two years combined. Similar tests were performed when data were grouped by grower.

The grower supplied daily irrigation volumes for individual crops were entered into a spreadsheet. Model output of the daily irrigation and irrigation events were queried and saved into the spreadsheet. Timelines of depth accumulation were plotted for modeled and reported values. Seasonal irrigation volumes are calculated by summing daily amounts and the mean difference and absolute mean difference were calculated for each crop and each county on a yearly basis. Mean difference and mean absolute differences were calculated for each crop for 2002 and 2003 combined. Finally, paired t-tests were conducted by crop on the irrigation volume amounts and soil moisture for 2002 and 2003 together.

Model Sensitivity Analysis

Four grower managerial and crop physiological parameters were adjusted to test model reaction. These tests are meant to compliment the previous sensitivity analysis of Moen (1999). He tested the sensitivity of the model to changes in soil map units of the STATSGO data set. His results indicate fewer total map units may be used across the state and more aggregation of soil texture classes within 4 km grid cells can occur. He also tested propagation of errors in the NEXRAD data set. The results indicate cells further from radar stations have greater errors. Neither of these model parameters was tested here because of the results from the previous study.

Instead, four crop and managerial model parameters were tested. Choice of these parameters was based upon results of the validation portion of the study. Daily irrigation accumulation led to questions regarding timing, amount per irrigation, and season length. Analysis of volumetric soil moistures at depths led to questions of root growth and development. The altered parameters include root growth rate, planting date, amount of water per irrigation event, and soil moisture irrigation trigger (Θ_c). As roots grow faster and deeper, there is more potential for plant water extraction at different depths. Planting date changes may affect annual soil moisture cycles and when the irrigation season begins and ends. Amount per irrigation and Θ_c changes affect the frequency and duration of irrigation cycles. Results can be seen with larger or smaller and more or less frequent irrigations.

Rooting growth rate was adjusted for each crop, and similar methods were used for analysis as with the validation portion. Mean and mean absolute differences, as well as paired t-tests were calculated for each parameter change. Similar methods were used to test soil moisture irrigation trigger (Θ_c), irrigation amounts, and planting date parameters. These parameter changes were run for all the study fields in 2002 and 2003. These statistics were calculated upon the differences between changed parameter and default simulated volumetric soil moisture and irrigation depths.

The variable Θ_c is the fraction of water withdrawn from plant available soil water that triggers an irrigation event. The variable was changed within the range of 0.40 to 0.60 of plant available water in increments of 0.05. The default value is 0.50. The output values of soil moisture and irrigation events were exported to a spreadsheet, where the soil moistures were averaged to 30.48 cm layers and the seasonal irrigation amount for each location was calculated. The values for each location were placed in a table and differences between the adjusted Θ_c results and default results were found. Mean differences in volumetric soil moisture were calculated from planting date, day of year (DOY) 135, until the model ended calculation for the particular crop. The total irrigation amount mean differences were calculated by crop for 2002, 2003, and the two years combined.

Irrigation amounts per even were changed from a default value of 25 mm to a maximum of 38 mm and a minimum of 12 mm, in 6 mm increments. The root growth rate look-up table in the model relates root depth to either accumulated growing degree units or days after planting, depending upon the crop type. The depth of the root at the given steps was increased by 10 and 25 percent and decreased by 10 and 25 percent for all crops. The model ran for each of these scenarios and descriptive statistics and paired t-tests were calculated. Planting of crops does not occur on the same day across the entire state. There can be a period of weeks between far southern and northern Michigan. The model sets the planting date of most crops at DOY 135, but a few of the specialty crops are set at DOY 150. The model ran with adjusted planting dates ranging from -10 days to +10 days, in 5 day intervals. Summary statistics and t-tests were performed on the soil moisture and irrigation volumes.

Once these summary statistics were calculated for the initial run and parameter sensitivity runs a "best fit" characterization of physiological and managerial parameters were made. After the most sensitive parameters were determined, these model variables were adjusted until the smallest mean difference between seasonal simulated and reported irrigation depth for each crop were found. These "best-fit" parameter values were recorded for each crop. Irrigation amount per event, trigger soil moisture deficit, and season length were adjusted. Summary statistics were calculated for each of these runs.

Results

Model Validation

The first and most important objective of this study was to determine how close the MWUR irrigation depth and soil moisture simulated outputs are to those reported and measured on commercial farms in Michigan. In an effort to quantify any differences, volumetric soil moisture was monitored in field during the 2002 and 2003 growing seasons for 6 different commercial crops: corn, potatoes, soybean, sugarbeet, carrot, and pepper. Corn, potato, and soybean crops were monitored across both years of the study. Overall, a total of seven corn, nine potato, two soybean, one carrot, one sugar beet, and one sweet pepper fields were monitored during the study. Grower-supplied irrigation data were not available in all the fields monitored, and these fields were not included in the statistical analysis.

Mean and mean absolute differences between simulated and reported seasonal irrigation depths by crop are given in Table 5. Simulated irrigation depths were greater than those reported by the growers for the individual 2002 and 2003 seasons and for each crop type considered in the comparison. The model also tended to overestimate seasonal irrigation across all crops, with a mean difference of 54 mm for potatoes, 59 mm for corn, and 117 mm for soybeans. Mean absolute differences, a better indicator of the magnitude of individual differences, ranged from 16.8 mm for carrots during the 2002 growing season to 159.0 mm for peppers in 2003. Simulated seasonal irrigation depths were on the order of 135 percent of the reported seasonal totals for corn, 124 percent for potato, and 197 percent for soybean over the duration of the study. From Table 6, model standard

	2002					2003				All Years		
	Corn	Potato	Soybean	Sugarbeet	Carrot	Corn	Potato	Soybean	Pepper	Corn	Potato	Soybean
Mean Difference (mm)	75.9	93.1	97.6	55.2	16.8	25.1	67.2	136.1	159.0	54.1	59.4	116.9
Mean Absolute Difference (mm)	75.9	93.1	97.6	55.2	16.8	81.3	67.2	136.1	159.0	78.2	83.1	116.9
Percent of Reported	153.1	120.3	164.0	138.1	105.9	115.1	130.5	253.1	225.2	135.4	124.4	196.9

Table 5: Mean and mean absolute difference between simulated and reported seasonal irrigation depth (mm) and simulated seasonal irrigation depth as a percent of reported irrigation, calculated by crop for seasons 2002, 2003, and the two years combined. Simulated depths calculated using default model settings.

	Corn	Potato	Soybean
Model SD	37.4	26.4	17.7
Reported SD	51.5	87.4	44.9

Table 6: Simulated and reported seasonal irrigation depth standard deviation for seasons 2002 and 2003 combined.

deviations of irrigated depth of water for the two years ranged from 17.7 mm in soybean to 37.4 mm in corn. Reported irrigation depth standard deviations for the same period ranged from 44.9 mm in soybean to 87.4 mm in potato. Across individual crop types that were replicated during the same season, there was large variation among the differences, ranging from 79.1 mm for corn in 2002 to 249.3 mm for potato in 2002. Individual field differences can be seen in Table 7. This data suggests there is large variability in irrigation depths between individual growers across the state.

A scatterplot of simulated versus reported seasonal irrigation depths is given in Figure 6. The broad scatter of the points and low r^2 of the fitted regression line indicate relatively poor agreement between estimated and observed and further illustrate the tendency of the model to overestimate irrigation. Regardless of the many differences between the simulated and observed irrigation totals, when they were compared statistically with a paired t-test, none were found to be significantly different at the α = 0.05 level, suggesting non-rejection of the null hypothesis that the means of the two populations are equal.

Comparisons were also made of simulated versus observed volumetric soil moisture. Soil moisture is a critical variable at the heart of the simulation. The values calculated for each layer of the model determine the water content available to the plant and strongly influence the frequency of simulated irrigation throughout the growing season. The soil moisture values the simulated by the model were aggregated to layers of a depth in the profile equal to that monitored by the capacitance probe, in this case three layers of 30.5 cm depth.

		Model Irrigation Depth (mm)	Reported Irrigation Depth (mm)	Difference (mm)	Absolute Difference (mm)
Location	**Crop**	**2002**			
Mecosta	**Corn**	225	203.2	21.8	21.8
Montcalm	**Corn**	200	111.8	88.2	88.2
Saginaw	**Corn**	200	99.1	100.9	100.9
St Joe	**Corn**	250	157.5	92.5	92.5
Mecosta	**Potato**	325	241.3	83.7	83.7
Montcalm	**Potato**	300	157.5	142.5	142.5
Montcalm	**Potato**	325	247.7	77.4	77.4
Saginaw	**Potato**	300	231.1	68.9	68.9
St Joe	**Potato**	325	431.8	-106.8	106.8
Saginaw	**Beets**	200	144.8	55.2	55.2
St Joe	**Soybean**	250	152.4	97.6	97.6
Mecosta	**Carrot**	300	283.2	16.8	16.8
		2003			
Mecosta	**Corn**	175	158.8	16.3	16.3
Saginaw	**Corn**	250	106.7	143.3	143.3
St Joe	**Corn**	150	234.2	-84.2	84.2
Mecosta	**Potato**	275	266.7	8.3	8.3
Saginaw	**Potato**	325	137.2	187.8	187.8
St Joe	**Potato**	250	182.9	67.1	67.1
St Joe	**Potato**	300	294.6	5.4	5.4
Saginaw	**Pepper**	286	127.0	159.0	159.0
St Joe	**Soybean**	225	88.9	136.1	136.1

Table 7: Simulated, reported, differences, and absolute differences of seasonal irrigation depth for individual study sites, 2002 and 2003.

