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Systematic Analysis Of Drainage Events In Free Draining And Managed Subsurface Drainage Systems

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SYSTEMATIC ANALYSIS OF DRAINAGE EVENTS IN FREE DRAINING AND MANAGED SUBSURFACE DRAINAGE SYSTEMS

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Of course ... to Mom, Dad, family and friends that have always stood by me and supported me in all my endeavors.

To all the great thinkers and intellectuals whose brilliantly laid ideas have inspired me and kept me moving forward.

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ABBREVIATIONS

ASL	Above Sea Level
CSCAP	Cropping Systems Coordinated Agricultural Project
DD	Depth of Drain
DPAC	Davis Purdue Agricultural Center
DS	Depth of Sensor
DWM	Drainage Water Management
HAD	Height Above Drain
HAS	Height of water Above Sensor
N	Nitrogen
NaN	Not a Number (an undefined or unrepresentable Matlab value)
NE	North East
NW	North West
RTK	Real Time Kinematic
SE	South East
SW	South West
VWC	Volumetric Water Content

ABSTRACT

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Understanding the hydrologic controls that regulate outflow from free and managed subsurface drainage systems during drainage events can offer improved insight on the overall functioning and effectiveness of the systems so that they can be better managed or retrofitted to increase their environmental benefits. This study used drainage, precipitation, water table, and soil moisture data from a monitoring site located in east central Indiana to investigate the event hydrology of 22 drainage events in free and managed subsurface drainage systems. Relationships between event drainage volume, drain flow hydrograph metrics, column soil moisture, water table depth, and precipitation characteristics were explored to determine the effect of precipitation characteristics and antecedent conditions on drainage volumes, reduction in drainage volumes, peak outflows, the time to peak, and the mechanisms by which runoff is generated in managed and free draining subsurface drainage systems. Drainage water management reduced event drainage volume and peak flows by 22% ± 12% and 29% ± 16% respectively, and increased the time to peak of drainage by 98% ± 52%. Higher total precipitation and precipitation time spread promote more infiltration throughout the course of the event and thus greater drainage volumes in managed and free draining systems, while the average precipitation intensity did not correlate with drainage volumes in both systems. Peak flows in free draining quadrants were positively affected by higher precipitation totals and the average precipitation intensity that can increase the infiltration rate. In managed quadrants, the antecedent soil moisture appeared to play a more important role in affecting peak flows than pre-

cipitation characteristics. The time to peak in the free draining quadrants decreased with higher average precipitation intensity and increased with higher precipitation time spread. As the average precipitation intensity increased the runoff potential increased on both managed and free draining quadrants. Saturation excess ponding or possibly overland flow occured in events that have a low average precipitation intensity, and a high precipitation time spread. Field observations indicate that saturation excess overland flow is more pronounced in managed quadrants because the water tables level rise higher than the water table of their free draining counterpart.

1. INTRODUCTION

1.1 Background

The International Commission on Irrigation and Drainage defined land drainage as "the removal of excess surface and subsurface water from the land to enhance crop growth, including the removal of soluble salts from the soil" (ICID,1979). This practice is important in maintaining and improving yields of worldwide farms whether they are located in humid areas that generally have an abundance of water such as the US Midwest and Northern Europe or in arid and semi arid regions that have high salinity levels that need control such as Egypt and India (Tanji and Kielen, 2002; Madramootoo et al., 2007). In the Midwest, the extensive artificial drainage of land that was enabled through public programs was essential to the improvement of the livelihood of early settlers and farmers in the region (Pavelis, 1987). The development of the drainage network involved numerous structural interventions (e.g. levees, drainage outlets, pumping for drainage, and drainage channels) that are complemented by on farm drainage measures such as subsurface (tile) drainage and field ditches that facilitate the drainage of poorly drained soils. It was estimated in 1987 that 50% of crop land in Indiana is artificially drained, and that 35% of that crop land has tile drainage improvements which made Indiana the state that has the highest percentage artificially drained land and most tile drainage installations in the United States (Pavelis, 1987).

The installation of these tile drains or subsurface drainage systems, generally at a 0.7 to 1 m depth brings direct agronomic and economic benefit to farmers. Tile drains reduce high water tables and prevent water logging, thus promoting warmer spring soil temperatures, enhancing soil aeration, increasing soil trafficability, as well as other benefits that have all allowed an increased land productivity and increased farm profitability (Fraser et al., 2001).

However, numerous studies have linked subsurface drainage improvements, along with the increase in nutrient addition on agricultural land, to problems of eutrophication, drinking water quality, and hypoxia (Commoner, 1970; David et al., 2010; Tomer et al., 2003; Skaggs et al., 1999). Environmental, ecological, and public health concerns have led researchers to seek more understanding of the hydrology, solute transport, and water quality issues that are associated with subsurface drainage, and the study and development of management practices that can mitigate the loss of nutrients and reduce off site environmental impacts.

Drainage water management (DWM) or controlled drainage is one management practice that aims to reduce flow from subsurface drains by installing in-line water control structures at field outlets that act as dams that keep water table levels above drain levels in order to conserve the nitrate laden drainage water at its point of generation (Frankenberger et al., 2004; Skaggs et al., 1999). Drainage water management is based on the premise that not all drainage water held inside the soil needs to be drained. An increase in anaerobic conditions inside the soil may promote favorable conditions for denitrification (Meek et al., 1969; Willardson et al., 1970).

Field studies at 20 different locations around the U.S. and northern Europe report that DWM reduces average annual drainage volumes from 18% to over 85% and does not greatly affect drainage nitrate concentrations (Skaggs et al., 2012). Various drain flow reductions have been reported from field experiments in the Midwest. Adeuya et al. (2012) reported a two year drain flow reduction of 19% from a 2 year study in Indiana on a Rensselaer soil, Helmers et al. (2012) reported a 37% reduction in flow from a 4 year study in Iowa on a Taintor/Kalona soil. Cooke and Verma (2012) reported reductions of 44%, 44%, 89%, and 38% on 4 fields over a two year study on Drummer, Drummer/Dana, Orion Haymond, and Patton/Montgomery soils, respectively. Fausey et al. (2004) reported a 40% reduction in drain flow from 5 years of observation on a Hoytville soil in Ohio. Such an across-site variability in drainage flow reduction is attributed to differences in soil properties, drainage system intensity, drainage operational strategy, topography, and climate (Skaggs et al., 2010).

Simulation studies of the potential impact of DWM have reported that besides conserving drainage water, the practice also increases seepage and surface runoff (Skaggs et al., 2010; Ale et al., 2009; Singh et al., 2007). Singh et at al. (2007) indicated that there might be a tradeoff between subsurface drainage water and surface runoff as a means of getting the water out of the field. Through DRAINMOD simulations for a 50 year period, Skaggs et al. (2010) showed that DWM conserves water, reduces drainage, and increases surface runoff. Moreover, Skaggs et al. (2010) concluded that DWM reduces drainage volumes by increasing surface runoff, lateral seepage, vertical seepage, and evapotranspiration. Field studies that have measured total outflows from DWM experiments have noted that DWM resulted in reduction of drainage flow that is accompanied by an almost equal increase of surface runoff that generally has a lower N and higher phosphorus concentration than drain water (Gaynor et al., 2002; Drury et al., 2009). Accordingly, by potentially increasing runoff, DWM could have a positive effect on N and a negative effect on phosphorus.

The examination of drainage flows on a daily basis (Adeuya et al., 2012), on a monthly basis (Helmers et al., 2012; Lalonde et al., 1996), on an annual basis (Helmers et al, 2012; Cooke and Verma, 2012; Drury et al., 2009) as done in most previous studies provides important information on how the free and managed drainage systems operate. The adoption of a drainage event based approach of comparing drainage volumes and hydro-climatic characteristics, however, provides a physical basis for the comparison of drain volumes on an intra/inter site level with respect to hydro-climatological forcings particularly when the date record is incomplete. Such an approach can be used systematically to examine conventional and managed tile systems across different sites which can make it useful for synthesis studies.

Although events represent only a portion of annual flow, the 15 events for which complete data are available from this study in 2012 (out of 19 drainage events) represented 67% and 90% of the measured annual drain flow that occurred from a free and managed drainage field, respectively. Accordingly, a better understanding of the hydrologic controls that regulate outflow from controlled and conventionally managed tile systems during such major drainage events can offer improved insight on the overall functioning and effectiveness of the treatments so that they can be better managed or retrofitted to increase environmental benefits by conserving more water and better promoting denitrification.

A number of studies have systematically examined storm event hydrology in artificially drained landscapes. Reid and Parkinson (1984) studied tile drainage hydrographs with respect to precipitation, topographic controls and seasonal variations in the antecedent conditions in Northern London. Seasonal differences in drain response were attributed to the effect of the antecedent soil moisture on how the soil redistributes water. The lag between rainfall and the peak during the non-winter events that had drier antecedent moisture conditions was generally lower than winter events. This suggested that there was a faster transmission of water through deep cracks during non winter events. Amatya et al. (2000) used a paired watershed approach to study storm event hydrology of free and managed subsurface drainage in Loblolly pine experimental watersheds in North Carolina where managed drainage significantly reduced total drainage volume and peak flow rates for all events. Vidon and Cuadra (2010) examined the hydrological controls that regulate matrix flow and macropore flow for eight drainage events that occurred during spring for two free draining subsurface drain systems in central Indiana. They found that antecedent soil moisture conditions had a minor role in affecting tile flow response while total precipitation is a more important predictor of mean and peak flow rate.

In their thorough treatment of the effect of subsurface drainage on streamflow peaks, Robinson and Rycroft (1999) reviewed a number of field drainage and simulations studies. They concluded that subsurface drainage increases the soil water capacity, promotes the infiltration of water and thus result in reduced overland flow and peak storm flow depending on the site wetness. In areas in which water is close to the surface because of high rainfall and poor permeability drainage increases the soil water storage capacity, reduces surface runoff and peak storm flows. On the other hand, in areas that have deep water tables because of dry climates and permeable soils, artificial drainage increases peak flows because of greater hydraulic gradients and short flow paths(Robinson et al., 1999).

Although much is known about factors that influence the hydrology of artificially drained landscapes, there is a need to investigate the hydrological controls in managed subsurface drainage systems in order to gain greater understanding of observed variability in the effectiveness of this conservation practice.

1.2 Objectives

The overarching goal of this study is to better characterize the hydrological behavior of free draining and managed subsurface drainage systems by systematically studying drainage events and their effect on hydrologic responses that occur in Field W at the Davis Purdue Agricultural Center (DPAC) that is located in Eastern Indiana. This is achieved by exploring the relationship between event outflow, drain flow hydrograph metrics, column soil moisture, water table depth, and precipitation characteristics.

The research detailed in this thesis has the following objectives:

1. Effectively handle and process environmental data that is collected from the drainage water management experiment at DPAC.

2. Examine the effect of precipitation characteristics and site antecedent conditions on the event scale drainage volumes and reduction in drainage volumes, peak drainage flows, and the time to peak of managed and free draining subsurface drainage systems.

3. Explore the mechanisms in which overland flow or ponding is generated on the field and relate these mechanisms to precipitation characteristics.

1.3 Thesis organization

The thesis is organized into four chapters. Chapter 2 describes DPAC's site environmental conditions, monitoring and data collection, and then details the data processing that has been done to integrate data for further analyses. Chapter 3 is the main focus of the thesis, characterizing the hydrological responses of managed and free draining subsurface drainage systems during individual drainage events. Research conclusions and suggestions for future research are presented in Chapter 4.

1.4 References

Lalonde, V., Madramootoo, C., Trenholm, L., and Broughton, R. (1996). Effects of controlled drainage on nitrate concentrations in subsurface drain discharge. *Agricultural Water Management*, 29(2):187–199.

Adeuya, R., Utt, N., Frankenberger, J., Bowling, L., Kladivko, E., Brouder, S., and Carter, B. (2012). Impacts of drainage water management on subsurface drain flow, nitrate concentration, and nitrate loads in Indiana. *Journal of Soil and Water Conservation*, 67(6):474–484.

Ale, S., Bowling, L., Brouder, S., Frankenberger, J., and Youssef, M. (2009). Simulated effect of drainage water management operational strategy on hydrology and crop yield for drummer soil in the midwestern united states. *Agricultural Water Management*, 96(4):653 – 665.

Amatya, D. M., Gregory, J. D., and Skaggs, R. (2000). Effects of controlled drainage on storm event hydrology in a loblolly pine plantation. *Journal of the American Water Resources Association*, 36(1):175–190.

Commoner, B. (1970). Threats to the integrity of the nitrogen cycle: Nitrogen compounds in soil, water, atmosphere and precipitation. In *Global Effects of Environmental Pollution*, pages 70–95. Springer.

Cooke, R. and Verma, S. (2012). Performance of drainage water management systems in Illinois, United States. *Journal of Soil and Water Conservation*, 67(6):453–464.

David, M. B., Drinkwater, L. E., and McIsaac, G. F. (2010). Sources of nitrate yields in the mississippi river basin. *Journal of Environmental Quality*, 39(5):1657–1667.

Drury, C., Tan, C., Reynolds, W., Welacky, T., Oloya, T., and Gaynor, J. (2009). Managing tile drainage, subirrigation, and nitrogen fertilization to enhance crop yields and reduce nitrate loss. *Journal of environmental quality*, 38(3):1193–1204.

Fausey, N., King, K., Baker, B., and Cooper, R. (2004). Controlled drainage performance on hoytville soil in ohio. In *Proceedings of the 8th International Drainage Symposium-Drainage VIII, Gargnano, Italy*, pages 84–88.

Frankenberger, J., Kladivko, E., Sands, G., Jaynes, D. B., Fausey, N., Helmers, M. J., Cooke, R., Strock, J., Nelson, K., and Brown, L. C. (2004). Drainage water management for the midwest. *Purdue Extension Publication, WQ-44*. Retrieved from `https://www.extension.purdue.edu/extmedia/WQ/WQ-44.pdf`.

Fraser, H., Fleming, R., and Eng, P. (2001). Environmental benefits of tile drainage. *Literature Review Prepared for: LICO. Land Improvement Contractors of Ontario. Ridgetown College, University of Guelph.*

Gaynor, J., Tan, C., Drury, C., Welacky, T., Ng, H., and Reynolds, W. (2002). Runoff and drainage losses of atrazine, metribuzin, and metolachlor in three water management systems. *Journal of environmental quality*, 31(1):300–308.

Helmers, M., Christianson, R., Brenneman, G., Lockett, D., and Pederson, C. (2012). Water table, drainage, and yield response to drainage water management in southeast Iowa. *Journal of Soil and Water Conservation*, 67(6):495–501.

Madramootoo, C. A., Johnston, W. R., Ayars, J. E., Evans, R. O., and Fausey, N. R. (2007). Agricultural drainage management, quality and disposal issues in north america. *Irrigation and drainage*, 56(S1):S35–S45.

Meek, B., Grass, L., and MacKenzie, A. (1969). Applied nitrogen losses in relation to oxygen status of soils. *Soil Science Society of America Journal*, 33(4):575–578.

Pavelis, G. A. (1987). *Farm drainage in the United States: History, status, and prospects*. Number 1455 in Miscellaneous Publication. US Department of Agriculture, Economic Research Service.

Reid, I. and Parkinson, R. J. (1984). The nature of the tile-drain outfall hydrograph in heavy clay soils. *Journal of Hydrology*, 72(34):289 – 305.

Robinson, M., Rycroft, D., Skaggs, R., Schilfgaarde, J. v., et al. (1999). *The impact of drainage on streamflow.* American Society of Agronomy.

Singh, R., Helmers, M., Crumpton, W., and Lemke, D. (2007). Predicting effects of drainage water management in iowa's subsurface drained landscapes. *Agricultural Water Management*, 92(3):162 – 170.

Skaggs, R., Youssef, M., Gilliam, J., and Evans, R. (2010). Effect of controlled drainage on water and nitrogen balances in drained lands. *Transactions of the ASABE*, 53(6):1843–1850.

Skaggs, R. W., Fausey, N. R., and Evans, R. O. (2012). Drainage water management. *Journal of Soil and Water Conservation*, 67(6):167A–172A.

Skaggs, R. W., Schilfgaarde, J. v., et al. (1999). *Agricultural drainage Monograph.* American Society of Agronomy.

Tanji, K. K. and Kielen, N. C. (2002). *Agricultural drainage water management in arid and semi-arid areas*. Food and Agriculture Organization of the United Nations.

Tomer, M., Meek, D., Jaynes, D., and Hatfield, J. (2003). Evaluation of nitrate nitrogen fluxes from a tile-drained watershed in central iowa. *Journal of environmental quality*, 32(2):642–653.

Vidon, P. and Cuadra, P. E. (2010). Impact of precipitation characteristics on soil hydrology in tile-drained landscapes. *Hydrological Processes*, 24(13):1821–1833.

Willardson, L., Meek, B., Grass, L., Dickey, G., and Bailey, J. (1970). Drain installation for nitrate reduction. *Ground Water*, 8(4):11–13.

2. EXPERIMENTAL SETUP, DATA COLLECTION, DATA HANDLING AND PROCESSING

The processing and analysis of environmental data that is collected at DPAC requires the use of computational tools that provide the capability of effectively handling large volumes of information in a consistent manner that ensures reproducibility and the management of all data operations. The effective processing and analysis of such data requires a good understanding of the experimental set-up and the field environmental conditions that are key in gaining insight about the working of the drainage water management system being studied. Accordingly this chapter's focus is on the site environmental conditions, experimental setup, data collection, and data handling and processing.