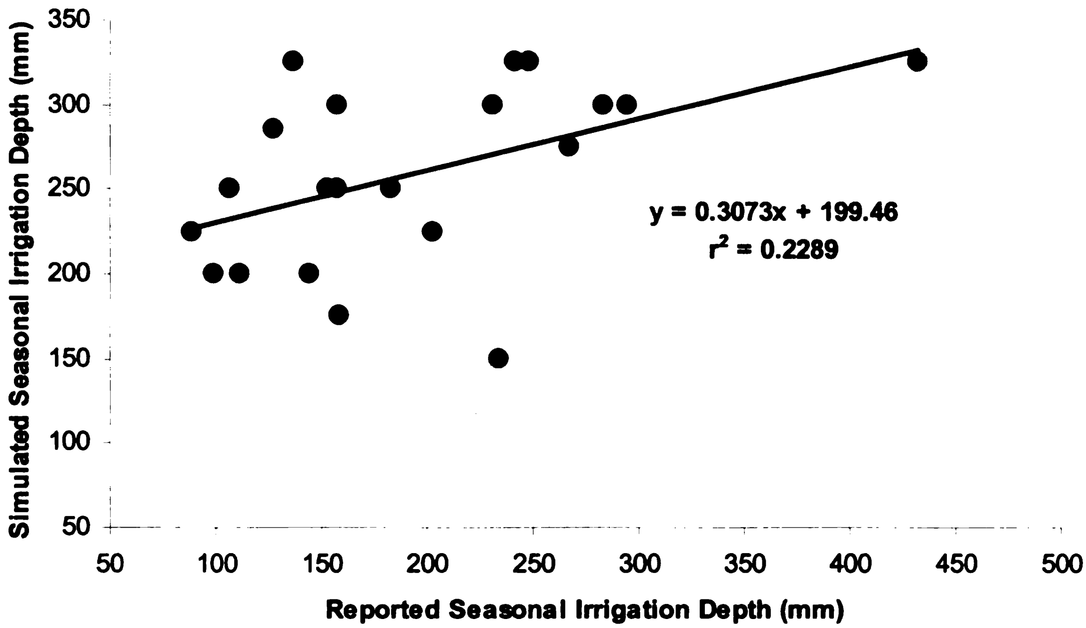


Figure 6: Simulated vs. Reported Seasonal Irrigation Depth (mm) for all reporting fields in 2002 and 2003. Simulated results calculated using default model settings.

Mean and mean absolute differences of volumetric soil moisture, averaged in the 30.5 cm layers and across replicates for each crop type, are given in Table 8. The differences in many of the layers were positive (indicating overestimation of soil moisture) with the exception of carrots, corn, and soybean in the top 0-30.5 cm layer, in which the negative difference suggested underestimation. For comparison, a typical range of plant available water content, approximately the difference between field capacity and wilting point of a soil, values are generally in the range of 0.08-0.10 in/in for the sands and loamy sands found at most study sites (Survey 1960; Survey 1983; Survey 1984; Survey 1994). The model calculates total volumetric soil water content and not plant available water, but the values from the soil survey give an indication of the range of values (from dry to wet conditions) expected from the model. The negative values in the top layer ranged from –0.040 cm^3/cm^3 for soybeans to –0.004 cm^3/cm^3 for corn. The differences for potatoes, sugarbeet, and peppers are positive and somewhat larger ranging from 0.002 cm^3/cm^3 for potatoes to 0.120 cm^3/cm^3 for sugarbeet. Paired t-test results indicate significant differences between the populations of modeled and observed soil moisture for most crops. The total number of samples was 108 for corn, 98 for potato, and 32 for soybean.

Lower in the soil profile, simulated soil moisture in the second and third 30 cm layers of the profile was greater than observed moisture for all crops. The mean differences increased with increasing profile depth for all crops. For example, the second layer ranged from 0.011 cm^3/cm^3 in soybean to 0.061 cm^3/cm^3 in potatoes over the two years of observations. Mean differences, and the output data itself, are consistent across most crops in the third layer. Mean absolute differences for all layers were of the same

	Mean Difference (cm^3/cm^3)	Mean Absolute Difference (cm^3/cm^3)	Significance
	0-30 cm Soil Profile Depth		
Corn	-0.004	0.049	*
Potato	0.002	0.032	
Soybean	-0.040	0.048	*
Carrot	-0.023	0.027	*
Sugarbeet	0.121	0.121	*
Pepper	0.057	0.057	*
All Crops	0.007	0.048	
	30-60 cm Soil Profile Depth		
Corn	0.018	0.061	
Potato	0.061	0.064	*
Soybean	0.011	0.043	
Carrot	0.051	0.051	*
Sugarbeet	0.119	0.119	*
Pepper	0.148	0.148	*
All Crops	0.048	0.068	
	60-90 cm Soil Profile Depth		
Corn	0.044	0.051	*
Potato	0.050	0.053	*
Soybean	0.053	0.053	*
Carrot	0.056	0.056	*
Sugarbeet	----	----	
Pepper	0.123	0.123	*
All Crops	0.054	0.058	
	All Layers		
Corn	0.019	0.054	*
Potato	0.037	0.050	*
Soybean	0.008	0.048	
Carrot	0.028	0.045	*
Sugarbeet	0.120	0.120	*
Pepper	0.110	0.110	*
All Crops	0.036	0.058	

Table 8: Mean and mean absolute differences between simulated and observed soil moisture (cm^3/cm^3), calculated by crop and soil profile depth for years 2002 and 2003 combined. Simulated soil moisture calculated using default model settings. Significance tested at $\alpha = 0.01$ level.

magnitude as mean differences, suggesting the level of individual differences were similar.

Differences between simulated and observed soil moisture were also analyzed geographically, as each field and each sample location may have unique soil properties, based upon soil type, parent material, topography, and other factors (Bechini et al. 2003). The ratio of simulated and observed soil moisture was calculated, as a percentage, over time during the growing season at each field sampled in an attempt to overcome any biases introduced by these geographical differences. An interesting trend was found for all layers of corn during the two-year period (Figure 7a, b, c, d). The simulated percentages were relatively high at the location in Saginaw County, similar to the observed values in Mecosta and Montcalm Counties, and less than the observed values in St. Joseph County. These differences suggest the possibility of spatial biases within the model, perhaps due to variation in physical properties of soils. At lower layers, these general trends, greater or less than observed, were similar within each of the fields.

Finally, the management strategy of the grower must be considered. In the MUWR system, the assumption is made that every grower applies an equal amount of water to supply plant needs at exactly the most opportune time. This assumption has obvious shortfalls because each grower may utilize different strategies or methods to determine when to irrigate. The numerous commercial and government irrigation schedulers and scheduling recommendations, including the new GAAMP (2003) protocol in Michigan, are just an indication of the variety of ways growers determine when to irrigate. Growers also face practical problems, such as the minimum time needed for the irrigation system to complete one watering cycle in a given field or a limited maximum

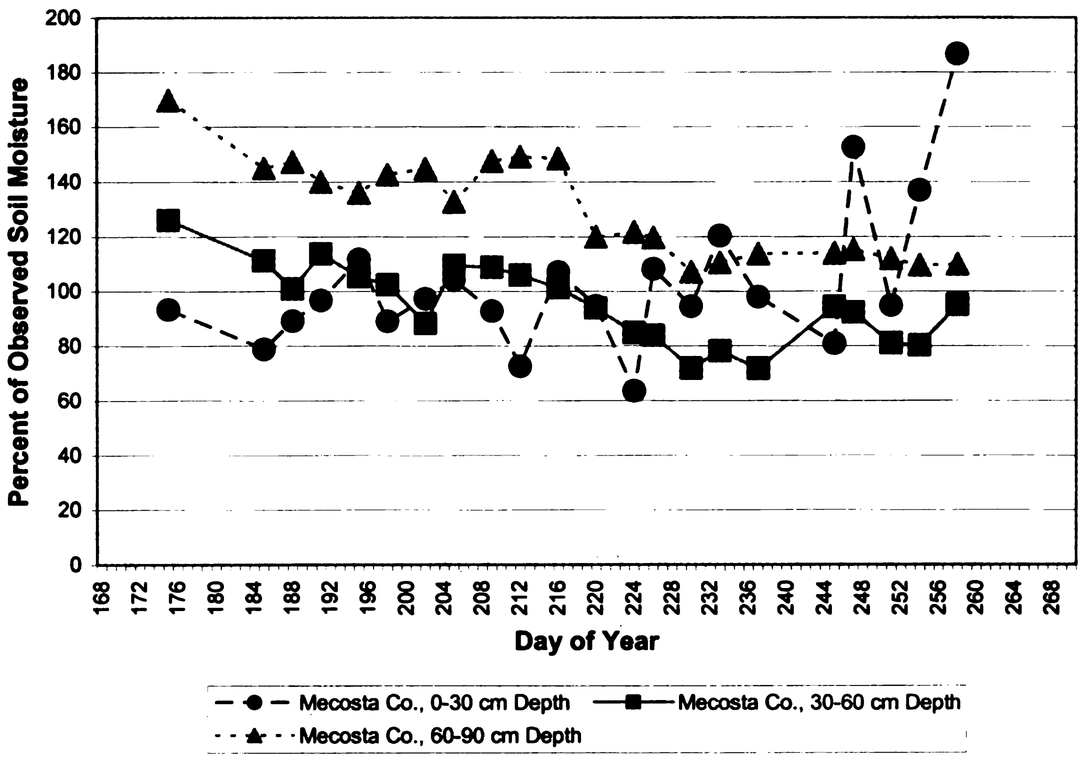


Figure 7a: Simulated volumetric soil moisture, as a percent of observed soil moisture by depth for corn in Mecosta County, 2003. Simulated values calculated using default model settings.

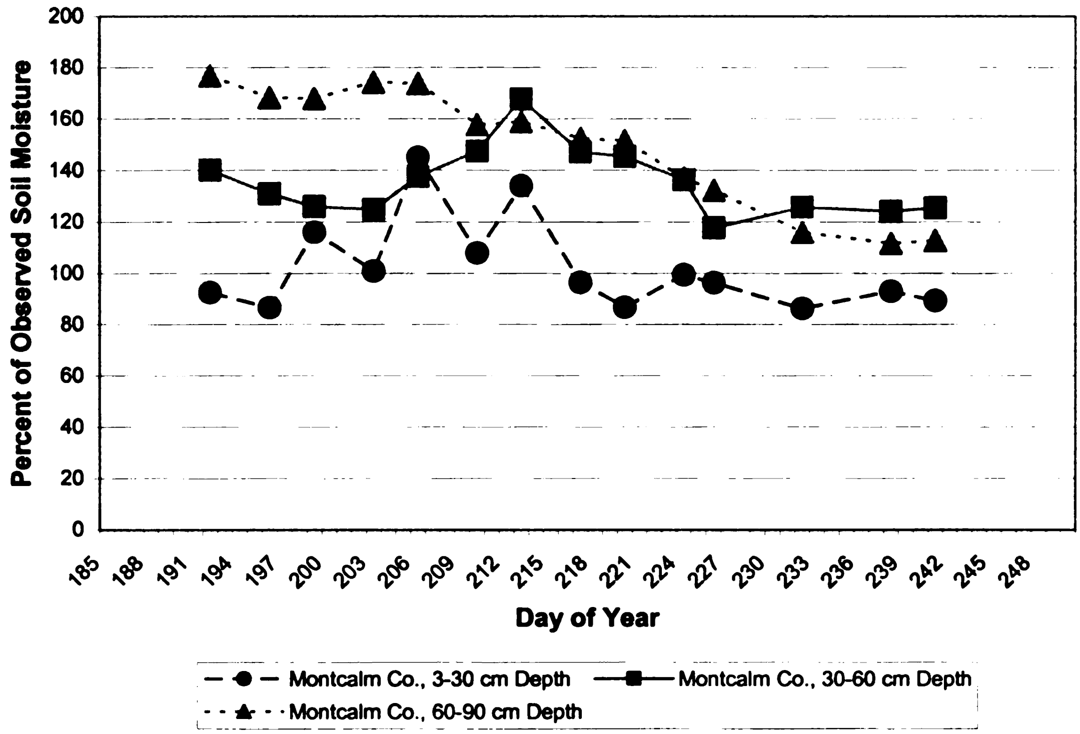


Figure 7b: Simulated volumetric soil moisture, as a percent of observed soil moisture by depth for corn in Montcalm County, 2002. Simulated values calculated using default model settings.

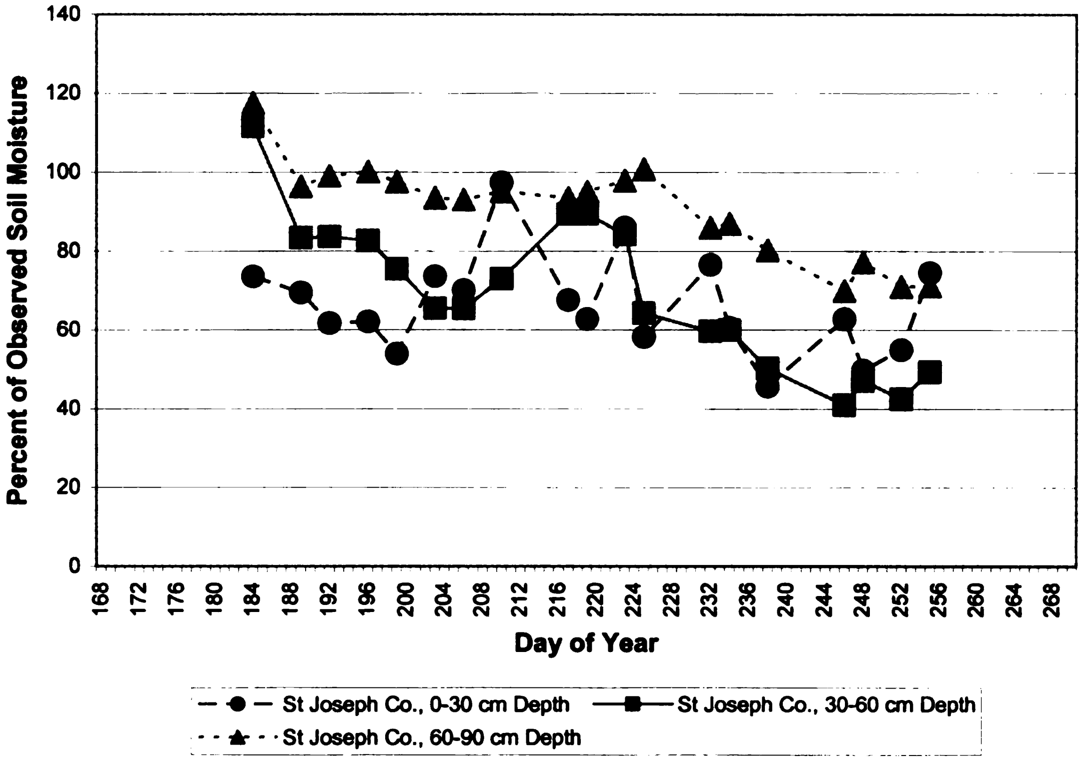


Figure 7c: Simulated volumetric soil moisture, as a percent of observed soil moisture by depth for corn in St. Joseph County, 2003. Simulated values calculated using default model settings.

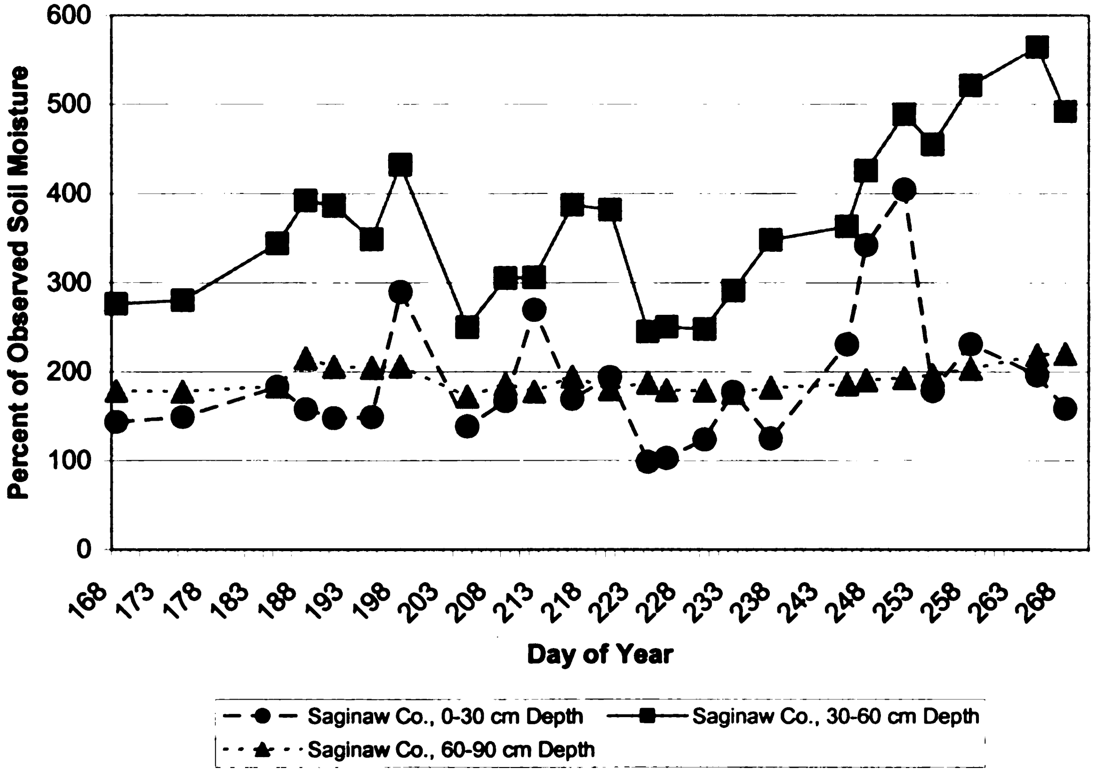


Figure 7d: Simulated volumetric soil moisture, as a percent of observed soil moisture by depth for corn in Saginaw County, 2003. Simulated values calculated using default model settings.

rate of water application. In Michigan, some growers may use various forms of irrigation scheduling models, while others simply schedule with the number of calendar days since precipitation (Wright and Bergsrud (1991), grower personal communication). In an attempt to determine any bias introduced from multiple managerial processes, mean differences and mean absolute differences were calculated for each grower. All growers except one reported less water use than estimated by the MWUR model, with the differences over both seasons ranging from -41.3 mm to 119.2 mm, in Table 9. With the exception of grower 3, the differences were greater during the 2002 season. The relatively higher rankings of the differences for growers 3 and 4 each year suggest some consistency of management scheme. Standard deviation of seasonal irrigation depths within individual grower's fields ranged from 47.1 mm to 137.4 mm (Table 10). Not all growers had the same crop type or distribution, but this does suggest a large amount of variability within an individual farm.

Taken collectively, the results of the direct comparisons indicate relatively poor agreement between the MWUR estimates of soil moisture and subsequent irrigation totals and those observed at the field level. This is somewhat surprising, given the satisfactory results of Andresen et al. (2000) on the only previous attempt to validate the model for this type of application a larger statewide scale. It is also surprising given a number of successful previous field-level applications of the base soil moisture algorithm, which serves as the base of the MWUR model (Ritchie 1985; Ritchie 1998; Andresen et al. 2002). Arguably the most important source of potential source of error is the National Weather Service Stage III precipitation estimates used as input by the MWUR model system (Moen (1999), pp. 138-148). While possibly related to some of the observed

Grower	2002						2003				All Years					
	1	2	3	4	5	6	1	3	4	6	1	2	3	4	5	6
Mean Difference (mm)	52.8	60.8	75.0	95.1	142	-107	12.3	163	70.7	-8.50	32.5	60.8	119	79.7	142	-41.3
Mean Absolute Difference (mm)	52.8	60.8	75.0	95.1	142	-107	12.3	163	70.7	75.7	32.5	60.8	119	79.7	142	86.0
Percent of Reported	124	128	151	161	190	75.3	105.8	232	137	95.9	115	120	185	148	92.1	85.4

Table 7: Mean and mean absolute difference between simulated and reported irrigation depths (mm) and simulated seasonal irrigation depth as a percent of reported irrigation, calculated by grower for years 2002, 2003, and the two years combined. Simulated depths calculated using default model settings.