2.1 General site conditions

The drainage water management research site (Field W) is located in eastern Indiana at the Davis Purdue Agricultural Center (DPAC) located at 40.266°N, 85.160°W. The 14.3 ha field is divided into four quadrants, northwest (NW), southwest (SW), northeast (NE), southeast (SE) that have a respective area of 3.5 ha, 3.5 ha, 3.6 ha, and 3.7 ha (figure 2.1) (Brooks, 2013; Utt, 2010; Adeuya, 2009). There is an elevation change of approximately 3 meters in Field W (figure 2.1). The dominant soil parent material in the area is clayey Wisconsin till that has been deposited during the Wisconsonian glacial period (Franzmeier et al., 2004). The soil series map as shown in figure 2.1 comes from a first order soil survey that was done by G. Steinhardt at the Purdue Agronomy Department. The first order soil survey provides a better delineation of the soils than the Soil Survey Geographic Database (SSURGO) digital soils map, but the soil series descriptions were not modified from SSURGO as it was found the official soil series descriptions provide an appropriate description of the soils in the area. The predominant soil series in each quadrant are shown in table 2.1 along with their drainage class and depth to restrictive layer (Soil Survey Staff, 2014).

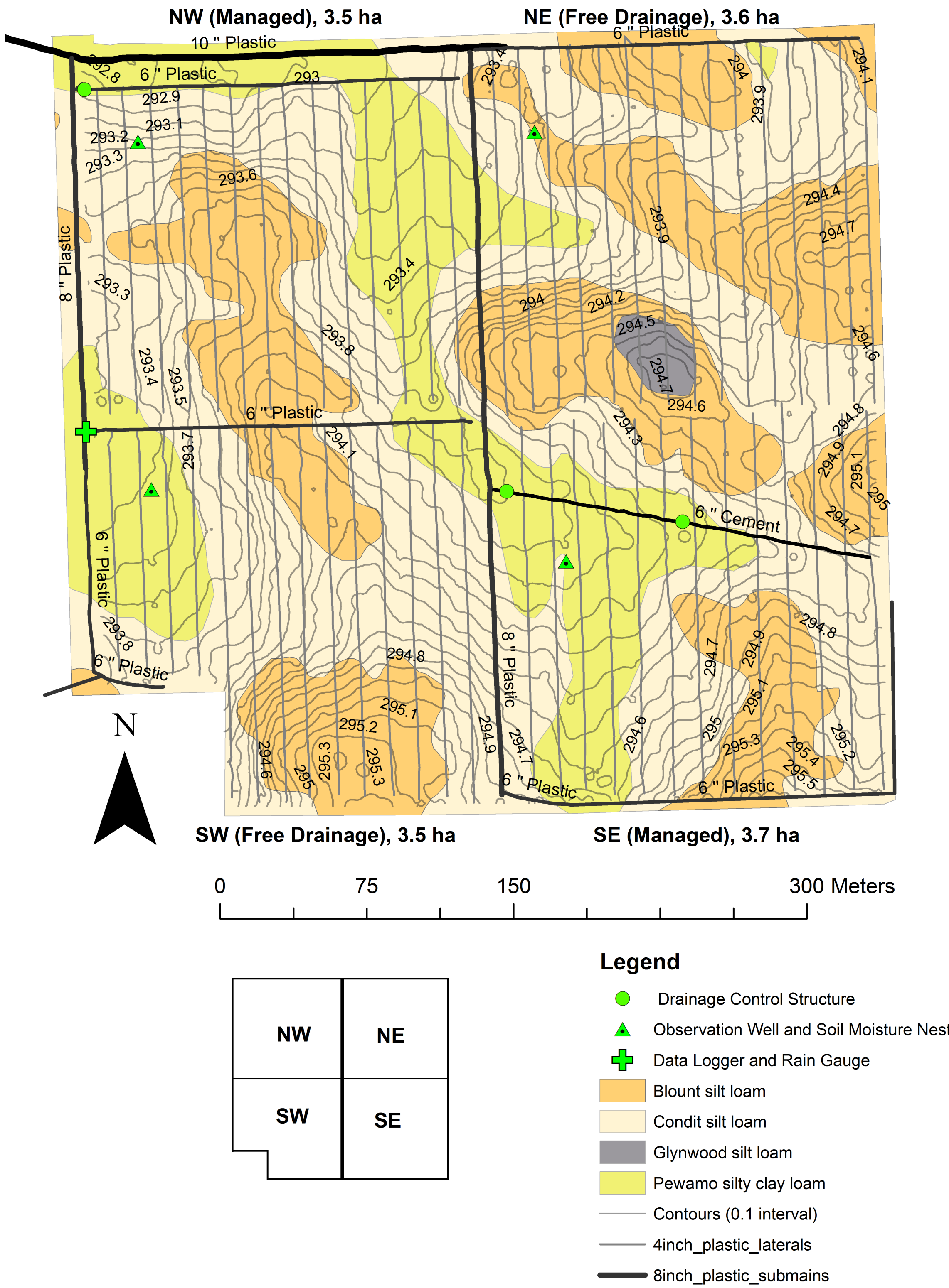


Fig. 2.1. Map of Field W at DPAC that highlights elevation, first order soil map, quadrant boundaries, and the locations of the main, submains, laterals, wells, soil moisture nests, and control structures.

Table 2.1.
Soil series at Field W by quadrant.

Soil Series %	NW	SW	NE	SE	Drainage Class	Depth to restrictive Feature
Pewamo Silt Clay Loam	27.4%	17.3%	3.4%	28.2%	Poorly Drained	More than 80 inches
Blount Silt Loam	24.8%	27.2%	49.2%	25.9%	Somewhat Poorly Drained	30 to 60 inches to densic material
Glynwood Silt Loam	0.0%	0.0%	3.4%	0.0%	Moderately Well Drained	25 to 50 inches to densic material
Condit Silt Loam	47.8%	55.5%	44.0%	46.0%	Very Poorly Drained	More than 60 inches

Soil was sampled by Eileen Kladivko and her lab at three locations and at four depths near each of the four observation wells (described below) (figure 2.1). The soil near the wells in the southern quadrants have a clay texture while in the northern quadrants the soil in the first 20 cm is clay loam and at greater depths it becomes clay (table 2.2). Since clay generally has a lower hydraulic conductivity than clay loam then such a variability in the soil layers across the four quadrants may have implications on the overall hydraulic behavior of the soil that can affect the readings from observation wells.

Table 2.2.
Basic soil characteristics at three locations near wells within each quadrant. Texture is according to USDA soil textural classification.

Quadrant	Depth	0-10 cm	10-20 cm	20-40 cm	40-60 cm
NW (Condit)	Dominant Soil Texture	Clay Loam	Clay Loam	Clay	Clay
	Mean % SOC	1.7	1.3	0.9	1.0
SW (Pewamo)	Dominant Soil Texture	Clay	Clay	Clay	Clay
	Mean % SOC	2.2	1.9	1.4	1.1
NE (Blount and Condit)	Dominant Soil Texture	Clay Loam	Silty Clay Loam	Clay	Clay
	Mean % SOC	1.7	1.3	0.9	0.8
SE (Pewamo and Condit)	Dominant Soil Texture	Clay	Clay	Clay	Clay
	Mean % SOC	2.6	2.0	1.5	0.9

The existing tile drains were installed in 2005. Each of the quadrants has its own 6" submain that connects to the outlet and empties into the main leading to the county main that is at the northwest corner of the field. Coming off of each submain are 4" laterals that are placed at a 45 ft nominal spacing. Submains are at a depth of 3.5 ft (1.06 m) at the beginnings and the end of the tile line while laterals are at the depth of the submain at the beginning and 3 ft (0.91 m) deep at the end of the line (according to the design report for the project from Schlatters Inc.).

Control structures were placed at the outlet of the NW and SE quadrants, and due to its topography, the SE quadrant has two control structures. The SW and NE quadrants are left to drain freely while the NW and SE quadrants are under managed drainage.

The control structures are Agri Drain Corp. Inline Water Level Control Structures (figure 2.2). The structures are installed in the 6" submain so that water enters the pipe, flows into the box and over the drop logs, and out to the downstream side of the structure to the county main. DPAC's farm superintendent controls the height of the drop logs in the structures of the managed fields. During 2012 and 2013 the height of drop logs was controlled to have a high water table during winter (0.1 below the surface) to offer water quality benefits, and a lower water table during summer (0.4 m below the surface) to reduce the likelihood of water logging in the soil that would cause damage to crops. Drop logs are usually pulled from the control structure before field operations to enhance the trafficability and workability of the soil so that it can support agricultural machinery. Figure 2.3 shows the height of the drop logs in the control structures during the 2011-2013 period.

(a) (b)

Fig. 2.2. Agri Drain Corp. Inline Water Level Control Structure (Agri Drain Corp. website)

Electromagnetic flow meters (Krohne Waterflux 3070) were installed in November 2011 (Brooks, 2013). These electromagnetic flow meters can accurately measure bidirectional flow at very low flow levels as well as high flow levels. The use of these electromagnetic flow meters offers a great advantage over other measurement methods as they can capture the timing and volume of backward flow that occurs during large flow events that result in restricted flow through the outlet. Having a measure of backward flow enables the calculation of the net drain flow that exits the field thus providing a better estimate of drainage volumes. A second flow measurement

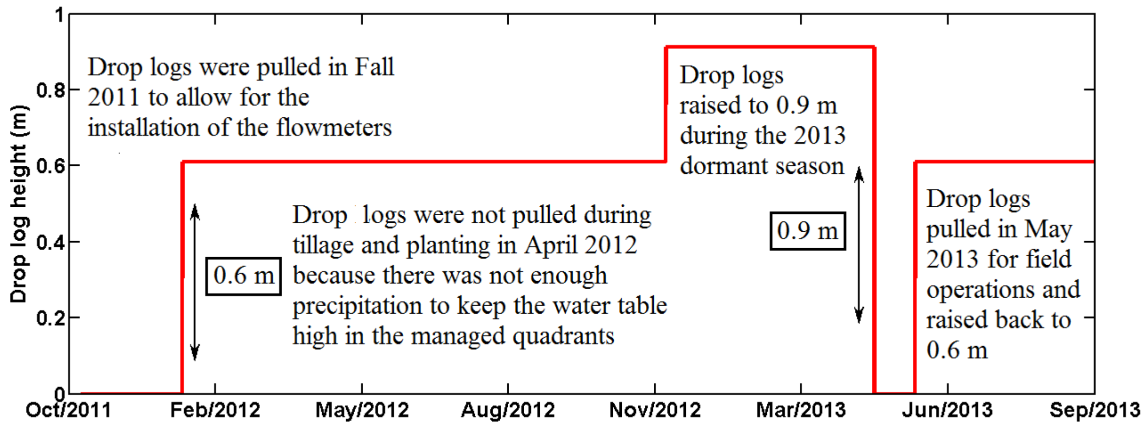


Fig. 2.3. Height of the drop logs in the control structure since the electromagnetic flow meters were installed (November 2011)

method, circular flumes, were installed for a previous project (Adeuya, 2009) as a low-cost instrument for measuring subsurface drain flow in drains under submerged outlet conditions (Cooke et al., 2004). Field measurement indicated that the circular flume require site-specific rating curves that vary depending on outlet submergence were developed (Adeuya, 2009). The flow measurement devices are shown in figure 2.4. For this study, only the electromagnetic flowmeter data were used.

Four long term water table monitoring wells were installed in each quadrant in 2005 at locations shown in figure 2.1 (Adeuya, 2009; Brooks, 2013). These wells are positioned at the mid-point between two lateral drains. In June of 2011, soil moisture sensor nests were installed in the field near each of the monitoring wells (Brooks, 2013). Each nest consists one 5TE and four 5TM Decagon capacitance based soil moisture sensors placed at depths of 10 cm, 20 cm, 40 cm, 60 cm, and 100 cm. Each of the sensors measures the soil volumetric water content (VWC) and the soil temperature in degrees Celsius. The top sensors (5TE) also measure the electrical conductivity of the soil in deciSiemens per meter (dS/m). While farm operations avoid the observation wells, the sensor nests are located in actively farmed areas. The 10 and 20 cm sensors are therefore removed during tillage operations and replaced

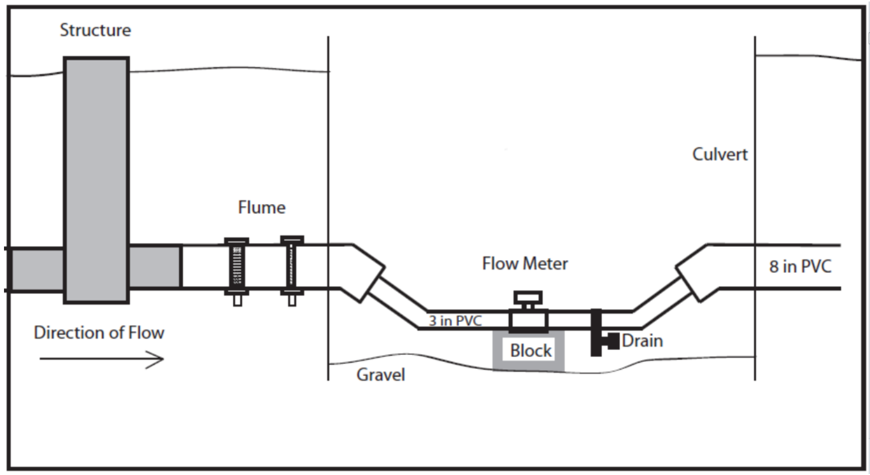


Fig. 2.4. Layout of flow measurement equipment at each control structure within the field (Brooks, 2013)

following planting. A tipping bucket rain gauge that measures rainfall in 0.01 inch increments and an anemometer were installed in 2005. Isco water samplers are used to automatically collect weekly, time-weighted drain water samples from the control structure of each of the quadrants in order to monitor water quality. Soil moisture and water table data are downloaded through direct connection to the field data loggers while drainage and precipitation data are downloaded through a wireless connection to a Raven XT modem that is tied to the Campbell Scientific CR 1000 data logger in which data is stored.

All the field instrumentation installed at DPAC is summarized in table 2.3.

Table 2.3.
Comprehensive list of measurement equipment at DPAC (Brooks, 2013)

Make	Model	Variable	Location	Time Resolution
Krohne	Waterflux 3070 electromagnetic flow meter and IFC 70 signal converter	Bidirectional drain flow	All quadrants	6 minute, 1 hour, daily
ISCO	Water sampler	Water quality	All quadrants	Weekly
Global Water	WL-16	Water table depth	All quadrants	1 hour
Decagon	5TE (10 cm), 5TM (others), Em50 data logger	Soil moisture, temperature, electrical conductivity	Near water table monitoring well in each quadrant	5 minute
Texas Electronics	TE525-L (0.01 in/0.254 mm)	Rain gauge	SW quadrant	6 minute, 1 hour, daily
Young	Wind Sentry Anemometer	Wind speed	SW quadrant	6 minute, 1 hour, daily

2.2 Data processing and handling

MATLAB was adopted as the technical computing environment for the processing, handling, analysis, and visualization of all the environmental data that is collected from the field experiment. MATLAB's high level programming language is versatile and well documented, can handle large volumes of environmental data, and can be adapted to do all required analyses and graphical visualization. Processing and effectively analyzing all the collected data from DPAC was challenging because data are stored in multiple formats and with various sampling time intervals. Moreover, the data contains erroneous readings, and missing data gaps.

Common to all data processing described in subsequent sections of this chapter is the conversion of all time stamps of collected data into MATLAB 'datenum' serial date numbers that allow for the synchronization of all the data sets to a common time reference. All readings are stored in structure arrays that group related data using data containers called fields (Mathworks, 2014).

2.2.1 Drainage data

Bidirectional drainage flow is logged every six minutes from the electromagnetic flowmeters into a CR1000 data logger. The data logger totalizes the drainage data to hourly and daily values. Data is downloaded as comma delimited text files that have six minute, hourly, and daily temporal resolutions. Hourly data from comma delimited files are added into a file that holds all of the raw drainage data. The file is further processed in a MATLAB script ('Process_DataLogger_Data.m', Appendix A.3) that does the following operations. Raw sensor reading are not altered in this process:

1. Convert the data logger time stamps to MATLAB 'datenum' serial date numbers. Add the serial date numbers and their associated sensor readings to records in a structure array that holds the drainage data of the four quadrants.

2. Fill missing data logger time stamp readings with empty readings in order to have a complete time series. Missing data logger readings occur when the data logger fails to record individual readings or when it was out for maintenance.

3. Convert the sensor pulse readings into cubic meters. Each pulse that the electromagnetic flow meter outputs represents 0.002 cubic meters (Brooks, 2013).

4. Calculate the net drain flow by subtracting the backward drain flow from the forward drain flow. The net flow is stored in the same structure array that holds the drainage data of the four quadrants.

During 2012 and 2013 the electromagnetic flow meters of the NW and SW quadrants were operational during most of the study period while the NE and SE quadrants' signal converters were hit by a lightning storm at the end of June 2012 and were replaced at the end of 2013 (figure 2.5). As a result, 12 and 15 months of measurements were lost, respectively, in the NE and SE quadrants.