Grower	All Years				
	1	2	3	4	6
Simulation Standard Deviation	64.5	66.1	52.5	31.5	87.8
Reported Standard Deviation	47.1	90.5	47.5	86.7	131.4

Table 8: Standard deviations of simulated and reported seasonal irrigation depth, by grower for seasons 2002 and 2003. Simulated irrigation depths calculated using default model settings.

differences between simulated and observed water content and use, the errors in precipitation associated with the NEXRAD estimates for sites in Michigan during the same time frame were only found to be on the order of 0.01 mm (Andresen and Aichele 2003), which even accumulated on a seasonal basis are far less than the observed field level differences. It was concluded that these differences in irrigation depth must be due to improper or inadequate parameterization of one or more variables associated with the MWUR model, possibly related to spatial heterogeneity on the field level scale (Basso et al. 2001; Anderson et al. 2003).

MWUR Model Sensitivity Analysis

Some of the discrepancies between modeled and reported irrigation depths may be simply explained as matter of timing. Figure 8a is an example of the simulated seasonal irrigation events well timed with grower reported events. Figure 8b is an example where simulated and reported irrigation depths are impacted by timing and amount of individual irrigation events. These untimely irrigations and excessive depth applied per event suggest the model is not characterizing the individual locations perfectly.

A question rising from these seasonal water accumulations relates to the reliability of reported seasonal irrigation depths to be the amount of water the crop needs. By plotting potential drainage against the difference between modeled and reported seasonal irrigation depths, an indication of water loss through the profile can be seen. The potential drainage was calculated from a simple daily water balance for each field. Daily

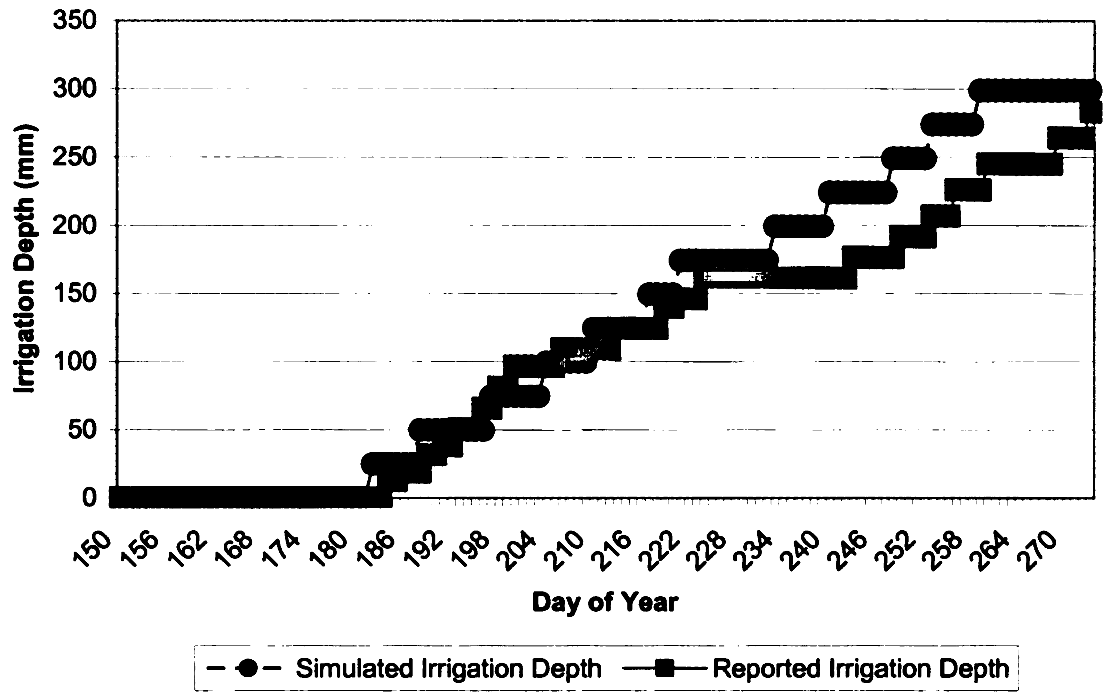


Figure 8a: Simulated and reported seasonal irrigation depth accumulations (mm), by day of year. A carrot field in Mecosta County, 2002.

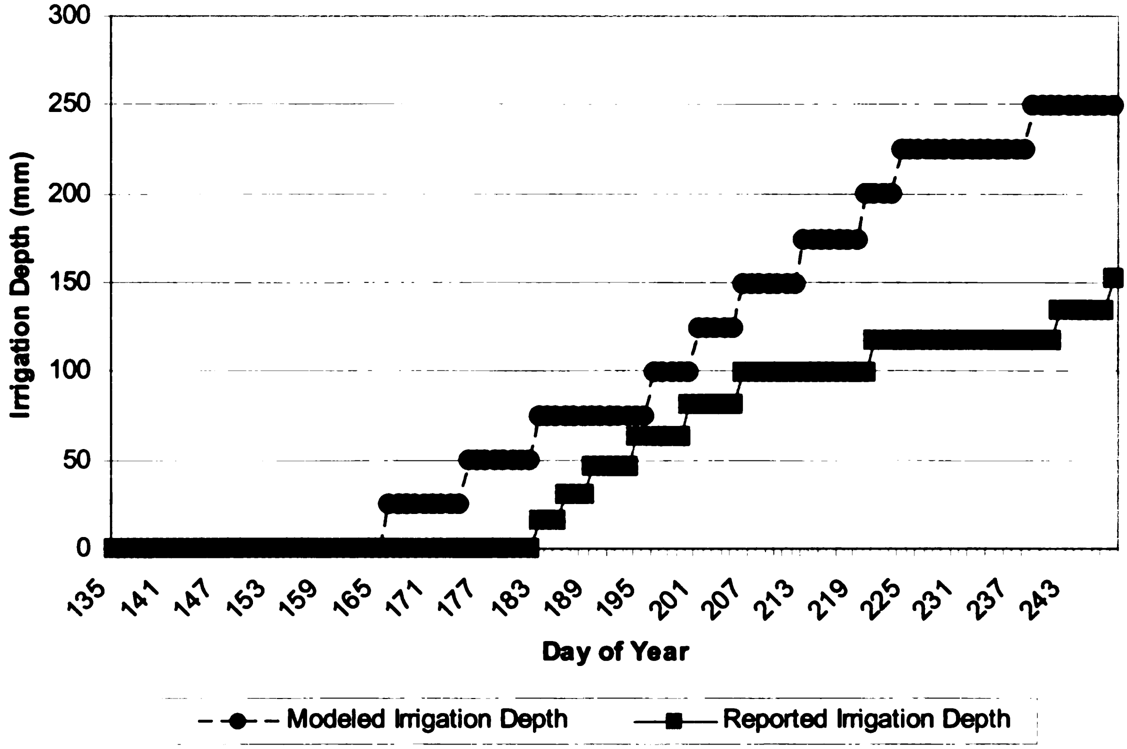


Figure 8b: Simulated and reported seasonal irrigation depth accumulations (mm), by day of year. A soybean field in St Joseph County, 2002.

model ET estimates are subtracted from reported irrigation and daily NEXRAD precipitation estimates to calculate change in soil water storage and potential drainage.

This simple drainage water balance is determined for each field. Assumptions had to be made about the drained upper and lower limits of the soil profile. Initial soil moisture values were derived from gravimetric soil samples in 2003 and initial capacitance probe values for 2002. The 2002 season does not contain a complete record of soil moisture because of the late starting date for tube installation.

The seasonal drainage is plotted against the difference between modeled irrigation amount and field reported irrigation. From Figure 9, a negative correlation is apparent; when the growers apply more water than the model, the estimated drainage tends to be greater. A stronger relationship can be seen in 2003 as opposed to 2002, which can be found in the Appendix. The result suggests the growers putting on much more water than the model may be over-irrigating their crops. It also suggests the model is a reasonable estimator of plant water needs under strict decision assumptions.

After determining drainage, seasonal trends of irrigation depth for individual fields in can best be seen through graphics in Figure 8a and Figure 8b. Seasonal water accumulation trends show the model applying more water less frequently than any of the growers, regardless of the total water applied. Also, the model tends to have a longer irrigating season than do the growers. In nearly all of the crops, the model is irrigating well after the grower ceases applying water. In many cases, the model is simulating irrigation events earlier in the year and continuing later in the season than are the growers.

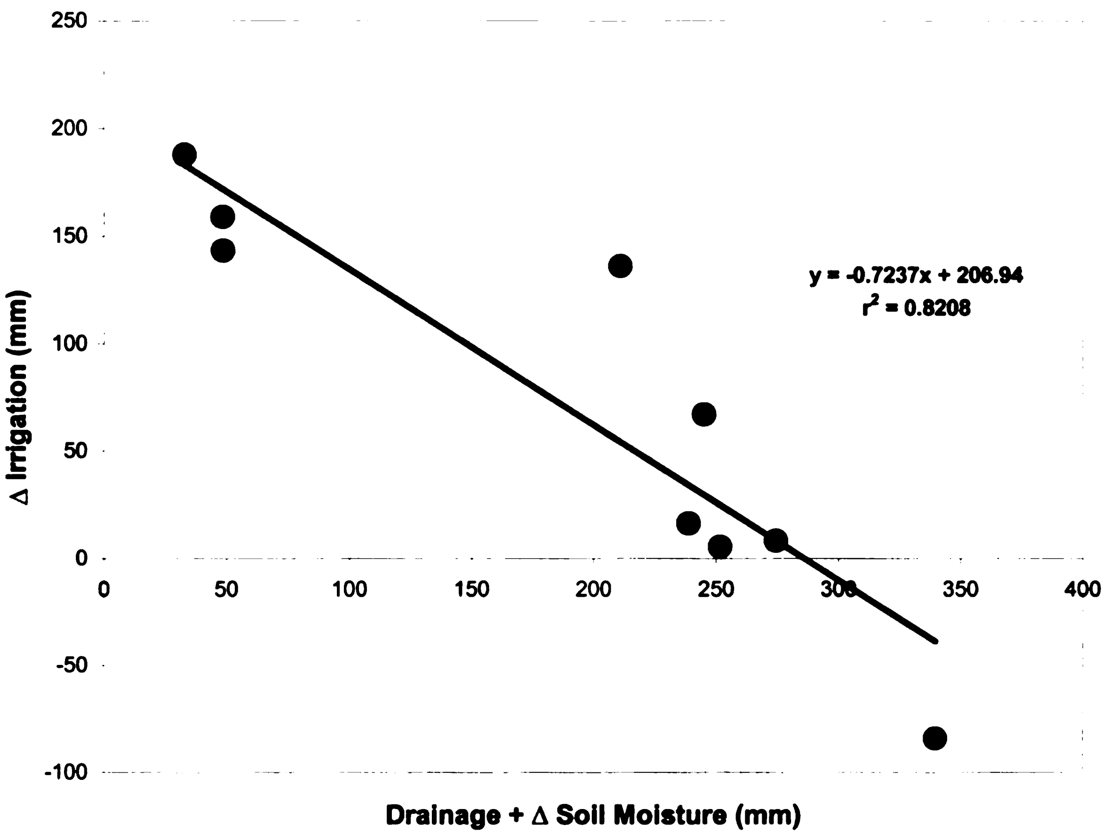


Figure 9: Difference between simulated and reported seasonal irrigation depth vs. total seasonal drainage and change in soil moisture across all study sites, 2003.

Figure 10 (a, b, and c) plot the seasonal timeline of volumetric soil moisture for both the model and observed values. The points in the observed plot are an average of the three samples within the field for each sample day. Maximum and minimum values are seen with the observed values as upper and lower error bars, respectively. This allows for the visualization of the range of values measured within the field. In many cases, especially Figure 10a and Figure 10b, the modeled soil and observed soil moistures show similar trends and mimic one another for major increases and decreases. Figure 10c shows the model having much greater soil moisture than observed, but closing the gap later in the season. This large difference between simulated and observed soil moisture in the lowest soil layer (60-90 cm) suggest the model is keeping the layer at or near field capacity, while in reality it is not. Simulated roots may not be taking up as much water in this layer as others either because they have sufficient water above 60 cm or the roots may not develop as much into layers below 60 cm. The figures for other locations indicate many of the same trends and can be found in the Appendix.

In an attempt to determine potential sources of error in the MWUR model system, several model variables describing both physiological and managerial aspects of the model were systematically adjusted in a series of simulations to assess its sensitivity. After studying the seasonal irrigation depth trends (Figure 8 a and b) and high simulated volumetric soil moisture in the lowest layer (Table 8), the variables include the depth of water applied per irrigation event (mm), root growth rate (mm/growing unit), irrigation trigger level (Θ_c), and planting date. When looking at seasonal irritation events and total depths for the study sites, differences between simulated and reported values could possibly be explained through timing (Θ_c), depth per irrigation event, planting date,

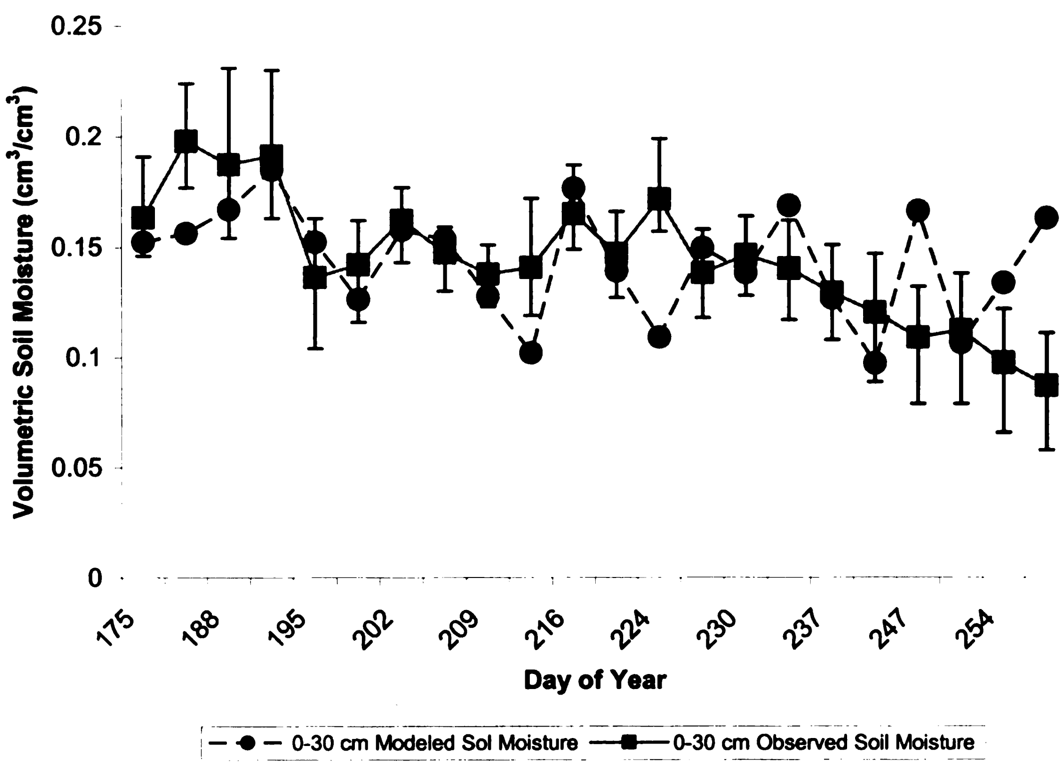


Figure 10a: Seasonal trend of simulated and observed volumetric soil moisture (cm^3/cm^3) for the 0-30 cm soil profile layer in corn, Mecosta Co. 2003. Observed values are average of three samples per field, with maximum and minimum values reported with upper and lower error bars, respectively. Simulated values calculated using default model settings.

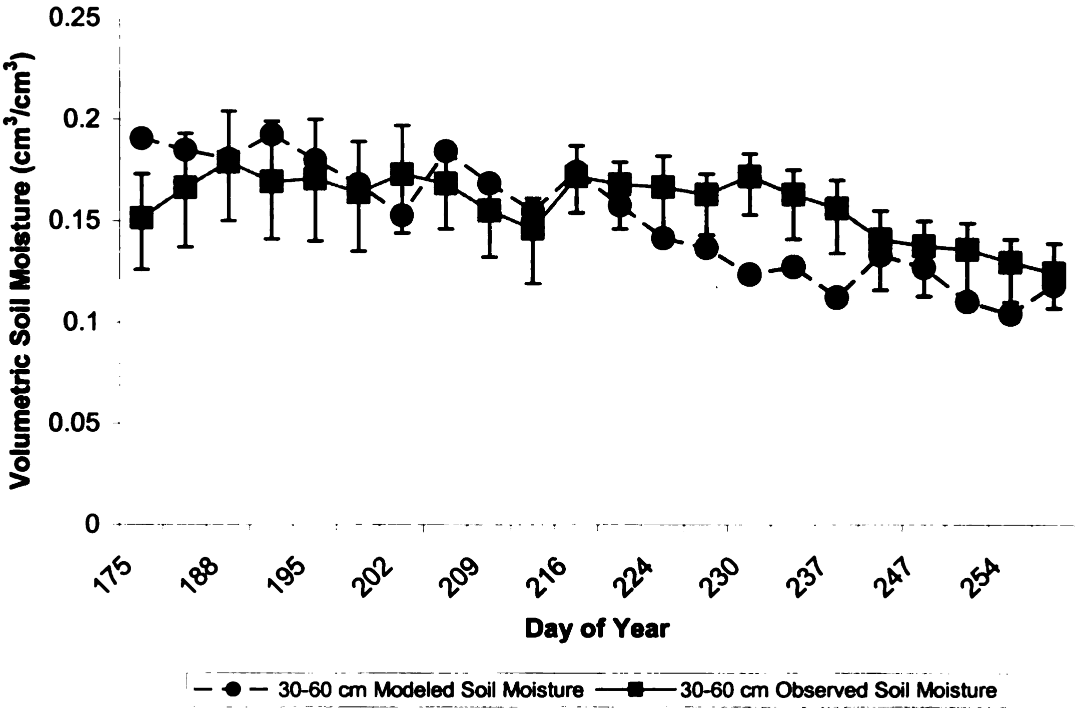


Figure 10b: Seasonal trend of simulated and observed volumetric soil moisture (cm^3/cm^3) for the 30-60 cm soil profile layer in corn, Mecosta Co. 2003. Observed values are average of three samples per field, with maximum and minimum values reported with upper and lower error bars, respectively. Simulated values calculated using default model settings.