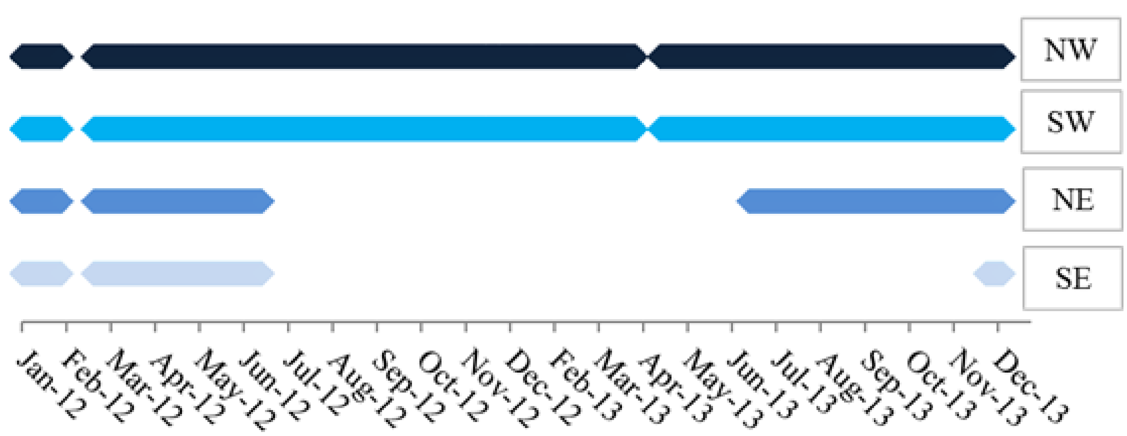


Fig. 2.5. Available drain flow data for the four quadrants

2.2.2 Soil moisture data

Raw soil moisture and temperature data files were downloaded from the data logger of each of the four sensor nests and converted to tab delimited text files using the Decagon ECH2O utility software. Data from tab delimited files was then added to quadrant specific text files that hold all of the raw soil moisture data. Each of these text files was processed in a MATLAB script ('SMT_RAW_DATA_PROC.m', Appendix A.2.1) that does the following operations. Raw sensor readings are not altered in this process:

1. Convert the data logger time stamps to MATLAB 'datenum' serial date numbers. Add the serial date numbers and their associated sensor readings to records in structure arrays that are specific to the quadrant.

2. Fill missing data logger time stamp readings with empty readings in order to have a complete time series. Missing data logger readings occur if the batteries in the logger are dead, the logger's memory is full, or the data logger fails to record individual readings.

3. Adjust the record's serial date numbers to account for daylight saving time changes. Such an adjustment has to be made because each time data is downloaded the hand held computer updates the data logger clock. Accordingly, when downloads are made during daylight savings time the data logger clock shifts one hour from the Eastern Standard Time (EST). All processed data is recoded with respect to EST.

4. Delete erroneous readings for the 10 and 20 cm sensors that were recorded during and after the 2012 corn planting period (April 20, 2012 through April 25, 2012). During the 2012 planting period all the 10 cm and 20 cm sensors were removed and temporarily placed with the 40 cm sensors to avoid machinery damage during tillage and planting of corn. In the 2013 planting period soy beans were planted and no tillage was done. As soybean planting does not affect the 10 cm soil layer, no sensors were removed from the soil.

5. Extract hourly readings from the sensor data set. Readings at the beginning of the hour were selected to represent hourly soil moisture.

Further processing has been done through the use of another MATLAB script ('Soil_Filling_Column_Daily_Monthly_MasterCODE.m', Appendix A.2.2) that fills in missing data using data from other depths and other quadrants, computes the total soil moisture in the column using the trapezoidal rule, and calculates the daily, and monthly soil moisture averages. Details about these operations can be found in sections 2.2.2.1 and 2.2.2.3.

2.2.2.1 Filling of missing data

During 2012 and 2013, 2.25% of soil moisture measurements were missing (figure 2.6).

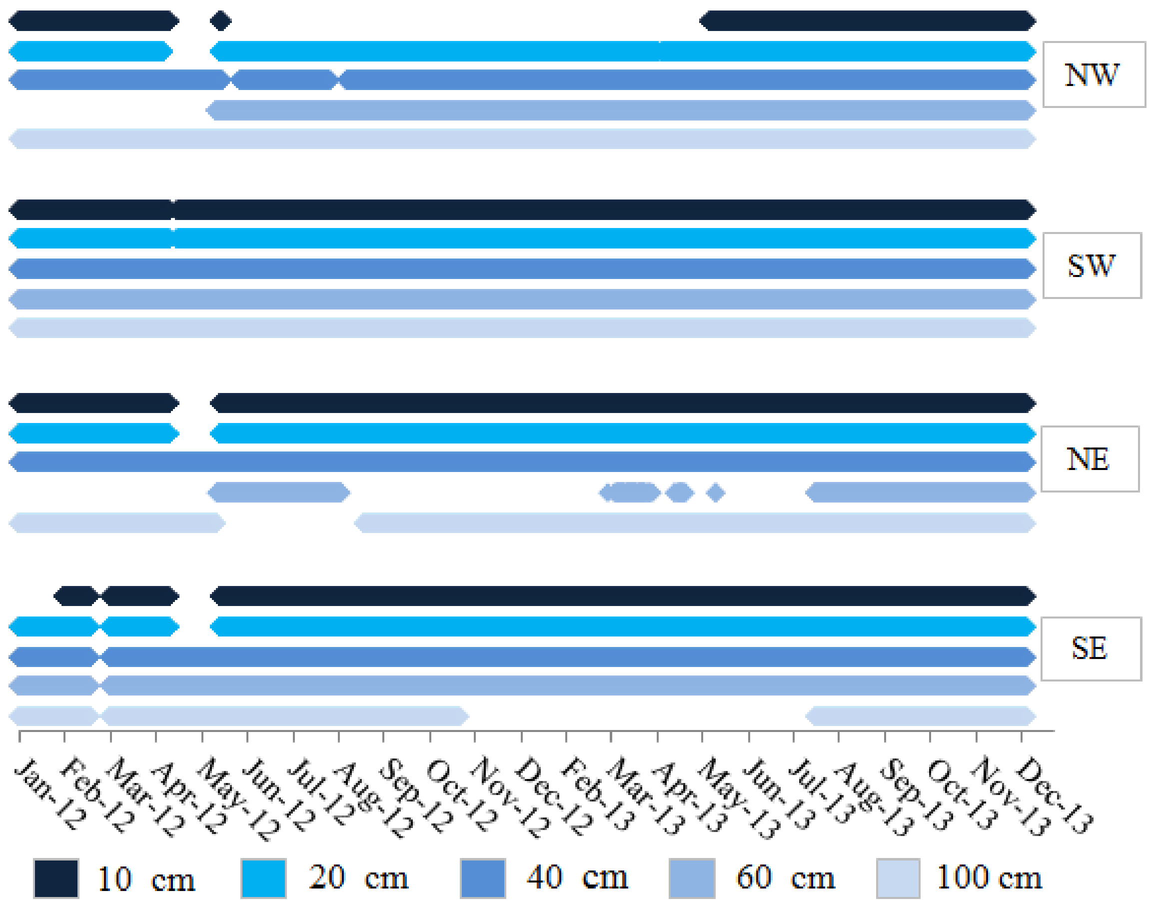


Fig. 2.6. Available soil moisture data for the four quadrants

Soil moisture data were filled to make a complete data set, following the three filling procedures developed by Brooks (2013). For filling short time gaps of less than three hours the autocorrelation of data of the observed time series was examined. It was found that sensors are all highly autocorrelated, with a significant lag autocorrelation that stays high up to lag twenty hours, as it would be expected from hourly soil moisture data (Brooks, 2013). Accordingly, data in the vicinity of the missing short time gaps was used for filling.

For longer periods of missing data when a single sensor failed, the cross correlations of sensors that are within the same quadrant were examined (Brooks, 2013). Available data from the malfunctioning sensor was matched to the nearest working sensor in the profile in order to look at their corresponding lag zero cross correlation structure (Table 2.4). The nearest sensor that had the highest correlation was used to fill the missing sensor's data gap. Equation 2.1 was used to scale the data from the nearest sensor by multiplying its values by the ratio of the twelve hour mean of the sensor to be filled (prior to the sensor malfunction) to the twelve hour mean of the sensor to be used for filling. This ratio is later referred to as the local scaling ratio:

$$Filled_t = Nearest_t(\frac{\sum_{i=t_0-1}^{t_0-12} Filled_i}{\sum_{i=t_0-1}^{t_0-12} Nearest_i}) \tag{2.1}$$

Table 2.4.
Intra-quadrant lag zero cross correlation coefficients of missing sensors. '-' means that cross correlation coefficient is not needed

	10 cm 20 cm	20 cm 40 cm	40 cm 60 cm	60 cm 100 cm
SE	0.949	0.729	0.867	0.550
SW	0.973	0.821	-	-
NW	0.848	0.973	0.975	0.592
NE	0.894	0.993	0.97	0.798

To calculate the scaling ratio, Brooks (2013) used the average of the soil moisture for the entire length of each individual sensor's time series, during periods when both sensors were operational. The reasoning behind using the mean over the entire time series was to avoid seasonal biases for shorter time periods.

Twelve hours before the malfunction of the sensor was used here to calculate the local scaling ratio. Using measured data after the installation of the sensor was avoided because it takes the newly inserted sensor hours before it starts reading the 'right' volumetric soil moisture. The calculated twelve hour average local scaling ratio alleviates the shifts in filled data that occur when the entire length of each individual sensor's time series data is used to calculate a long term scaling ratio as done by Brooks (2013). The local scaling ratio works better with shorter term periods (Figures 2.7 and 2.8) than long term periods (Figure 2.9)).

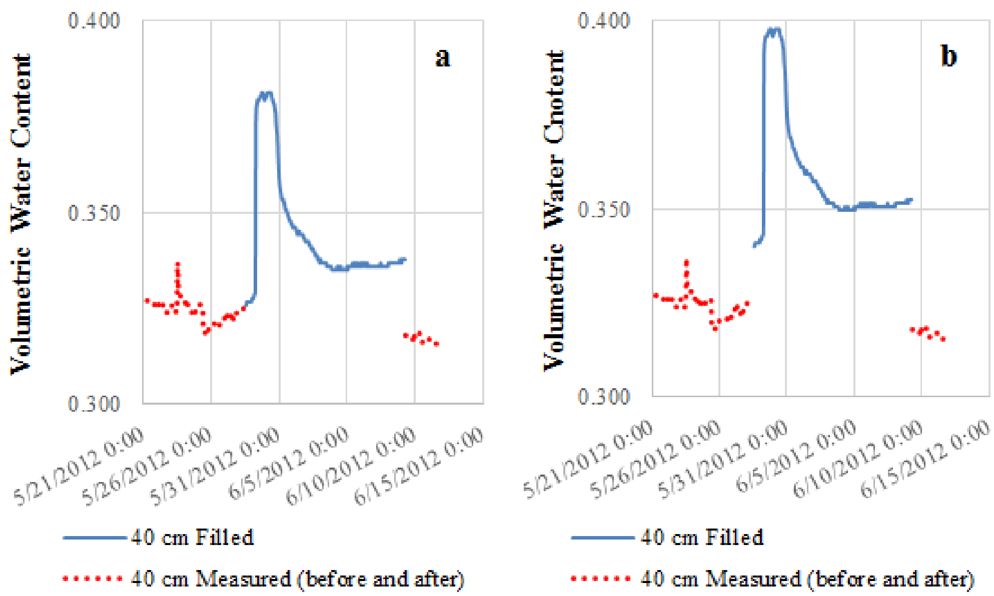


Fig. 2.7. Example from the NW quadrant of short term filled data of the 40 cm sensor using (a) local scaling ratio, and (b) long term scaling ratio (Brooks, 2013).

The third type of missing data was when all sensors within one soil moisture nest were missing because the data logger's battery was empty. Such battery failures occured in the NE and SE quadrants. Cross correlation coefficients were found between sensors where data are missing and their same depth counterparts in quadrants in which there was no battery failure (Brooks, 2013). The quadrant that had the highest mean zero lag correlation across all sensors was used. As detailed above, the twelve hour average local scaling ratio was also used to scale the filled data. It also did alleviate the shift in the filled data that occurred when using the entire length of sensors data to calculate the long term scaling ratio.

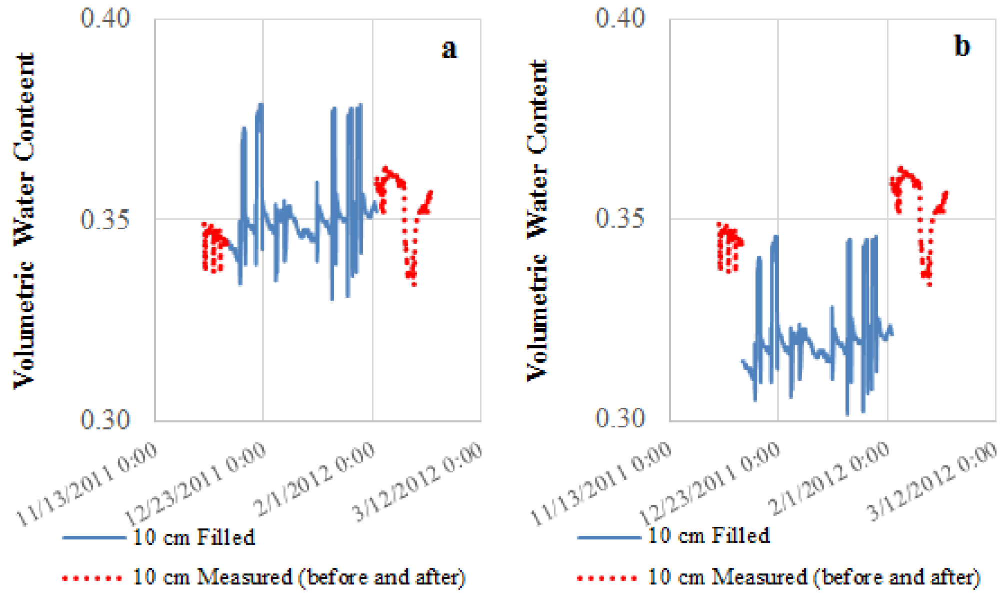


Fig. 2.8. Example from the SE quadrant of short term filled data of the 10 cm sensor using (a) local scaling ratio, and (b) long term scaling ratio (Brooks, 2013).

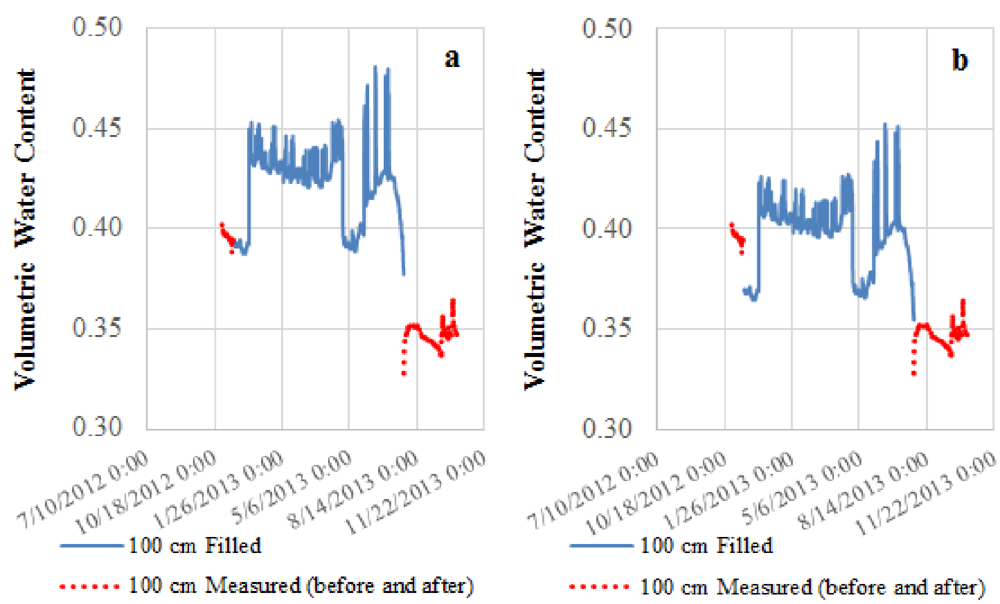


Fig. 2.9. Example from the NW quadrant of long term filled data of the 100 cm sensor using (a) local scaling ratio, and (b) long term scaling ratio (Brooks, 2013).

2.2.2.2 Checking soil moisture data against measured soil porosity

The bulk density of the sampled soil by Eileen Kladivko and her lab at three locations, three repetitions for each location, and at four depths (0-10 cm, 10-20 cm, 20-40 cm, 40-60 cm) near each of the four observation wells was measured in the lab for each repetition. The average soil porosity at every depth for each location was calculated using the following equation:

$$\phi = 1 - \frac{\rho_{bulk}}{\rho_{particle}} \tag{2.2}$$

where ϕ is the porosity, ρ_{bulk} is the soil bulk density in g/cm^3, and $\rho_{particle}$ is the normal particle density that is assumed to be $2.65 g/cm^3$. To ensure the quality of the measured moisture data, the volumetric water content as recorded by every sensor was examined to see if its measured values exceeded the corresponding soil porosity. The result was that the volumetric water content as logged by the sensors did not exceed the calculated soil porosities thus insuring that the soil moisture measurements are below their maximum values.