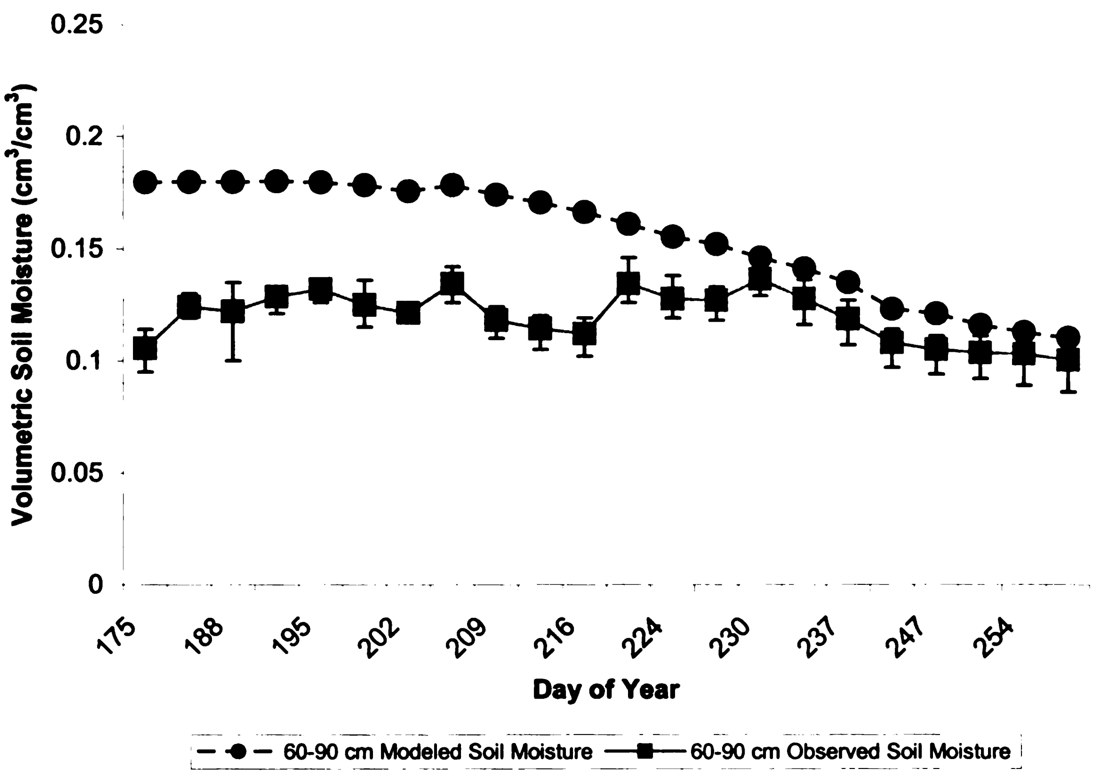


Figure 10c: Seasonal trend of simulated and observed volumetric soil moisture (cm^3/cm^3) for the 60-90 cm soil profile layer in corn, Mecosta Co. 2003. Observed values are average of three samples per field, with maximum and minimum values reported with upper and lower error bars, respectively. Simulated values calculated using default model settings.

and/or root development (affecting depth and amount of root water uptake). Root growth rates were altered in an attempt to explain the large differences between simulated and observed soil moisture in the lowest layer (60-90 cm) of the study profile. During the sensitivity analysis runs, all other variables in the model were held constant at default values and the locations were the same as those sampled in the field portion of the study during 2002 and 2003. All default and adjusted model parameters may be found in the Appendix.

The triggering mechanism, Θ_c, is the fraction of plant available water (PAW) in the rooting zone at which water is added by irrigation. By default, the value is set at 0.50 of PAW; so when the plant available water in the root zone drops below 0.50, the model initiates an irrigation event. When the trigger levels are lowered, a reduction of seasonal irrigation volume is expected, as more plant available water is consumed before the next irrigation is required. The opposite response would be expected as the trigger is increased. Four different trigger levels surrounding the default level of 0.50 were used in the sensitivity analysis for each of the crops and locations of the reported fields: 0.40, 0.45, 0.55, and 0.60 of PAW.

Differences between the adjusted and default values of the irrigation trigger for all crops over both seasons are given in Table 11. The changes in trigger level did have the expected results for seasonal irrigation volume for each crop, with smaller irrigation totals for lesser irrigation trigger levels and vice versa. By crop, the greatest range of mean differences was found for potato, which also has the shallowest rooting depth. The lowest trigger level, 0.40 of PAW, resulted in a mean reduction of 95 mm of irrigation depth to a high of an increase of 150 mm of water with the 0.60 of PAW trigger level.

Irrigation Trigger (Θ_c)	Corn		Potato		Soybean		Carrot		All Crops	
	Mean Difference (mm)	Mean Absolute Difference (mm)	Mean Difference (mm)	Mean Absolute Difference (mm)	Mean Difference (mm)	Mean Absolute Difference (mm)	Mean Difference (mm)	Mean Absolute Difference (mm)	Mean Difference (mm)	Mean Absolute Difference (mm)
40% Θ_c	-56.3	56.3	-91.7	91.7	-100.0	100.0	-62.5	62.5	-76.7	76.7
45% Θ_c	-28.1	28.1	-47.9	47.9	-50.0	50.0	-37.5	37.5	-40.2	40.2
55% Θ_c	21.9	21.9	72.9	72.9	25.0	25.0	37.5	37.5	47.8	47.8
60% Θ_c	43.8	43.8	150.0	150.0	75.0	75.0	87.5	87.5	100.5	100.5

Table 9: Mean and mean absolute differences between simulated seasonal irrigation depths of altered model settings and default model setting (50% of plant available soil moisture), by crop for years 2002 and 2003 combined. Changes in model settings made to the irrigation trigger level, which is based upon the percent of plant available soil moisture. Default setting is 50% of plant available soil moisture.

For corn, the differences ranged from –56 mm to 44 mm. Overall for both seasons for all crops, the increase in the difference with increasing trigger level was 66.3 mm of irrigation water depth. While the direction of the changes in irrigation with different triggers was consistent across crops and seasons, the magnitude of the differences varied.

A second important input variable related to grower management strategy is the amount of water applied per irrigation event. The model default value of this variable is 25 mm and is considered constant throughout the season. In the sensitivity analysis, this variable was altered in seasonally constant 6 mm increments from a minimum of 12 mm per irrigation to a maximum of 38 mm per irrigation (values of 12, 19, 32, and 38 mm). Differences in seasonal irrigation totals between these altered and default values are given in Table 12. Potatoes were, by far, the most sensitive crop to changes in this variable, with a maximum increase in seasonal irrigation volume of 127 mm for the 38 mm application level during the combined seasons and a reduction of 80 mm for the 12 mm application. In contrast, the differences for corn ranged from a deficit of 8.25 mm (at 12 mm application) to an excess of 7.5 mm (at 38 mm application). Similar patterns were observed for the other crops. The ranges of differences were greater for soybeans, but less than that of potatoes.

The two other parameters changed were root growth rate and planting date. Root growth rate alterations did have an effect on soil moisture values (Table 13), especially in deeper layers. The seasonal irrigation amounts increased with a reduction in growth rate and a decrease in water with increases in growth rate (Table 13). The new water volumes do not show as great a range as with amount per irrigation or Θ_c. Planting date changes resulted in no sensible changes for either soil moisture or seasonal irrigation volume.

Irrigation Depth per Event	Corn		Potato		Soybean		Carrot		All Crops	
	Mean Difference (mm)	Mean Absolute Difference (mm)	Mean Difference (mm)	Mean Absolute Difference (mm)	Mean Difference (mm)	Mean Difference (mm)	Mean Absolute Difference (mm)	Mean Difference (mm)	Mean Absolute Difference (mm)	Mean Difference (mm)
12mm	-8.3	10.8	-80.2	80.2	-57.5	57.5	-41.0	41.0	-49.2	50.0
19mm	0.4	9.4	-39.8	39.8	-38.0	38.0	-18.5	18.5	-23.0	26.7
32mm	1.8	14.3	66.5	66.5	34.5	34.5	29.0	29.0	40.8	44.7
38mm	7.5	18.0	126.5	126.5	66.5	66.5	86.0	86.0	78.6	81.8

Table 10: Mean and mean absolute differences between simulated seasonal irrigation depths of altered model settings and default model setting (25mm per irrigation event), by crop for years 2002 and 2003 combined. Changes in model settings made to the irrigation depth per event default of 25 mm per irrigation event.

Root Development	Corn		Potato		Soybean		Carrot		All Crops	
	Mean Difference (mm)	Mean Absolute Difference (mm)	Mean Difference (mm)	Mean Absolute Difference (mm)	Mean Difference (mm)	Mean Absolute Difference (mm)	Mean Difference (mm)	Mean Absolute Difference (mm)	Mean Difference (mm)	Mean Absolute Difference (mm)
-25% Root Development	3.1	15.6	39.6	39.6	0.0	0.0	37.5	37.5	23.8	27.7
-10% Root Development	3.1	9.4	4.2	16.7	0.0	0.0	12.5	12.5	5.7	13.3
+10% Root Development	0.0	12.5	-6.3	10.4	-37.5	37.5	-25.0	25.0	-9.5	15.3
+25% Root Development	-21.9	28.1	-12.5	20.8	-25.0	25.0	-25.0	25.0	-19.1	24.9

Table 11: Mean and mean absolute differences between simulated seasonal irrigation depths of altered model settings and default model setting (varying by crop), by crop for years 2002 and 2003 combined. Changes in model settings made to the root development rate, which based upon either growing degree units or calendar days after planting, depending on crop type.

Planting Date	Corn		Potato		Soybean		Carrot		All Crops	
	Mean Difference (mm)	Mean Absolute Difference (mm)	Mean Difference (mm)	Mean Absolute Difference (mm)	Mean Difference (mm)	Mean Difference (mm)	Mean Absolute Difference (mm)	Mean Difference (mm)	Mean Absolute Difference (mm)	Mean Difference (mm)
DOY 125	0.0	6.3	-8.3	16.7	-25.0	25.0	25.0	25.0	-2.2	15.2
DOY 130	3.1	3.1	0.0	16.7	-25.0	25.0	0.0	0.0	-1.8	11.4
DOY 140	-9.4	9.4	6.3	14.6	-12.5	12.5	-25.0	25.0	-1.9	13.5
DOY 145	-12.5	12.5	-14.6	14.6	0.0	25.0	-25.0	25.0	-12.5	14.4

Table 12: Mean and mean absolute differences between simulated seasonal irrigation depths of altered model settings and default model setting (planting date on day of year 135), by crop for years 2002 and 2003 combined. Changes in model settings made to the planting date default of DOY 135.