2.2.2.3 Calculation of the soil water storage in the column

The total moisture within the soil column integrates the volumetric water content over the length of the whole column as follows

$$Storage(t) = \int_0^z \theta(z,t)\ dz \qquad (2.3)$$

where t is time, θ is the volumetric water content, and z is depth (mm). Ideally, continuous soil moisture measurements throughout the column would be available. In this experiment point soil moisture data is being measured at five depths throughout the 100 cm column without equal spacing. Common methods of integration of such data are the trapezoidal method and Simpson's 1/3 rule (Hupet et al., 2004; Hupet and Vanclooster, 2004; Mittelbach et al., 2012). Through modeling quasi continous soil water content profiles and comparing them to different integration methods, Hupet (2004a) determined that Simpson's 1/3 rule yielded the best results. Simpson's 1/3 rule is a formula that approximates the integral of functions using quadratic polynomials. The application of Simpson's 1/3 rule requires three equidistant points making it not applicable to all sensors in this experiment's soil moisture nest. Accordingly, it was determined that it is best to use the trapezoidal rule, a variation of Simpson's rule based on simpler approximations. The trapezoidal rule is simply linear interpolations between consecutive moisture sensors; it works by approximating the area under the function $f(x)$ (eq. 2.4).

$$T = \int_a^b f(x)\ dx \cong \frac{1}{2}(b-a)(f(a)+f(b)) \qquad (2.4)$$

where a and b are the arguments, $f(a)$ and $f(b)$ are the function values at a and b, and T is the area under the trapezoid. It is assumed here that the top 10 cm layer is represented by the 10 cm soil moisture sensor (figure 2.10 b, eq. 2.5). Brooks (2013) employed a method that he called the midpoint rule which is a reformulation of the trapezoidal rule (figure 2.10). The two methods yield the same soil moisture storage in the column, but the trapezoidal rule yields a better physical representation of the soil moisture profile. Equation 2.6 was used to calculate the estimated soil water storage at each of the sensor nest locations.

$$Storage \cong z_1\theta(z_1) + \sum_{i=1}^{N=4} \frac{\theta(z_i) + \theta(z_{i+1})}{2}(z_{i+1} - z_i) \tag{2.5}$$

where θ is the volumetric soil moisture content at depth z

$$Storage(mm) \cong 150\theta_1 + 150\theta_2 + 200\theta_3 + 300\theta_4 + 200\theta_5 \tag{2.6}$$

Figure 2.11 shows the daily average of the soil storage in the column across the four quadrants of the whole data set.

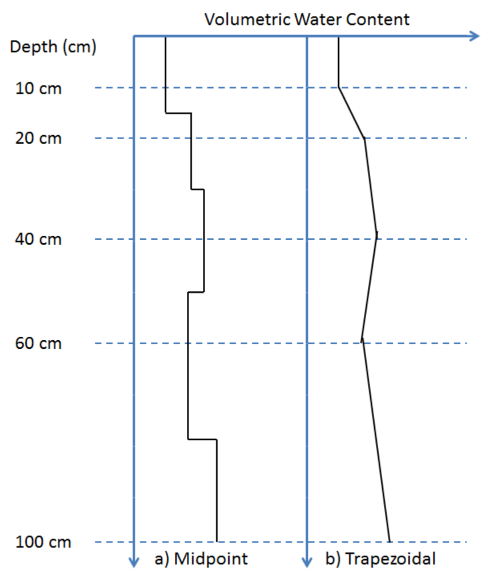


Fig. 2.10. Two formulations of the same technique for soil moisture integration: the midpoint method and the trapezoidal method

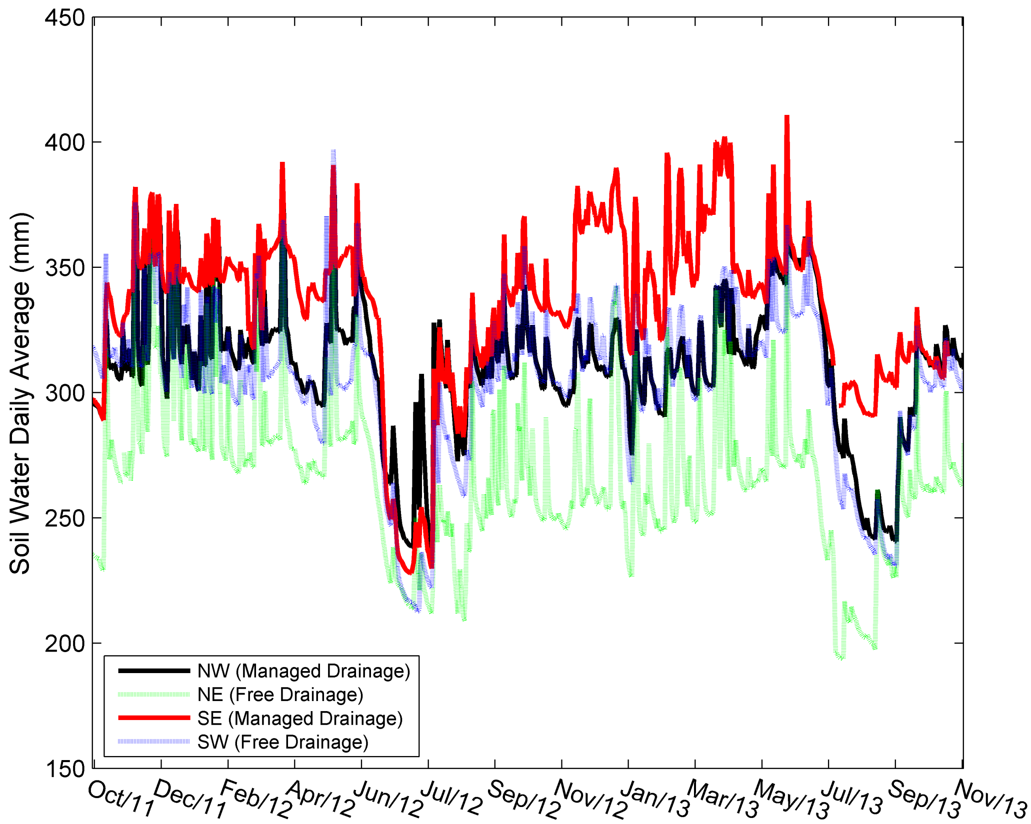


Fig. 2.11. Daily soil water average in the four quadrants during the period that extends from October 2011 until November 2013

2.2.3 Precipitation data

Two C shell scripts, and two C programs developed by Laura Bowling and Chun-Mei Chiu were used in order to generate continuous hourly and daily precipitation records for DPAC for the time period of October 2005 through October 2013 using a combination of the three following sources:

- Field W: Project weather station at Field W is located on the western side of the field, between the NW and SW quadrants at 40.266°N, 85.162°W, and at an elevation of 293.3 meters ASL. Measured variables: Hourly wind speed (WS) and summer precipitation (P).

- Purdue Automated Station: A Purdue automated station that is located at DPAC at 40.250°N, 85.150°W, and at an elevation of 294.1 meters ASL. Measured variables: 30 minute data for wind speed (WS), precipitation (P), solar radiation (R), and air temperature (T).

- COOP Station: National Climatic Data Center Coop Station 122825, Farmland 5 NNW (COOP) that is located at DPAC at 40.253°N, 85.1482°W, and at an elevation of 294.1 meters ASL. Measured variables: Daily precipitation, daily maximum air temperature (Tmax) and daily minimum air temperature (Tmin).

The Field W tipping bucket was assumed to give the best representation of precipitation received by Field W, when it was operational. This tipping bucket is covered during winter months (typically from December 1 to March 31) because it is not modified to measure solid precipitation. The COOP gauge is assumed to give the best record of total snow precipitation. For periods in which the Field W tipping bucket gauge was uncovered or the data for Field W was otherwise missing, and in which the Purdue Automated Station is operational, a ratio of the precipitation totals of the Field W to the Purdue Automated Stations (0.91) was used to estimate the Field W precipitation. If Purdue Automated Station data is missing, the Field W hourly precipitation was estimated by multiplying the COOP daily precipitation data by a ratio of precipitation totals of the Field W to the COOP stations (0.94) and dividing into 24 hour precipitation. For periods in which the Field W tipping bucket gauge was covered and in which the COOP and Purdue Automated stations were operational, a ratio of COOP to Purdue Automated stations (1.02) was multiplied with the Purdue Automated station hourly precipitation in order to get an intermediate precipitation data set that has adjusted hourly snowfall values.

2.2.4 Shallow observation well data

2.2.4.1 Processing water table data

Hourly well data text files were downloaded from the water level loggers that are inside the shallow observation well of each of the four quadrants. Data from quadrant specific text files were combined and processed in a MATLAB script ('Combine_Write_Depth_WT.m', Appendix A.1) that does the following operations on the data:

1. Convert the data logger time stamps to a MATLAB 'datenum' serial date numbers. Add the serial date numbers and their associated sensors readings to records in structure arrays that are quadrant specific.

2. Fill missing data logger time stamp readings by inserting empty readings in order to have a complete time series. Reasons for having missing data logger readings are because the batteries in the logger are dead, the logger's memory is full, the data logger fails to record readings, or there is a sensor malfunction.

3. Convert the sensor reading to water table depth below the soil, by converting feet to meters, subtracting sensor readings from the depth of the sensors below the ground surface (table 2.5).

Table 2.5.
Depth of water level sensors below ground

Quadrant	NW	SW	NE	SE
Depth of sensor below ground (m)	1.74/2.13[1]	2.00	2.00	2.09

[1] Before and after 9/5/12

Water table data was available for most of the data collection period of 2012 and 2013 (figure 2.12). Missing water table data was either because of dead batteries in the water level sensor data loggers or because of sensor malfunction.

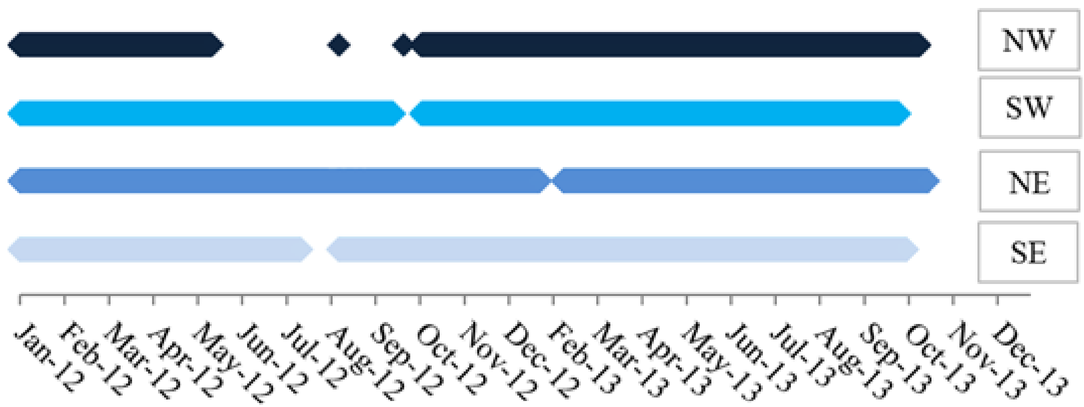


Fig. 2.12. Available water table data for the four quadrants

For subsequent analysis, further processing was done on the water table depth data in order to reference it to the subsurface drain elevation below the soil. The height above drain (HAD) was calculated using eq. 2.7:

$$HAD = HAS - (DS - DD) \tag{2.7}$$

where HAS is the water height above the sensor or the water level sensor reading, DS is depth of the sensor below the soil surface, and DD is the depth of the subsurface drain. These values are shown in figure 2.13.

The subsurface drain depth below the soil near each well was estimated by making use of the location of observation wells, Real Time Kinematic survey elevation point data that was previously done at Field W (Adeuya, 2009) and the guidelines which the contractor followed in order to lay the laterals (submains are at a depth of 1.06 m at the beginnings and the end of the tile line while laterals are at the depth of

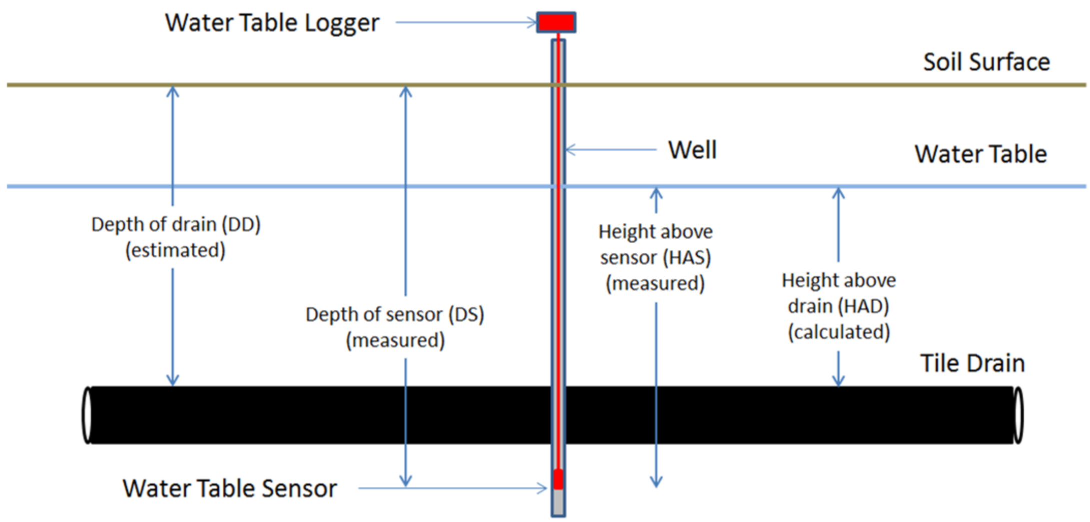


Fig. 2.13. Layout of shallow observation well, water level sensor, and subsurface drain

the submain at the beginning and 0.91 deep at the end, see section 2.1). From the contractor's design report, the laterals are generally at a slope of 0.5%; this slope estimate was used to calculate the change in tile elevation from the submain, that was assumed to be 1.06 m deep, to the well's location. The change in ground elevation from the submains to the location of the wells was then added to that estimate in order to get depth of laterals near each well (see table 2.6). Figure 2.14 illustrates the layout of the well, submain, control structure and lateral in the field.

Table 2.6.
Linear interpolation results for the approximate tile depth below the ground

		NW	SW	NE	SE
Distance along lateral from well to submain (m)	$[L]$	28	32	43	32
Approximate submain depth (m)	$[D_{sub}]$	1.06	1.06	1.06	1.06
Change in tile elevation from submain to well (m)	$[\Delta z_{tile}]$	0.14	0.16	0.21	0.16
Elevation difference between submain and well (m)	$[\Delta z_{ground}]$	0.28	0.05	0.12	0.05
Approximate lateral depth at the well (m)	$[D_{lat}]$	1.2	0.95	0.96	0.95

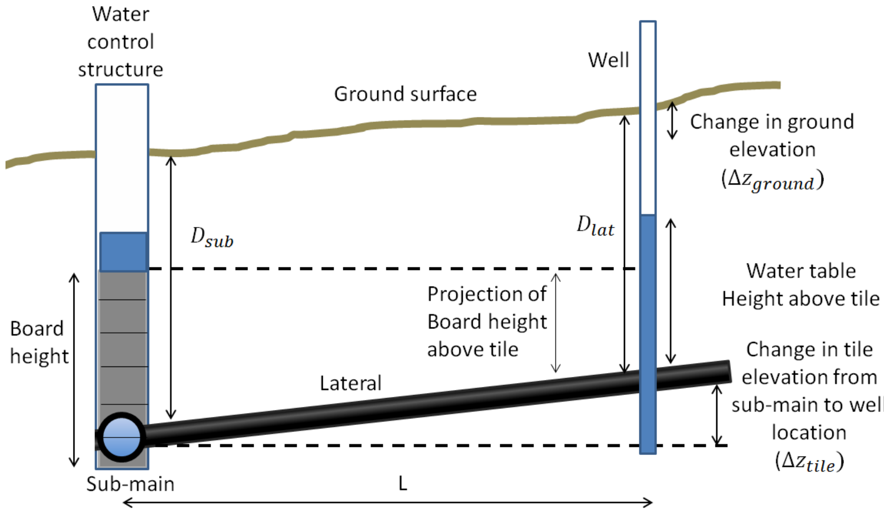


Fig. 2.14. Profile view of the layout of the well, lateral, submain, and control structure in the field.

2.2.4.2 Projecting the drop log height to the water table level above drain

In order to observe the effect of different drop log heights on the water table height above drain, the change in lateral elevation from the submain to the well (submain depth at the control structure was assumed the same as the depth where the submain meets the lateral) and the radius of the submain (12.5 cm) were subtracted from the structure board heights so that the projection of the boards onto the water level above the drain could be plotted (figure 2.14). To check the accuracy of this estimation, manual readings of the water height inside the structure that were made by the farm superintendent are plotted on figure 2.15. The readings match the fluctuations in the water table well and are generally close to the level of the water table as recorded at the wells.

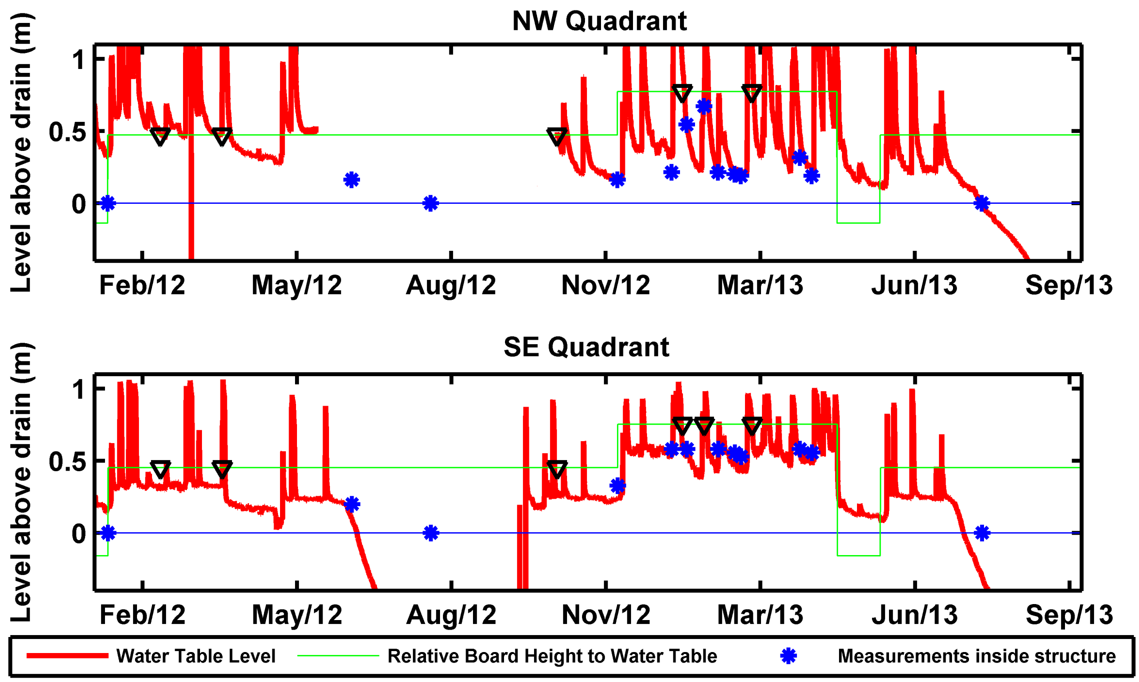


Fig. 2.15. Water table level above the drain of the NW and SE quadrants along with the relative drop log height to the water table and the manual measurements that were made inside the structure. Black triangles indicate periods in which there was flow from the structure when the manual measurement was made.

2.3 Data summary

Figures 2.16 to 2.19 are a result of the data handling and processing that has been done in this chapter. Each of the figures represents one quadrant and has four graphs that are the net drain flow from the outlet of the quadrant, the level of the water table above the drain, the soil volumetric water content (VWC) at five depths, and the precipitation at Field W.

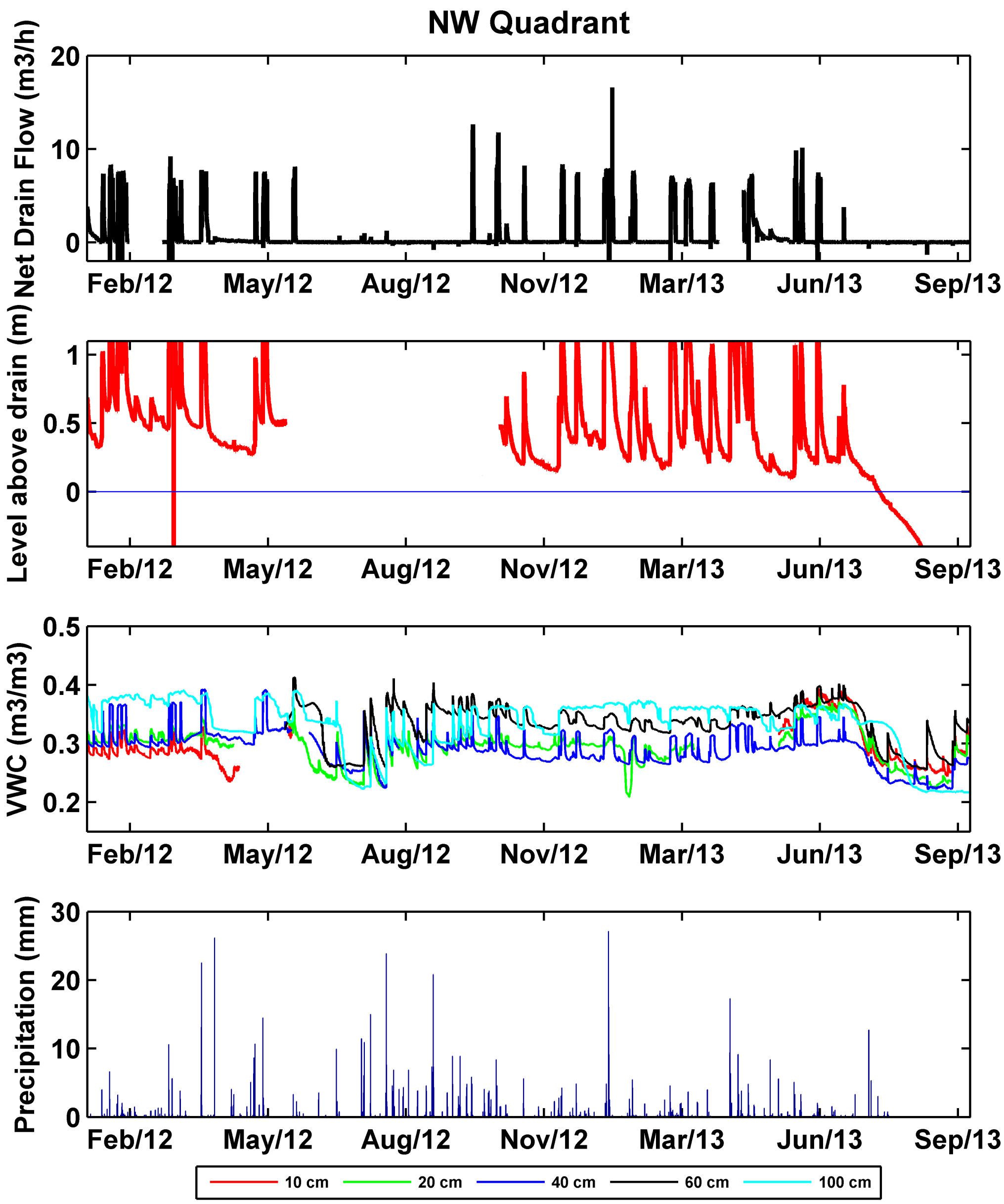


Fig. 2.16. Drain flow, water table, soil moisture, and precipitation for the NW quadrant from January 2012 until September 2013.

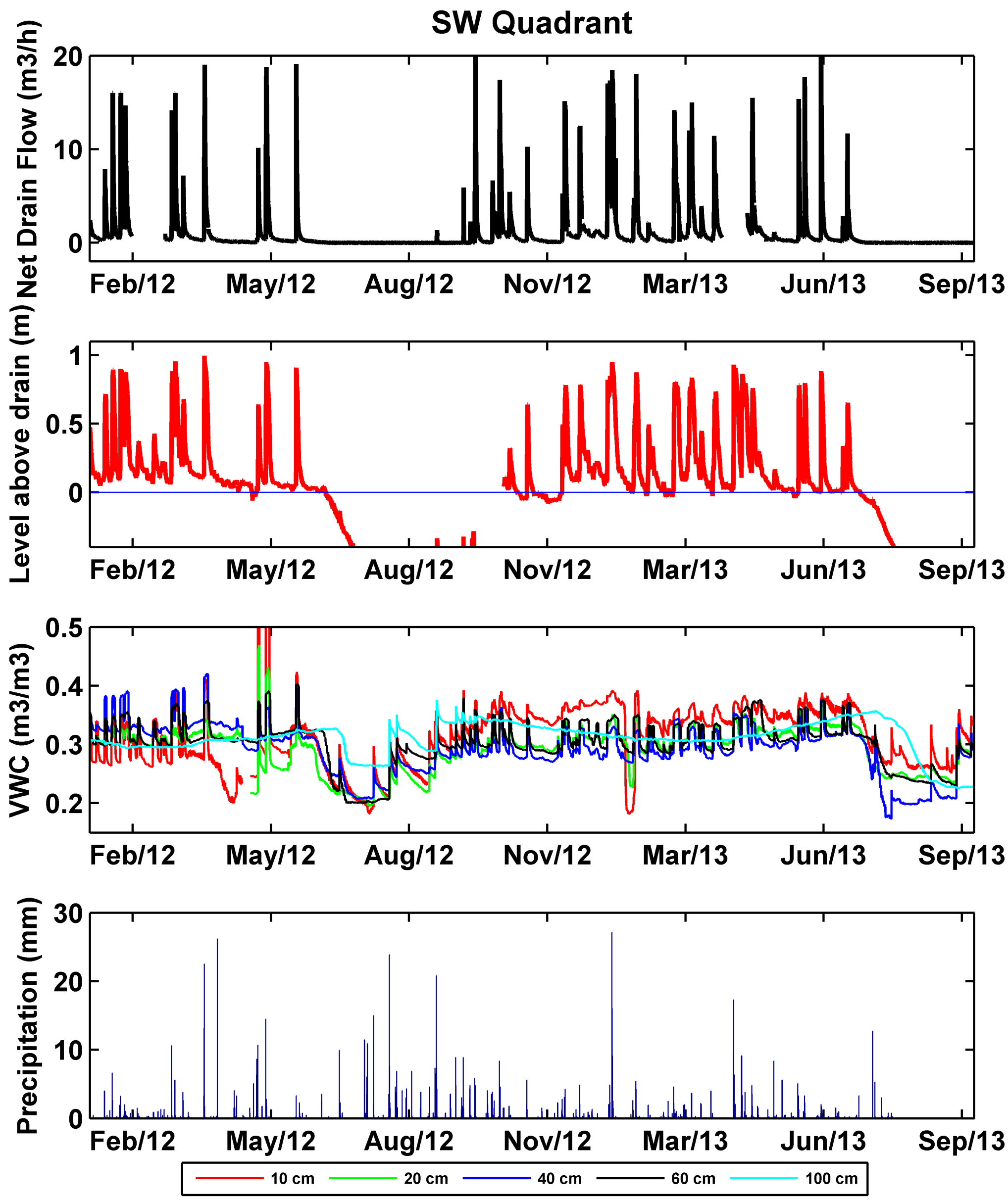


Fig. 2.17. Drain flow, water table, soil moisture, and precipitation for the SW quadrant from January 2012 until September 2013.

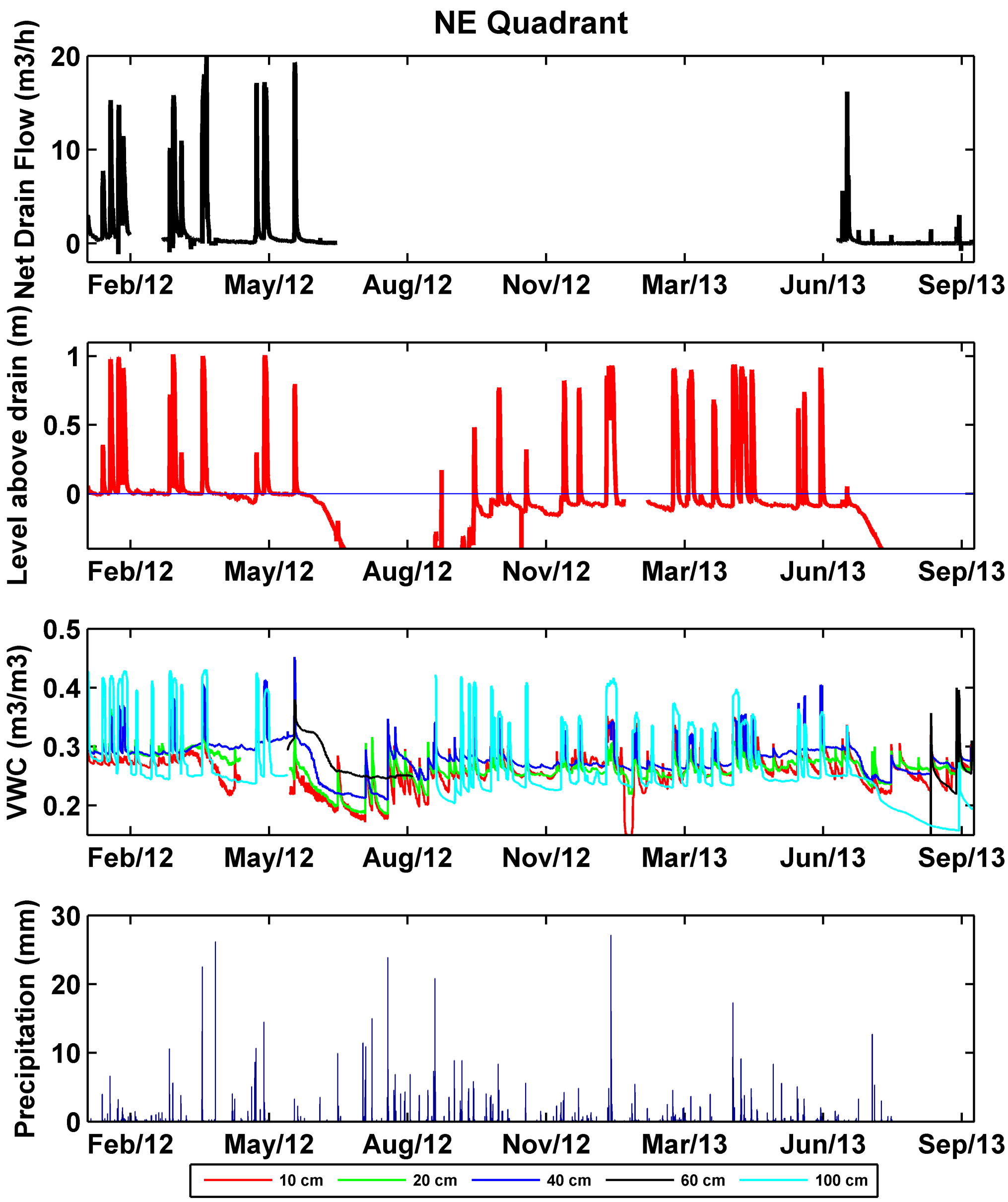


Fig. 2.18. Drain flow, water table, soil moisture, and precipitation for the NE quadrant from January 2012 until September 2013.

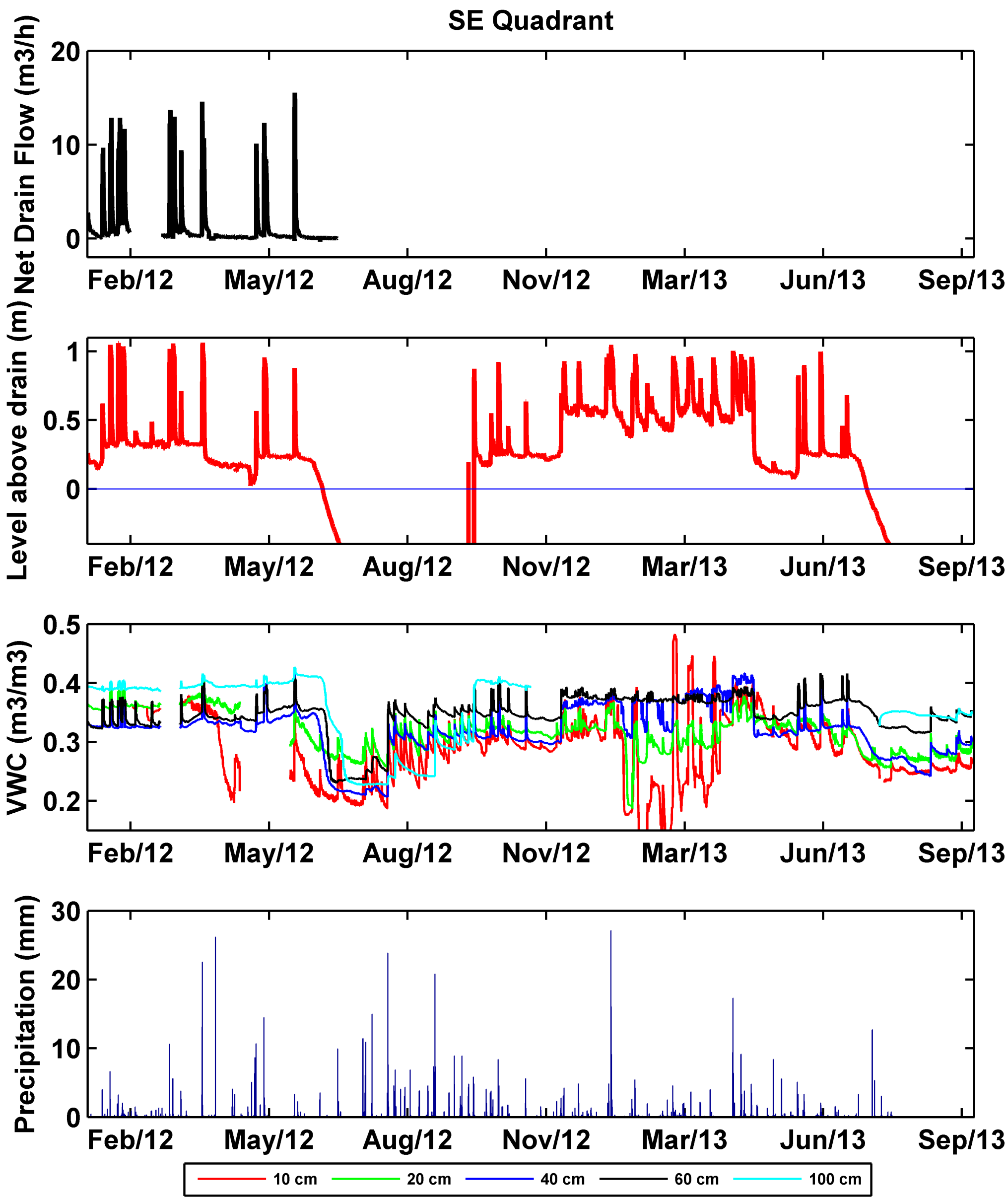


Fig. 2.19. Drain flow, water table, soil moisture, and precipitation for the SE quadrant from January 2012 until September 2013.