Mean absolute differences were of the same magnitude for all four tests performed and suggest little individual difference within each test. These results suggest the model is most sensitive to Θ_c and irrigation depth per event, of the four parameters tested. Both of these variables deal directly with water availability and are directly related to decisions growers must make on their own farms.

MWUR Performance with Changes to Managerial Variables

From the preceding discussion, there is ample evidence to suggest that a major limitation of the MWUR system is the lack of representative input information relating to a few key managerial variables. Given the data taken from the field observations and the previous model sensitivity results, it is possible to adjust the input variables and rerun the model with the hopes of improving its performance. While insufficient data were available for both model redevelopment and test validation, this procedure may still provide an estimate of the potential performance.

In the earlier sensitivity analysis, four physiological and managerial model parameters were examined for mode output sensitivity. The most sensitive variables found were the trigger level, Θ_c, and the depth of water per irrigation. These variables were then altered in combination to minimize the mean differences between simulated and reported seasonal irrigation water depths. Mean and mean absolute differences were calculated in the same manner as in previous sections of the study. Regardless of the drainage results, the assumption is made that the growers apply an appropriate amount of water for their crops and what they are applying is the "reality of the real world". Amount per irrigation, Θ_c, and season length for potatoes (personal communication) were altered to reduce the mean difference between modeled and reported seasonal irrigation depths for individual crops to a minimum. An irrigation depth of 19 mm was used because this value is approximately the average depth per irrigation growers across the study use. Simulation runs were conducted with varying values of Θ_c, until the smallest mean differences in seasonal irrigation depth were achieved. The default season length of potatoes (124 days) was noticed to be long for the varieties grown in this study. Typical season lengths range from 90-100 days, according to Chris Long, potato specialist in the Department of Crop and Soil Science at Michigan State University (personal communication) but most of the growers in this study had varieties with season lengths on the order of 100 days (grower personal communication). Also, The Ohio State University Extension bulletin number 672-03 shows season lengths for some of the varieties grown in Michigan to range from 90-115 days (Smith 2003). Therefore, an arbitrary season length of 101 days was selected.

Corn mean differences could be reduced to –1.02 mm, with a mean absolute difference of 49.9 mm for years 2002 and 2003 combined, see Table 15. While the mean difference was greatly reduced, mean absolute difference remained large and suggests overall improvement of model performance was the result of large over and under predictions at different locations or years. In this case the year 2002, saw too much water and 2003 saw too little. The trigger level was reduced to a value of 40 percent of plant available water, which is within the range suggested by Rhodes and Bennett (1990) for simulating corn development.

Potato mean differences were reduced to –2.75 mm for the two years combined with a mean absolute difference of 62.6 mm. Again, mean absolute difference was large,

Crop	2002					2003				All Years		
	Corn	Potato	Sugarbeet	Carrot	Soybean	Corn	Potato	Soybean	Pepper	Corn	Potato	Soybean
Mean Difference (mm)	23.4	18.1	7.2	-17.2	-0.4	-33.5	17.2	6.1	6.0	-1.0	-2.8	2.8
Mean Absolute Difference (mm)	30.0	29.5	7.2	17.2	0.4	76.4	69.8	6.1	6.0	49.9	62.6	3.3
Percent of Reported	116.4	92.9	93.9	99.7	105.0	79.9	107.8	106.9	104.7	99.3	98.9	102.4

Table 13: Mean and mean absolute difference between simulated and reported seasonal irrigation depth (mm), calculated by crop for years 2002, 2003, and the two years combined. Simulated depths calculated using altered model settings (to improve mean differences of seasonal irrigation depth).

Grower	2002						2003				All Years					
	1	2	3	4	5	6	1	3	4	6	1	2	3	4	5	6
Mean Difference (mm)	-3.8	37.5	6.3	25.6	228.0	266.0	-41.7	60.1	-20.8	-37.5	-22.7	37.5	33.2	-14.0	228.0	-80.3
Mean Absolute Difference (mm)	9.4	49.0	8.4	26.0	247.7	431.8	41.7	60.1	26.9	101.7	25.6	49.0	34.2	18.0	247.7	123.0
Percent of Reported	98.3	120.4	103.6	116.5	92.1	61.6	80.4	148.6	89.2	82.0	89.5	120.4	123.5	101.4	92.1	71.6

Table 14: Mean and mean absolute difference between simulated and reported seasonal irrigation depth (mm), calculated by grower for years 2002, 2003, and the two years combined. Simulated depths calculated using altered model settings (to improve mean differences of seasonal irrigation depth).

but in this instance 2002 and 2003 saw approximately the same mean difference, 18.1 and 17.2 mm, respectively. Therefore, the overall mean difference was the result of over and under predictions, rather than across the board improvement in model performance. The season length was changed from 124 days to 101 days, Θ_c increased to 0.55 of plant available water, and irrigation amount decreased to 19 mm. Soybeans decreased their two season mean difference to 2.85 mm and mean absolute difference to 3.25 mm. The irrigation trigger and amount per irrigation were decreased to 38 percent plant available water and 19 mm, respectively. These values are similar to those reported by Wright and Stark (1990) for simulation of potato development.

The improved seasonal irrigation depth results from the altered management variables showed a much improved scatter plot of modeled verses observed seasonal irrigation volume (Figure 11). The r^2 values are increased from 0.020 in for default model runs to 0.366 in for best-fit model runs. Also, the slope of the trend line is closer to one than that of the original default trend line slope. The overall root mean square error for all crops in both seasons improved from 97.8 mm for default to 64.4 mm for altered model runs (Table 17).

While improvements were made to the mean differences of seasonal irrigation water depth, the same cannot be said for simulated volumetric soil moisture. The largest differences, by crop, between the adjusted and default model runs were for potato, with a mean difference of -0.033 cm^3/cm^3 Table 18) in the 0-30 cm layer. Yet the 30-60 cm layer was wetter by a mean difference of 0.066 cm^3/cm^3. Corn was drier through the entire profile, with the largest change in the second layer. The mean differences show the altered simulations result in drier soil moisture than default simulations in the top two

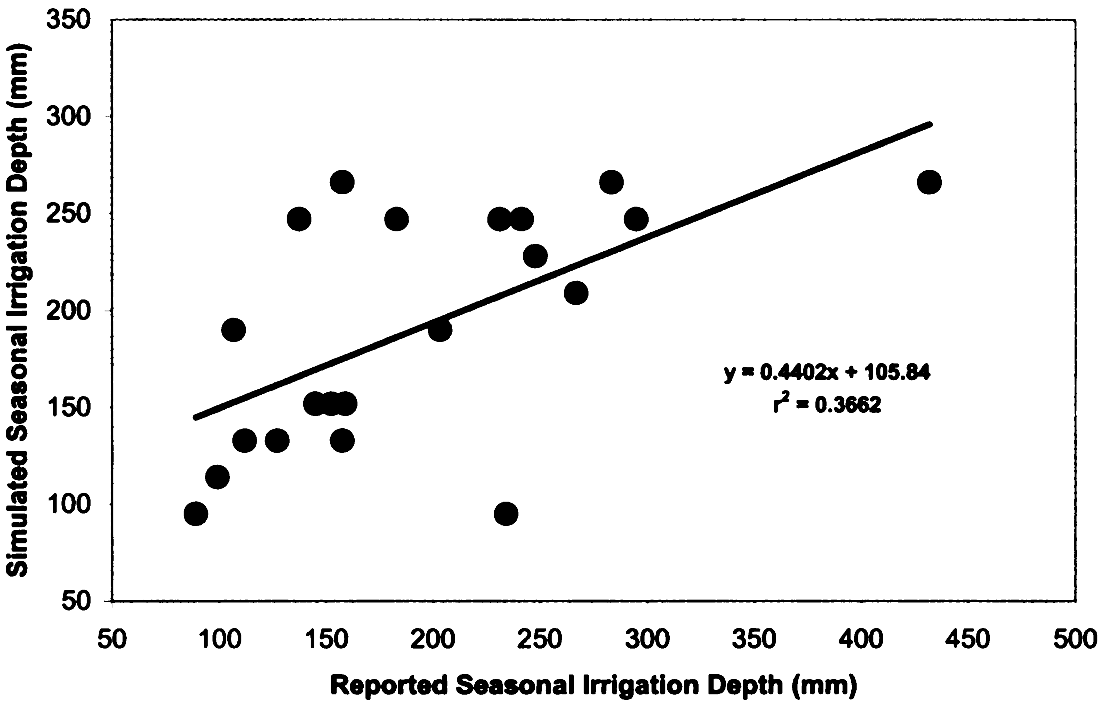


Figure 11: Simulated vs. reported seasonal irrigation depth (mm) for all study fields in 2002 and 2003. Simulated values calculated using altered model settings (to improve mean differences of seasonal irrigation depth).

	Root Mean Square Error	
	Default Irrigation Depth (mm)	Altered Settings Irrigation Depth (mm)
Corn	88.6	64.2
Potato	99.6	80.1
Soybean	131.9	4.2
All Crops	97.8	64.4

Table 17: Mean square error for default and altered simulated seasonal irrigation depth for corn, potato, soybean, and all crops for 2002 and 2003.

	Mean Difference (cm^3/cm^3)	Mean Absolute Difference (cm^3/cm^3)
	0-30 cm Soil Profile Depth	
Corn	-0.013	0.015
Potato	-0.033	0.044
Soybean	-0.017	0.017
Sugarbeet	-0.012	0.016
Carrot	0.006	0.018
Pepper	-0.005	0.012
	30-60 cm Soil Profile Depth	
Corn	-0.019	0.027
Potato	0.016	0.034
Soybean	-0.016	0.016
Sugarbeet	-0.011	0.011
Carrot	-0.007	0.008
Pepper	-0.010	0.010
	60-90 cm Soil Profile Depth	
Corn	-0.005	0.005
Potato	0.099	0.101
Soybean	0.182	0.182
Sugarbeet	----	----
Carrot	-0.001	0.001
Pepper	-0.001	0.001
	All Layers	
Corn	-0.012	0.016
Potato	0.027	0.060
Soybean	-0.011	0.011
Sugarbeet	-0.012	0.014
Carrot	0.000	0.009
Pepper	-0.005	0.008

Table 18: Mean and mean absolute differences between default and altered simulated volumetric soil moisture (cm^3/cm^3), by profile depth and crop for the years 2002 and 2003 combined.

layers. These results are reasonable; with less irrigation water applied, more of the moisture must come from the soil profile. The unexpected caveat in Table 18 is the wetter soil conditions for the second layer in potatoes. By increasing Θ_c, the plant was able to use more water from the higher layer.