2.4 References

Adeuya, R. K. (2009). *The impacts of drainage water management on water table depth, drain flow and yield.* Phd thesis, Purdue University.

Brooks, K. (2013). Measurement of drain flow, soil moisture, and water table to assess drainage water management. Masters thesis, Purdue University.

Cooke, R. A., Wildman, T. A., and Northcott, W. J. (2004). Accurate, Low-cost Instrument for Measuring Subsurface Drain Flow Under Submerged Outlet Conditions. In *Pp. 332-339 in Drainage VIII the Proceedings of the Eighth International Drainage Symposium.*

Franzmeier, D., Steinhardt, G. C., and Schulze, D. G. (2004). *Indiana Soil and Landscapes Evaluation Manual.* AY-323. Purdue University Cooperative Extension.

Hupet, F., Bogaert, P., and Vanclooster, M. (2004). Quantifying the local-scale uncertainty of estimated actual evapotranspiration. *Hydrological Processes*, 18(17):3415–3434.

Hupet, F. and Vanclooster, M. (2004). Sampling strategies to estimate field areal evapotranspiration fluxes with a soil water balance approach. *Journal of Hydrology*, 292(1-4):262–280.

Mathworks (2013 (accessed January 27, 2014)). *Matlab Programming Fundamentals (2013b).* http://www.mathworks.com/help/pdf_doc/matlab/matlab_prog.pdf.

Mittelbach, H., Lehner, I., and Seneviratne, S. I. (2012). Comparison of four soil moisture sensor types under field conditions in Switzerland. *Journal of Hydrology*, 430-431:39–49.

Soil Survey Staff, Natural Resources Conservation Service, USDA (accessed on January 1, 2014). *Soil Survey Geographic Database for Randolph county, Indiana.* http://datagateway.nrcs.usda.gov.

Utt, N. (2010). Impacts of drainage water management on crop growth, soil quality, and nitrate loads. Masters thesis, Purdue University.

3. SYSTEMATIC ANALYSIS OF DRAINAGE EVENTS

The goal of this chapter is to characterize the hydrological behavior of free draining and managed subsurface drainage systems by systematically studying drainage events and their effect on hydrologic responses that occur in Field W at the Davis Purdue Agricultural Center (DPAC) that is located in Eastern Indiana. This is achieved by exploring the relationship between event outflow, drain flow hydrograph metrics, column soil moisture, water table depth, and precipitation characteristics. Specific objectives are to :

1. Determine the effect of precipitation characteristics and antecedent conditions on :
   (a) Drainage volumes and the reduction in drainage by DWM
   (b) Peak flows
   (c) Time to peak
2. Explore the mechanisms in which overland flow or ponding is generated on the field and relate these mechanisms to precipitation characteristics.

3.1 Event definition, selection, and data extraction

A drainage event was identified if it produced a peak drain flow greater than 5 m^3/h and data was available for the event for at least two quadrants. The start of the event was defined as one hour before precipitation started, and the end of the event when drain flow in the NW quadrant was less than 70 liters for 10 consecutive hours. Basing the end of the event on the drain flow from one quadrant was necessary to make data extraction for the same event from all quadrants consistent. The NW quadrant was chosen because the western quadrants have the most complete drainage data set and the NW quadrant has a shorter flow duration than the SW quadrant thus allowing for a shorter event definition. MATLAB was used for all analyses. Figure 3.1 shows a sample drainage event with net discharge, water table depth, and soil moisture in the column.

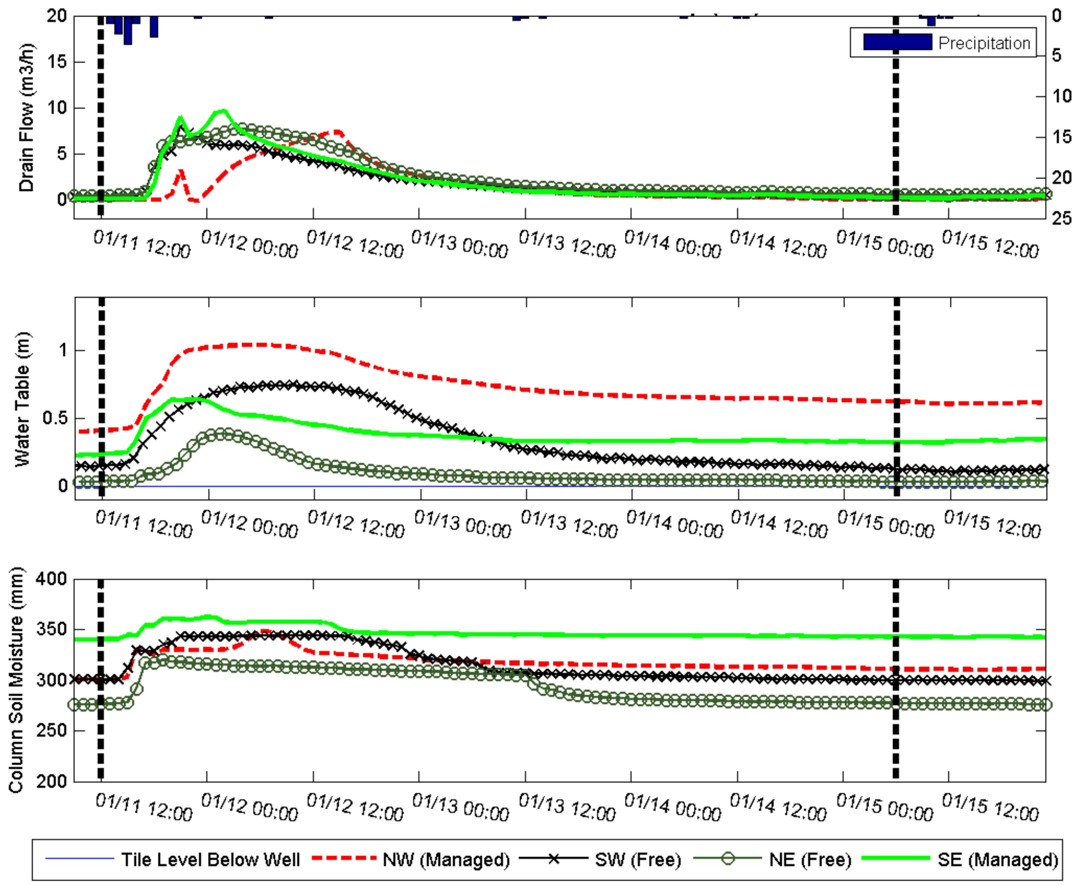


Fig. 3.1. Example of a drainage event from January 11, 2012 12:00 to January 15, 2012 6:00. Total event precipitation was 12.75 mm. The event start and end times are indicated by the vertical dashed lines.

Sixteen hydrological metrics were extracted from each event as summarized in table 3.1.

A total of 22 events were identified in 2012 and 2013. Table 3.2 indicates the number of events for which drainflow, water table, and soil moisture data are available for each of the quadrants.

Table 3.1.: Extracted hydrological metrics from each drainage event.

Precipitation Metrics		
Metric Name	**Unit**	**Description**
Total precipitation depth	mm	Total precipitation amount that fell between the event start and event end as defined by the event selection protocol.
Hours of precipitation	hours	Number of hours in which precipitation was recorded by the gauge.
Average precipitation intensity	mm/hr	Average precipitation during the hours of precipitation.
Precipitation time spread	hours	Weighted Standard deviation of the precipitation time series.
Drainage Metrics		
Metric Name	**Unit**	**Description**
Total drainage volume	m3	Total amount of drainage from each quadrant during an event.
Peak Flow	m3/h	Maximum hourly discharge during an event.
Time to peak	hours	Time interval from the start of the event until the peak of the hydrograph.
Water Table Height Metrics		
Metric Name	**Unit**	**Description**
Maximum water table height	m	Maximum water table height above drain during an event.
Antecedent water table height	m	Water Table height above drain at event start.
Post event water table height	m	Water Table height above drain at event end.
Hours of water table above the ground	hr	The number of hours in which the water table is above the ground level.

Soil Moisture Metrics		
Metric Name	**Unit**	**Description**
Antecedent soil column moisture	mm	Water content in the soil column at the start of an event.
Post event soil column moisture	mm	Water content in the soil column at the end of an event.
Maximum event soil column moisture	mm	Maximum water content in the soil column during an event.
Multivariate Metrics		
Metric Name	**Unit**	**Description**
Drainage to precipitation ratio	mm/mm	Drainage to Precipitation Ratio (%): Q/P
Event duration	hours	Hourly duration from the start until the end of the event (as specified by the event definition).

Table 3.2.
Number of events with complete data per quadrant.

	Drainage	Water Table	Soil Moisture
NW Events	22	19	22
SW Events	22	21	22
NE Events	11	21	22
SE Events	11	22	22

3.1.1 Events in which drainage occurred as a result of melting snow

Events 18 and 19 happened in March 2013 in a period in which rainfall followed a few days of snow accumulation. The event start was defined by the start of the rain event, therefore the earlier snow precipitation was not originally captured in the event precipitation total. The daily contribution of snow melt to the drainage event was estimated from the daily change in snow depth, as recorded by the National Climatic Date Center (NCDC) Coop station, as it was melting and generating a drainage response at Field W. The snow density was estimated by assuming that the prior precipitation as measured from the Coop station came completely as snowfall. This enabled the calculation of the precipitation to snow fall depth ratio that was used to estimate the water equivalent. The sum of melt water and rainfall that occurred during each event was used as an input for the total precipitation.

3.1.2 Precipitation time spread

A metric called 'precipitation time spread' was developed to quantify how precipitation is distributed over the course of a drainage event. This is a measure of the standard deviation of the center of mass of precipitation and represents how concentrated or dispersed the precipitation is that occurs during the course of the drainage event. For each drainage event equations 3.1 and 3.2 were employed to calculate the precipitation weighted standard deviation of the precipitation time series as follows:

$$\bar{t} = \frac{\sum_{i=1}^{N} t_i p_i}{\sum_{i=1}^{N} p_i} \tag{3.1}$$

where $\bar{t}$ is the weighted mean or the center of mass of the precipitation event in hours, t_i is the time (in hours) of each precipitation pulse with respect to the start of the event, p_i is t_i's corresponding precipitation that is used as a weight, and N is the duration (hours) of the drainage event. The weighted standard deviation, σ_t is calculated as:

$$\sigma_t = \sqrt{\frac{\sum_{i=1}^{N} (t_i - \bar{t})^2 p_i}{\sum_{i=1}^{N} p_i}} \tag{3.2}$$

In order to illustrate how the precipitation time spread works, it was calculated for two hypothetical precipitation events with the same number of precipitation pulses but distributed differently along a 12 hour event time frame (figure 3.2). The two events have the same precipitation depth and average precipitation intensity but the location of their center of mass differ. The precipitation time spread of events a and b are respectively 3.45 hours and 1.57 hours.

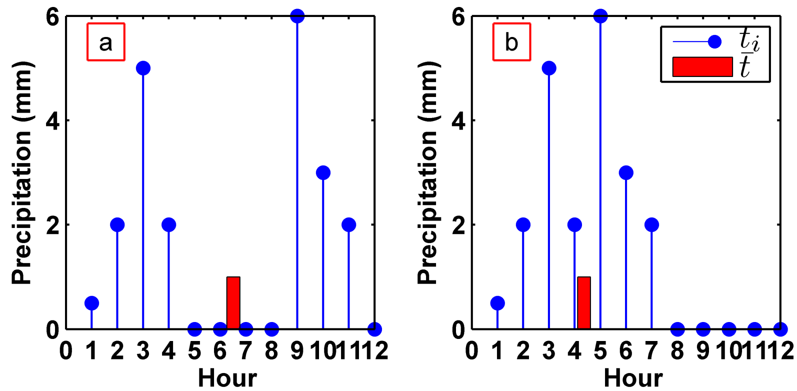


Fig. 3.2. Precipitation time spread of (a) 3.45 hours and (b) 1.57 hours. The center of mass of the precipitation event is indicated by the red column, $\bar{t}$.

3.2 Results and discussion

3.2.1 Event precipitation characteristics

The total precipitation depth, average precipitation intensity, and precipitation time spread for all the drainage events are shown in table 3.3 and figure 3.3. Events 18 and 19 occurred mainly as a result of snow melt; thus both of these events have a total precipitation depth but no precipitation intensity and precipitation time spread were calculated.

Event 3 had the lowest total precipitation that resulted mostly from a precipitation event that is comprised of six hours of continuous precipitation that had a precipitation depth of 7 mm. Event 22 had the highest total precipitation that resulted mostly from a precipitation event that is comprised of four hours of continuous precipitation that had a precipitation depth of 58 mm. To put the two precipitation events in context, they were compared to the depth-duration-curves of the area (NOAA,2006). The 7 mm precipitation event and the 58 mm precipitation event correspond to precipitation events that have less than a year and 10 year return periods, respectively.

The total precipitation depth (figure 3.4 a) and average precipitation intensity (figure 3.4 b) had a right skewed distribution with the majority of the events having a total precipitation depth between 10 and 30 mm and an average precipitation intensity that is between 0.5 and 3 mm/hr. Six out of 22 events have a high precipitation time spread which indicates that more than one storm occurred during these events or precipitation pulses were spread out throughout the drainage event (figure 3.4 c). A scatter plot of the average precipitation intensity versus the total precipitation (figure 3.5) showed that in general, the events that had a precipitation that is between 10 and 20 mm are the events that had an average precipitation intensity that is less than 4 mm/h. Figure 3.6 illustrates, as expected, that events that had a high average precipitation intensity (greater than 3 mm/hr) tend to have a low duration of precipitation while events that had lower precipitation intensity tend to have a high duration of precipitation.

Table 3.3.
Precipitation characteristics of the 22 drainage events.

Event	Event Start Date	Total Precip. (mm)	Average Precip. Intensity (mm/hr)	Precip. Time Spread (hr)
1	01/11/12	12.8	1.0	24.0
2	01/17/12	19.0	1.4	25.6
3	01/22/12	10.0	0.7	25.4
4	01/25/12	15.5	0.5	29.9
5	02/29/12	17.3	1.4	5.3
6	03/02/12	20.1	1.7	7.7
7	03/08/12	11.9	1.1	8.0
8	03/23/12	46.6	2.3	30.3
9	05/01/12	15.2	2.5	4.4
10	05/07/12	49.8	5.5	8.5
11	05/29/12	36.3	7.3	4.0
12	10/05/12	29.7	2.5	10.7
13	10/23/12	17.3	3.5	8.5
14	11/12/12	16.8	1.4	7.3
15	12/20/12	14.3	1.4	5.8
16	01/29/13	20.0	0.8	17.6
17	02/26/13	25.4	0.9	33.7
18	03/08/13	23.4	-	-
19	03/27/13	10.2	-	-
20	05/27/13	20.8	4.2	3.5
21	06/01/13	18.5	3.7	2.6
22	06/12/13	61.7	6.9	17.5

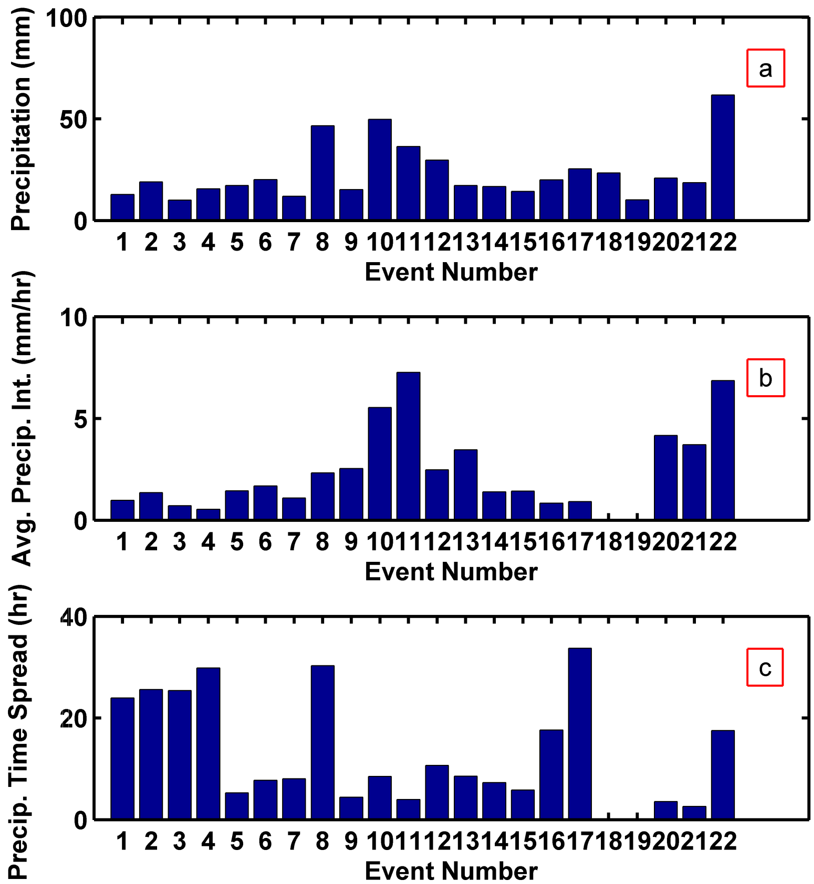


Fig. 3.3. a) Total precipitation, b) average precipitation intensity, and c) precipitation time spread of all events.

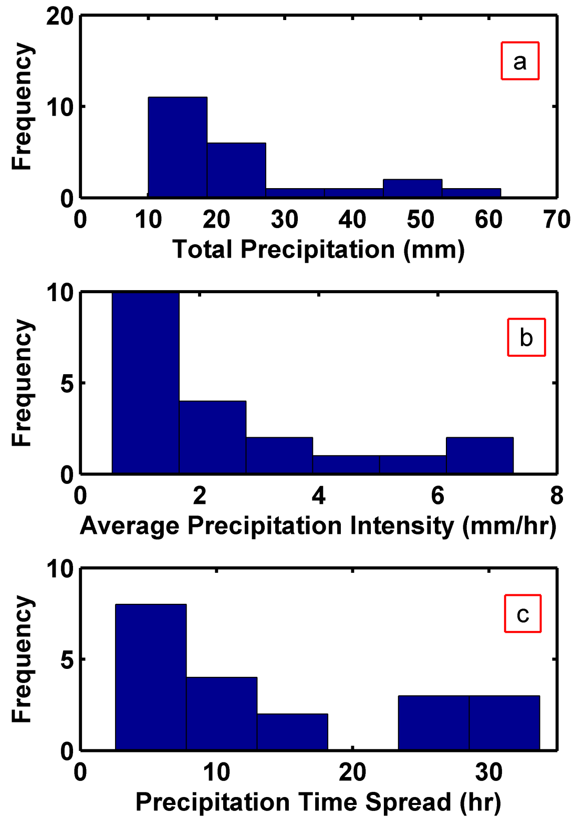


Fig. 3.4. Frequency histogram of the a) total precipitation, b) average precipitation intensity, and c) precipitation time spread for all events

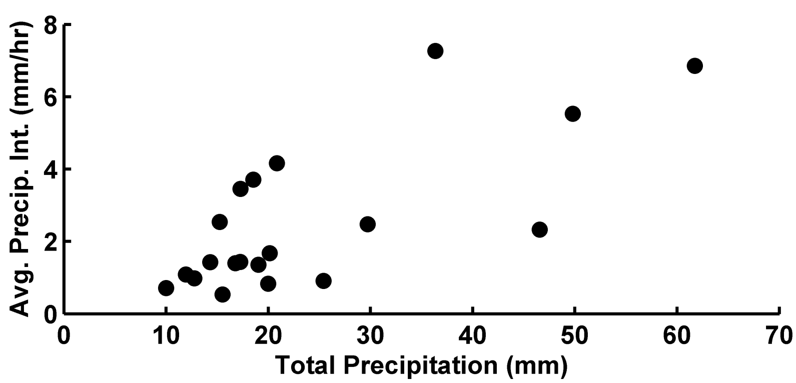


Fig. 3.5. Average precipitation intensity versus the total precipitation of each event.

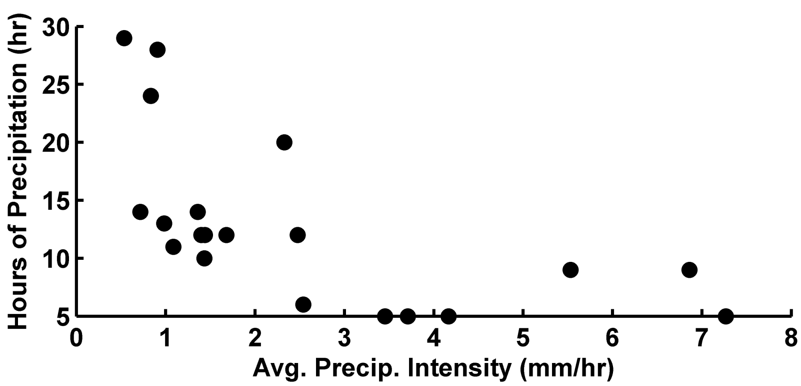


Fig. 3.6. Hours of precipitation versus average precipitation intensity of each event.

3.2.2 Drainage volumes and reduction in drainage

Figure 3.7 and table 3.4 illustrate that one overall effect of DWM during precipitation events is to reduce the volume of outflow from managed quadrants. However, the difference in the drainage volume between the managed and free draining quadrants is not consistent, as a multitude of factors can affect drainage volumes (table 3.4).

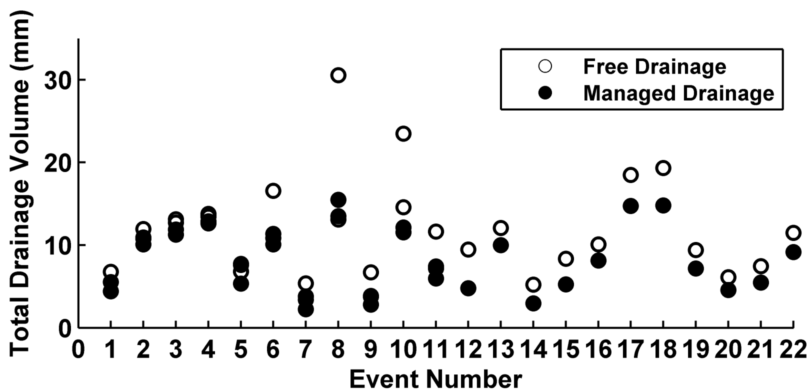


Fig. 3.7. Total drainage volume of all quadrants for all events.

Table 3.4.
Event difference in drainage volume between free and managed quadrants for events in which drainage data for all quadrants is available.

Event	Event Drainage Volume (mm)				Reduction in Drainage	
Quadrant	NW (Managed)	SE (Managed)	NE (Free)	SW (Free)	mm	%
1	4.4	5.5	6.8	5.5	1.2	19%
2	10.9	10.1	12.0	10.8	0.9	8%
3	11.3	11.9	13.1	12.7	1.3	10%
4	12.6	12.9	13.4	13.8	0.8	6%
5	5.4 ‘	7.7	7.6	6.8	0.7	9%
6	10.1	11.4	16.6	10.9	3.0	22%
7	2.2	3.8	5.4	3.4	1.4	31%
8	15.5	13.5	30.6	13.1	7.3	34%
9	2.8	3.8	6.7	3.9	2.0	38%
10	12.1	11.5	23.5	14.6	7.2	38%
11	6.0	7.2	11.7	7.4	3.0	31%
Average	-	-	-	-	2.6	22%
Median	-	-	-	-	1.4	22%

3.2.2.1 Effect of precipitation characteristics on drainage volumes

The three precipitation metrics are compared to drainage volume in figure 3.8. Precipitation depths does not show that there is a clearly discernible relationship (figure 3.8 a) although the locally weighted scatter plot smoothing (LOWESS) of the managed and free draining quadrant data suggests a tendency towards increasing drainage volumes with increasing precipitation. On average, across all events, the free draining quadrants have a higher drainage volume than managed drainage. The general difference is 1.3 to 2 mm during precipitation events that have totals between 10 and 20 mm of rainfall and 2.5 to 3 mm during precipitation events that have totals that are greater that 20 mm (figure 3.8 a).

The average precipitation intensity as a standalone variable does not have any observable impact on drainage volume (figure 3.8 b) while the precipitation time spread is a more important hydrologic control that affects drainage volumes as shown in figure 3.8 c. This can be expected as the more the precipitation is spread across the drainage event the more time is available for water to infiltrate and thus increase the drainage volume. There also appears to be a correlation between the total drainage volume and the event duration (figure 3.9).

All statistics were examined at a 5% significance level. Correlation analysis based on Kendall's tau rank correlation coefficient reveals that out of the four examined precipitation characteristics, the total precipitation, hours of precipitation, and the precipitation time spread are significantly correlated ($p \leq 0.05$) to the drainage volume in both managed and unmanaged quadrants with the latter having the highest Kendall's tau (table 3.5). On the other hand, the average precipitation intensity does not appear to have a direct effect on drainage volume ($p > 0.05$); this observation is further discussed in section 3.2.5 as precipitation intensity might have an important effect on overland flow generation.

Table 3.5.
Kendall's τ for rank correlation of precipitation characteristics, event duration, and antecedent conditions with drainage volume in managed and free quadrants.

Metric	Managed Drainage Volume		Free Drainage Volume	
	τ	p Value	τ	p Value
Total Precipitation	0.30	0.02	0.35	<0.01
Average Precipitation Intensity	-0.12	0.37	-0.04	0.77
Precipitation Time Spread	0.50	<0.01	0.41	<0.01
Hours of Precipitation	0.40	<0.01	0.30	0.02
Event Duration	0.74	<0.01	0.61	<0.01
Antecedent soil column moisture	0.16	0.21	-0.02	0.89
Antecedent water table height	0.18	0.18	0.07	0.57

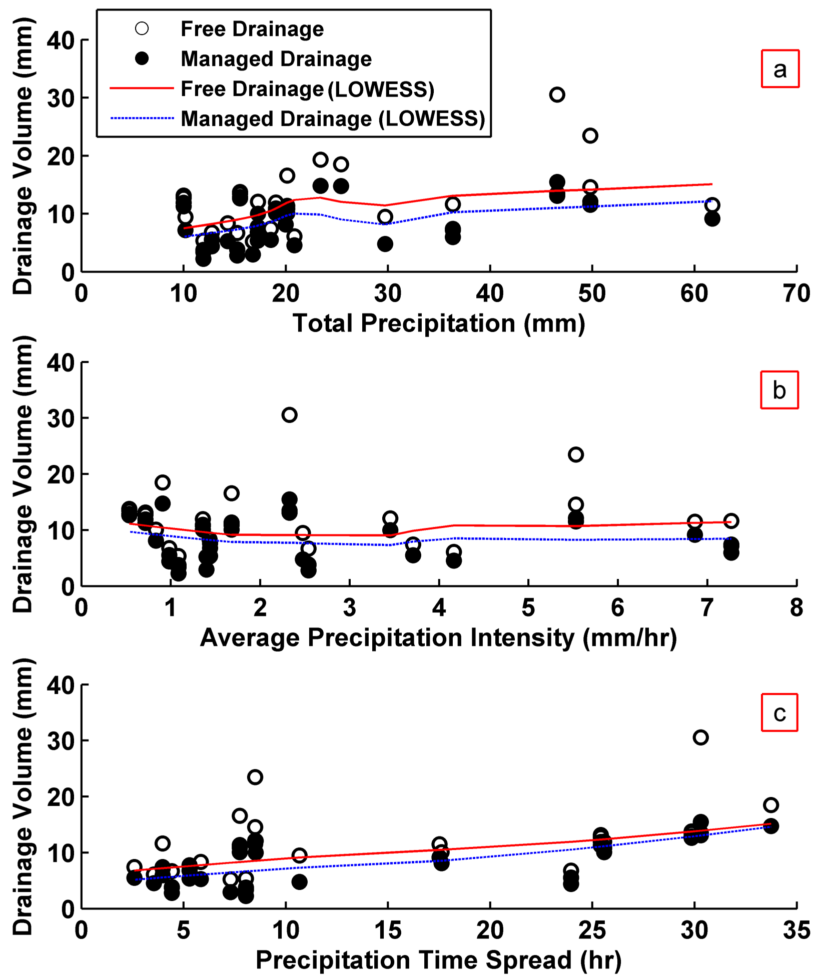


Fig. 3.8. Event drainage volume of managed and free draining quadrants versus a) total precipitation b) average precipitation intensity, and c) precipitation time spread.

3.2.2.2 Effect of antecedent conditions on drainage volumes

Figure 3.10 shows scatter plots of drainage volume versus the antecedent water table in each of the four quadrants. The antecedent water table height varies over a range of 0.7 m in the NW and SW quadrants, and over a narrower range of 0.1 m and 0.4 m, respectively, in the NE and SE quadrants. The NE quadrant is the driest

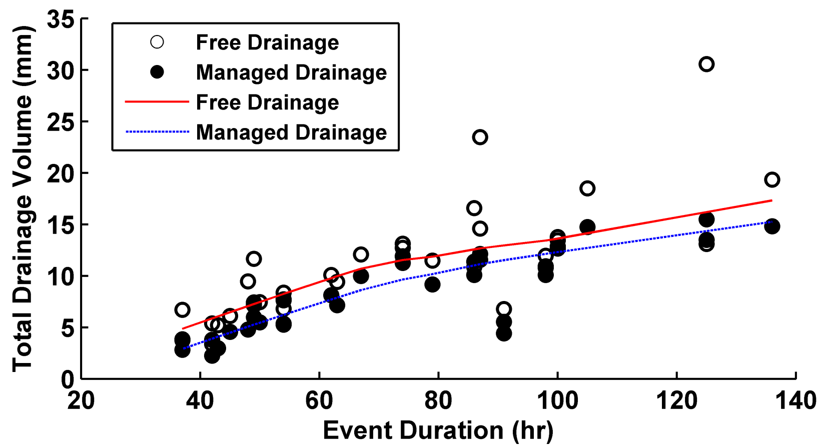


Fig. 3.9. Event drainage volumes of managed and free draining quadrants versus the event duration.

among all four quadrants and it has an event drainage volume that is greater than all other quadrants; this has also been observed by Brooks (2013). This might suggest that the NE quadrant is more efficient in draining water than its SW counterpart. The NE quadrant antecedent water table height fluctuates around a height of 0.05 m above the drain and it does not seem to affect the drainage volume in the quadrant (figure 3.10).

Kendalls tau (τ) rank correlation results of the correlation between antecedent conditions (both antecedent water table height and antecedent soil moisture) and drainage volumes are not statistically significant ($p > 0.05$) (table 3.5). The previous examination of the initial height of the water table's effect on drainage volumes (figure 3.10) suggests one probable reasons behind this statistical insignificance. The antecedent conditions in each quadrant appear to operate in loosely defined and different ranges; thus using data from both managed or free quadrants in the test fails to highlight if there is any relationship in the data (figure 3.10).

These results agree with the finding of Vidon and Cuadra (2010) who concluded that antecedent conditions cause some variability in the tile flow response but it is precipitation that is the main driver and predictor of volume for drainage events that happen during the fallow season.

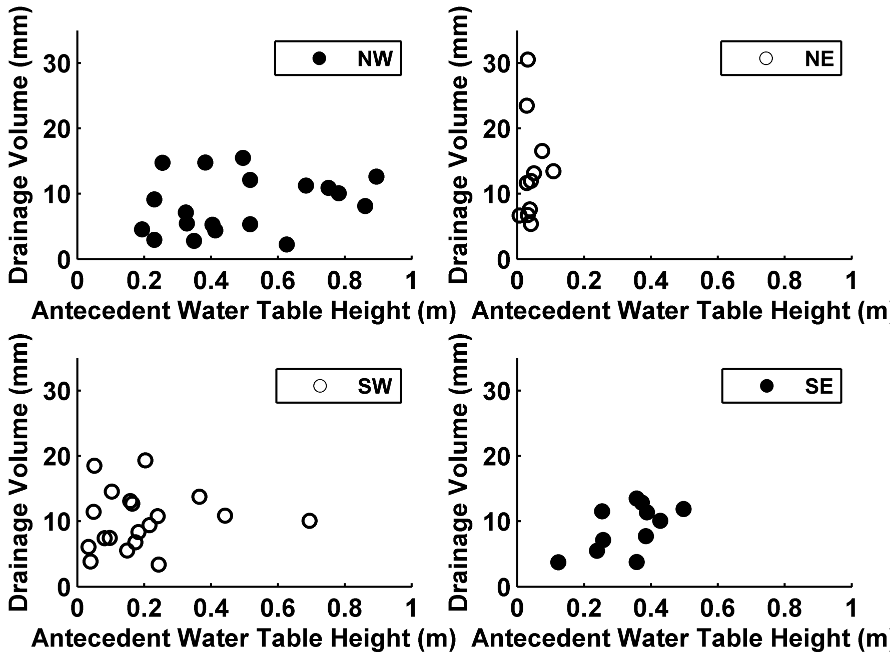


Fig. 3.10. Event drainage volumes of managed and free draining quadrants versus antecedent water table heights.