The alterations actually resulted in slightly worse mean and mean absolute differences between the simulated soil moisture after alterations and observed values (Table 19). Yet, improvement between simulated and observed soil moisture was seen in the 30-60 cm layer. The lowest layer studied showed little difference between soil moisture from altered and default model runs. Mean differences are very similar for all crops and layers in Table 8 and Table 19. This is consistent with the results in Table 18 and would generally indicate the alterations made to model settings result in more water extraction from the top two layers.

	Mean Difference (cm^3/cm^3)	Mean Absolute Difference (cm^3/cm^3)
	0-30 cm Soil Profile Depth	
Corn	-0.017	0.050
Potato	-0.003	0.031
Soybean	-0.057	0.060
Carrot	-0.017	0.028
Sugarbeet	0.109	0.109
Pepper	0.053	0.053
All Crops	-0.004	0.046
	30-60 cm Soil Profile Depth	
Corn	-0.001	0.065
Potato	0.051	0.056
Soybean	-0.004	0.047
Carrot	0.044	0.044
Sugarbeet	0.108	0.108
Pepper	0.139	0.139
All Crops	0.037	0.067
	60-90 cm Soil Profile Depth	
Corn	0.039	0.051
Potato	0.041	0.043
Soybean	0.053	0.053
Carrot	0.056	0.056
Sugarbeet	----	----
Pepper	0.122	0.122
All Crops	0.049	0.054
	All Layers	
Corn	0.007	0.055
Potato	0.029	0.043
Soybean	-0.003	0.053
Carrot	0.028	0.043
Sugarbeet	0.108	0.108
Pepper	0.105	0.105
All Crops	0.027	0.056

Table 19: Mean and mean absolute differences between simulated and observed volumetric soil moisture (cm^3/cm^3), by soil profile depth and crop for 2002 and 2003 combined. Simulated values calculated using altered model settings (to improve mean differences of seasonal irrigation depth).

Conclusions

The first main objective of this study was to test the MWUR model output against field measured and reported values of field level volumetric soil moisture and seasonal irrigation depth. Secondary objectives in this portion of the study were to develop a sampling scheme to adequately describe the simulation.

- The MWUR model did not perform as well as expected, after initial tests by Moen (1999) and Andresen (2003), in the estimation of seasonal irrigation water use. Simulated water use for corn was 35 percent greater than reported, 24 percent greater for potatoes, and 97 percent greater for soybean.
- The simulation adequately estimated volumetric soil water in the top 30 cm of the soil profile under most cropping types. The difference between simulated and observed soil moisture for all crops was approximately a positive 7 percent of the typical plant available water for the model. Yet the simulation greatly overestimated volumetric soil moisture in the subsequent two layers, resulting in overestimations in the range of 48 percent of typical plant available moisture in the second layer to 56 percent of typical plant available water in the third layer.
- Tests to determine any bias introduced by varying grower scheduling practices indicate the model adequately estimates water needs for crops under ideal conditions, but cannot account for the variation in grower scheduling methods.

The second main objective of this study was to test model sensitivity to multiple managerial and physiological parameters. The four variables chosen, base upon the validation portion of the study and a review of the literature, were depth of water per irrigation, soil trigger level (Θ_c), root growth rate, and planting date.

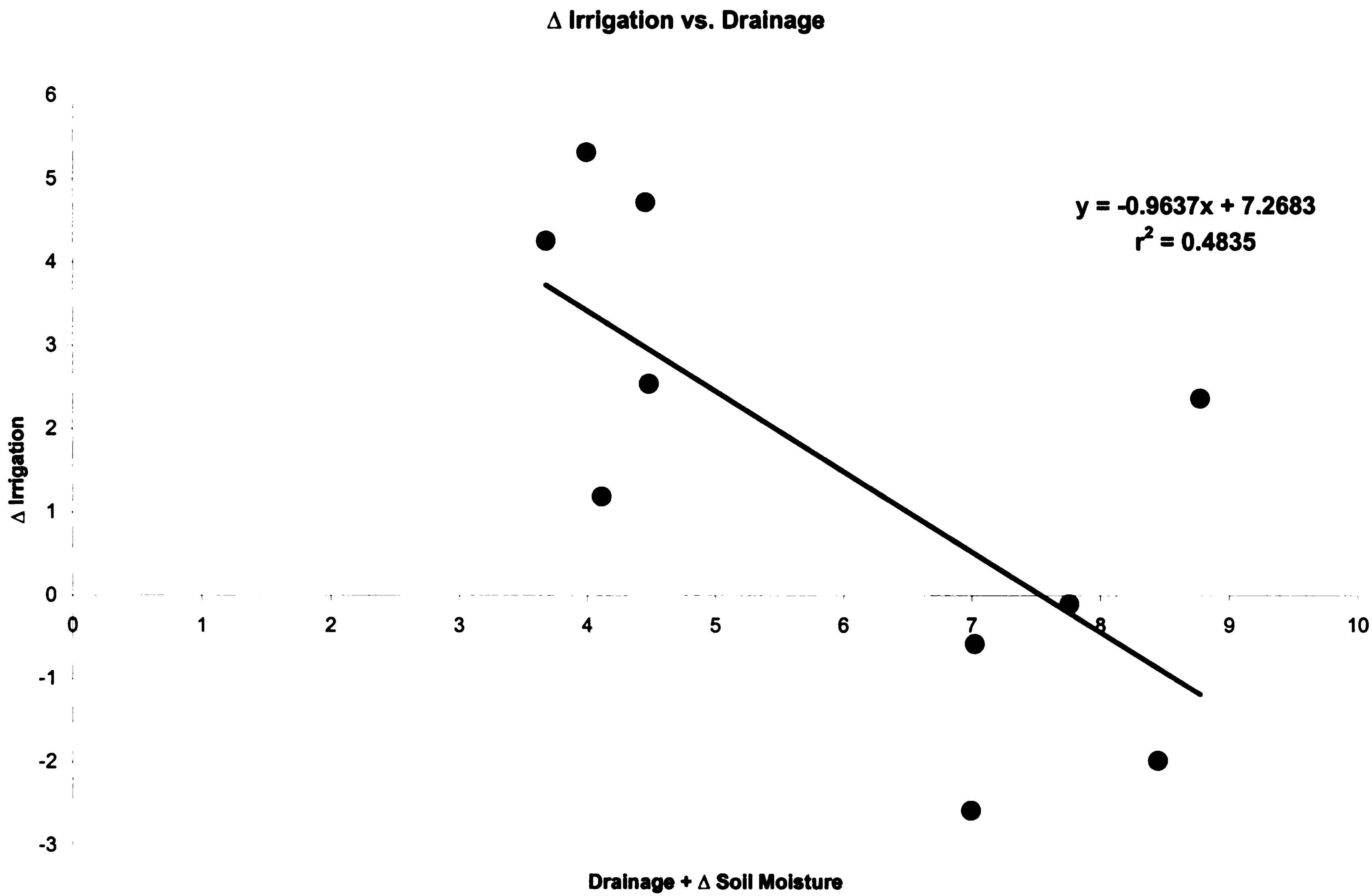
- The simulation was most sensitive to the depth of water per irrigation and Θ_c. Mean differences from default ranged between a decrease of 76 mm to an increase of 100 mm of seasonal irrigation depth for Θ_c changes. Mean differences from default ranged between 49 mm less to 78 mm more seasonal irrigation depth for changes to depth per irrigation.
- These sensitive parameters were then altered to optimize model seasonal irrigation water depth to reported values by attaining the smallest mean difference possible for various crops. This exercise resulted in the model accounting for 99 percent of the reported depth for corn, 99 percent for potatoes, and 102 percent for soybean.
- These changes, most times, resulted in lower volume and more frequent irrigation events. They also indicate, again, the model has problems strategizing irrigations the same as the growers in this study and suggest potential problems with initialization of crop and management parameters.

The simulation has shown that it is possible to properly estimate seasonal irrigation water depth for a variety of crops across a large region. Work should continue to properly initialize model parameters to the strategies of the majority of growers in Michigan. Also, more work should be done to determine causes of positive simulation biases of volumetric soil moisture at the lower layers of the model soil profile.

Appendix

Year	Crop_ID	Crop	Report Group	Crop_Group	Units	PlantingDate	MaxRootDepth	ThetaC	IrrAmount
2002	69	Corn for Grain or Seed	Corn for Grain or Seed	1	t	135	100	50	25
2003	69	Corn for Grain or Seed	Corn for Grain or Seed	1	t	135	100	50	25
2002	90	Soybeans	Soybeans	1	c	135	75	50	25
2003	90	Soybeans	Soybeans	1	c	135	75	50	25
2002	99	Potatoes	Potatoes	1	c	135	50	50	25
2003	99	Potatoes	Potatoes	1	c	135	50	50	25
2002	398	Carrots	Vegetables - Group 3	0	c	150	60	50	25
2003	398	Carrots	Vegetables - Group 3	0	c	150	60	50	25
2002	721	Sugar Beets	Sugar Beets	1	t	135	100	50	25

Table 20: Default model values for crops used in study, 2002-03.


Δ Irrigation vs. Drainage
y = -0.9637x + 7.2683
r² = 0.4835
Δ Irrigation
Drainage + Δ Soil Moisture
6
5
4
3
2
1
0
-1
-2
-3
0
1
2
3
4
5
6
7
8
9
10

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