3.2.2.3 Effect of antecedent conditions on the reduction in drainage volumes

Reduction in drainage due to drainage water management from the 11 events in which drainage data for all quadrants is available is tabulated in table 3.4. The percentage reduction for each event is the reduction between the average of the drainage volume of the free draining quadrants and the average drainage volume of the managed quadrants. Event reduction ranged between 8% and 38%, with an average and standard deviation of 22% ± 12%.If the event reduction from the NW and SW pair from the remaining 11 events, in which the NE and SE data are missing, is to be averaged with the 11 events in which data from all quadrants are available then event reduction of the 22 events had an average of 25%, a value that is close to the average reduction of the 11 events in which drainage data for all quadrants is available.

As an alternative evaluation of event reduction in drainage volumes, all quadrants were paired with both of their counterparts (i.e. each freely drained was paired with both managed quadrants) and the percentage reduction in drain flow was calculated. The association between the percentage reduction in flow for each of the pairs, and precipitation characteristics and antecedent conditions was tested using Mann Kendall's non parametric test for correlation (table 3.6). Most results were not statistically significant, and variables that were statistically significant for one pair were not significant for the rest of the quadrant pairs (table 3.6). Such an inconsistency across the quadrant pairs might be expected partly because there is a small sample size of pairings, and because antecedent conditions and soil effective properties can vary significantly across the four quadrants thus increasing the variability in the observed results. However, to examine if there is a potential effect of antecedent conditions on drain reduction, scatter plots of the antecedent water table height of the managed quadrants versus the percent reduction in drain volume were plotted for all quadrant pairs (figure 3.11). The figure highlights that there is a relation, though not significant (table 3.6), between the antecedent water table and the NW/SW, SE/NE, and NW/NE paired percent drainage reductions. As expected, a lower antecedent water table in managed quadrants can result in greater reduction in drainage volumes.

Moreover, though the data is dearth and most results are statistically insignificant, table 3.6 shows that across three quadrant pairs higher precipitation time spread results in lesser reduction in drainage volume. This goes in line with the finding in section 3.2.2.1 that a higher precipitation time spread results in greater drainage volumes for both free draining and managed system. This might indicate that greater drainage volumes result in less drainage reduction; the hypothesis was tested by Kendalls tau rank correlation test between reduction pairs and drainage volumes of both managed and free draining quadrants. The test was statistically insignificant for both managed and free draining quadrants.

Table 3.6.
Kendall's τ for rank correlation of precipitation characteristics, event duration, and antecedent conditions with the percent reduction in drainage volume from the managed and free pairs.

Metric	NW/SW Pair	P Value	NW/NE Pair	P Value	SE/NE Pair	P Value	SE/SW Pair	P Value
Total Precipitation	-0.38	0.12	0.12	0.64	0.41	0.08	0.09	0.76
Average Precipitation Intensity	0.05	0.88	0.49	0.04	0.56	0.02	0.02	1.00
Precipitation Time Spread	-0.53	0.03	-0.38	0.12	-0.16	0.54	0.16	0.54
Antedent soil column moisture	-0.45	0.06	-0.24	0.36	0.24	0.36	0.42	0.09
Antecedent water table height	-0.31	0.24	-0.49	0.06	-0.40	0.10	0.00	1.00

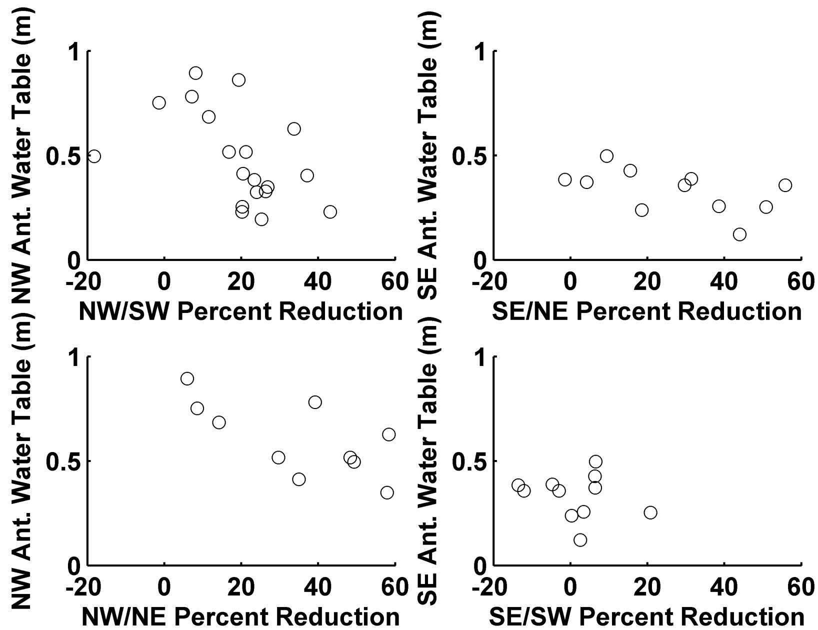


Fig. 3.11. Antecedent water table height of the managed quadrants versus the percent reduction in drain volume of all quadrant pairs.

Overall, there were no statistically significant correlations between antecedent conditions and drainage volumes in managed and free quadrants suggesting that the total precipitation and the precipitation time spread (hours of precipitation is integrated into the precipitation time spread measure) are more important hydrological controls that can significantly affect drainage volumes during drainage cycles. Moreover, there was no significant correlation between the total precipitation and the precipitation time spread indicating that the effect of each of these two characteristics on drainage volume is independent.

3.2.3 Peak drainage flow and reduction in peak drainage flow

The peak flow from the managed quadrants was lower than the freely draining quadrants in all events except the first event (figure 3.12 and table 3.7). The two managed quadrants are plotted separately as it appears that the NW quadrant has a quasi-constant peak flow throughout all the events while SE quadrant's peak flow has more fluctuations (table 3.7). This constant peak flow may be the result of the NW quadrant having a lower total hydraulic head at its outlet than the NE, SE, SW quadrants which results in a flow restriction.

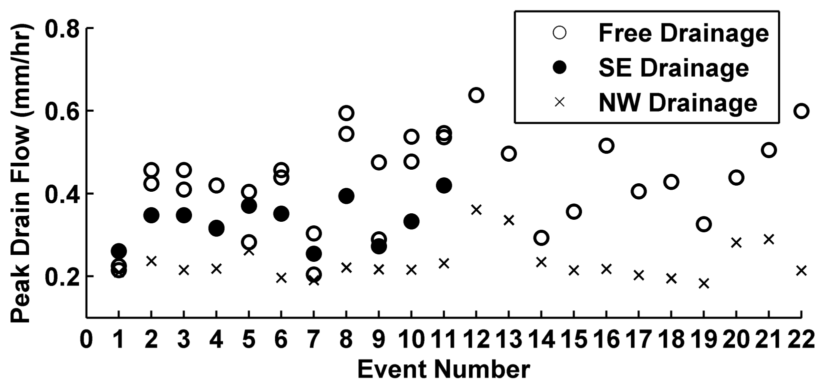


Fig. 3.12. Peak flows of managed and free draining quadrants for all events.

Table 3.7.
Event difference in peak flow between free and managed quadrants for events in which drainage data for all quadrants is available.

Event	Event Peak Flow (mm/hr)				Decrease in Peak Flow	
Quadrant	NW (Managed)	SE (Managed)	NE (Free)	SW (Free)	mm/hr	%
1	0.21	0.26	0.21	0.22	-0.02	-7%
2	0.24	0.35	0.42	0.46	0.15	34%
3	0.22	0.35	0.41	0.46	0.15	35%
4	0.22	0.32	0.32	0.42	0.10	28%
5	0.26	0.37	0.28	0.40	0.03	8%
6	0.20	0.35	0.44	0.46	0.17	39%
7	0.19	0.25	0.30	0.20	0.03	13%
8	0.22	0.39	0.59	0.54	0.26	46%
9	0.22	0.27	0.48	0.29	0.14	36%
10	0.22	0.33	0.48	0.54	0.23	46%
11	0.23	0.42	0.54	0.55	0.22	40%
Average	-	-	-	-	0.13	29%
Median	-	-	-	-	0.15	35%

3.2.3.1 Effect of precipitation characteristics and antecedent conditions on peak flows

On average, across all events, the free draining quadrants have a higher peak flow than managed drainage (figure 3.13). The general difference is 0.1 to 0.2 mm/h during precipitation events that have totals between 10 and 20 mm of rainfall and 0.2 to 0.35 mm during precipitation events that have totals that are greater that 20 mm (figure 3.13 a). On the other hand, the peak flow of the managed quadrants is not influenced by any of the three precipitation characteristics. The peak drain flow of free draining quadrants increases with increasing precipitation depth and average precipitation intensity (figure 3.13 a, b). No quadrants appear to be affected by the precipitation time spread as indicated by the LOWESS line (figure 3.13 c).

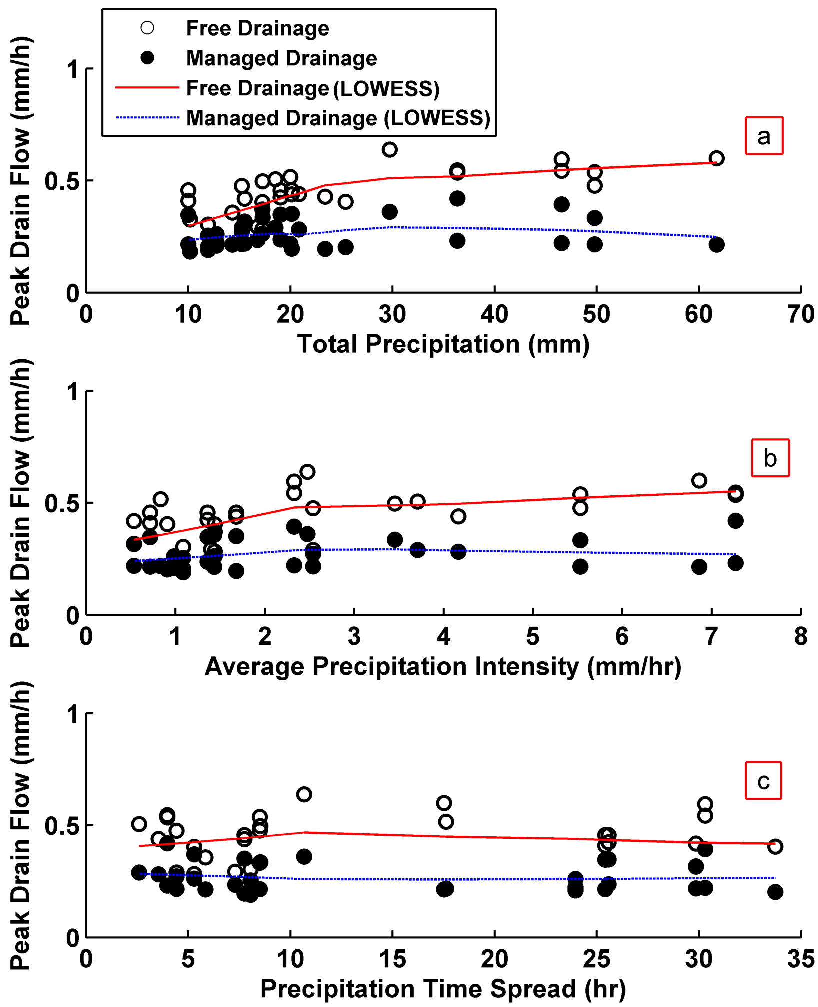


Fig. 3.13. Event peak flow of managed and free draining quadrants versus a) total precipitation, b) average precipitation intensity, and c) precipitation time spread.

Correlation analysis based on Kendall's tau rank correlation coefficient confirmed that total precipitation and average precipitation intensity are important event characteristics that affect the peak flow of free draining quadrants ($p \leq 0.05$) (table 3.8). The average precipitation intensity correlates with peak flow in free draining quadrants; such a relation is possible as higher than average precipitation intensities can maximize the infiltration rate up to the infiltration capacity to the soil, thus maximizing peak flow rate. In their correlation analysis of eight spring storms, Vidon and Cuadra (2010) found a significant correlation between the peak flow and total precipitation depth but no correlation with the average precipitation intensity. It might be the case that their sample size of eight storms does not have similar characteristics to precipitation events that are examined here, moreover their paper did not specify how the average precipitation intensity was calculated.

In managed quadrants, the total precipitation and average precipitation intensity did not show any correlation with the peak flow; such a result might be attributed to the attenuation of peak flows that is due to management. The precipitation time spread, hours of precipitation, event duration, and antecedent water table height fail to reject the null hypothesis that there was no correlation with peak flow rate at a 0.05 significance level in both free draining and managed quadrants. In contrast, there is a correlation between peak flow in the managed quadrants and the antecedent soil moisture; it might be that the column soil moisture is more representative of antecedent conditions than the water table height above the drain as it accounts for all the water that is in the column in both the saturated and unsaturated zones in the soil. These results suggest that in managed quadrants, precipitation characteristics do not influence the peak flow as much as antecedent conditions do. To provide an explanation for this result, it can be argued that the more moist the soil column is, the less infiltration water is required to fill up the pore space and make the water table rise above the board height. Accordingly, more water is available to contribute to the increase of the pressure head at the board level thus leading to an increase in the peak flow. Numerical modeling and more experimental data can help in further validating this suggested explanation. If drainage water management is to be used to reduce peak flows, then boards can be raised and then lowered before precipitation events to drain the held back water and thus increase the storage capacity of the system. During anticipated precipitation events, such 'pre-draining' could be important in further reducing peak flows from the system by providing temporary stormwater storage, much as detention ponds are using in urban environments to buffer the impact of new developments.

Table 3.8.
Kendall's τ for rank correlation of precipitation characteristics, event duration, and antecedent conditions with peak flow in managed and free quadrants.

Metric	Managed Peak Flow		Free Peak Flow	
	τ	p Value	τ	p Value
Total Precipitation	0.16	0.19	0.54	<0.01
Average Precipitation Intensity	0.15	0.24	0.42	<0.01
Precipitation Time Spread	-0.08	0.53	0.02	0.89
Hours of Precipitation	-0.09	0.50	-0.14	0.31
Event Duration	-0.02	0.88	0.07	0.59
Antecedent soil column moisture	0.40	<0.01	0.23	0.06
Antecedent water table height	-0.14	0.28	0.00	1.00

3.2.3.2 Event reduction in peak flow

In the 11 events in which drainage data for all four quadrants are available, the average event decrease in peak flow between the average peak flow of the free draining quadrants and the average peak flow of the managed quadrants is 29% ± 16% and it ranges between -7% and 46% (table 3.7). If the event peak flow reduction from the NW and SW pair of the remaining 11 events, in which the NE and SE data are missing, is averaged with the 11 event in which data from all quadrants are available then the mean decrease in peak flow would be 37% which is an 8% increase from the 11 event mean.

To sum up, peak flows in free draining quadrants were positively affected by higher precipitation and the average precipitation intensity that can maximize infiltration.

In managed quadrants, the antecedent soil moisture appears to play a more important role than precipitation characteristics in affecting peak flows.

3.2.4 Time to peak and reduction in the time to peak

Drainage water management generally increased the time to peak of drain flow during most of the events (figure 3.14 and table 3.2.4).

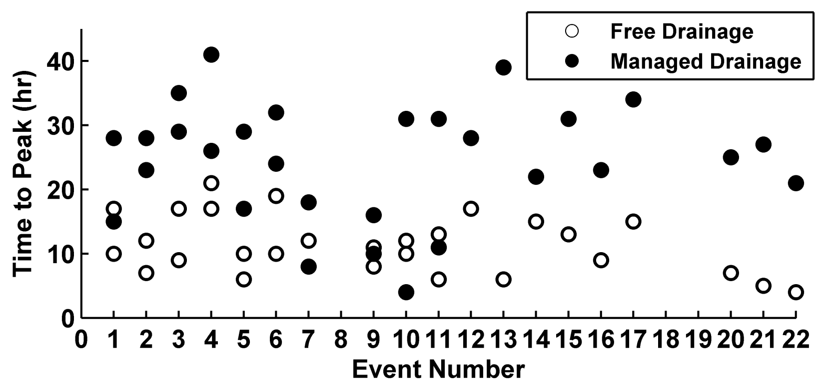


Fig. 3.14. Time to peak of managed and free draining quadrants for all events.

Table 3.9.
Event increase in time to peak for events in which drainage data for all quadrants is available.

Event	Event Time to Peak (hr)				Increase in Time to Peak	
Quadrant	NW (Managed)	SE (Managed)	NE (Free)	SW (Free)	Hours	%
1	28	15	17	10	8	59%
2	23	28	12	7	16	169%
3	29	35	17	9	19	146%
4	26	41	21	17	15	76%
5	29	17	10	6	15	188%
6	24	32	19	10	14	93%
7	18	8	12	8	3	30%
8†	-	-	-	-	-	-
9	16	10	11	8	4	37%
10	31	4	10	12	7	59%
11	31	11	13	6	12	121%
Average	-	-	-	-	11	98 %
Median	-	-	-	-	13	85 %

† The time to peak of event 8 has been discarded because it is not one of a typical hydrograph.

3.2.4.1 Effect of precipitation characteristics on the time to peak

The total precipitation depth as a standalone variable did not appear to influence the time to peak of drain flow (figure 3.15 a). On average, throughout all events and precipitation depths, there is a 10 hour difference between the time to peak of managed and free draining quadrants. The scatter plot of the time to peak and the average precipitation intensity along with the locally weighted scatter plot smoothing indicate that the time to peak decreases with the increase of average precipitation intensity (figure 3.15 b). It also appears that there is a positive correlation between the precipitation time spread and time to peak (figure3.15 c).

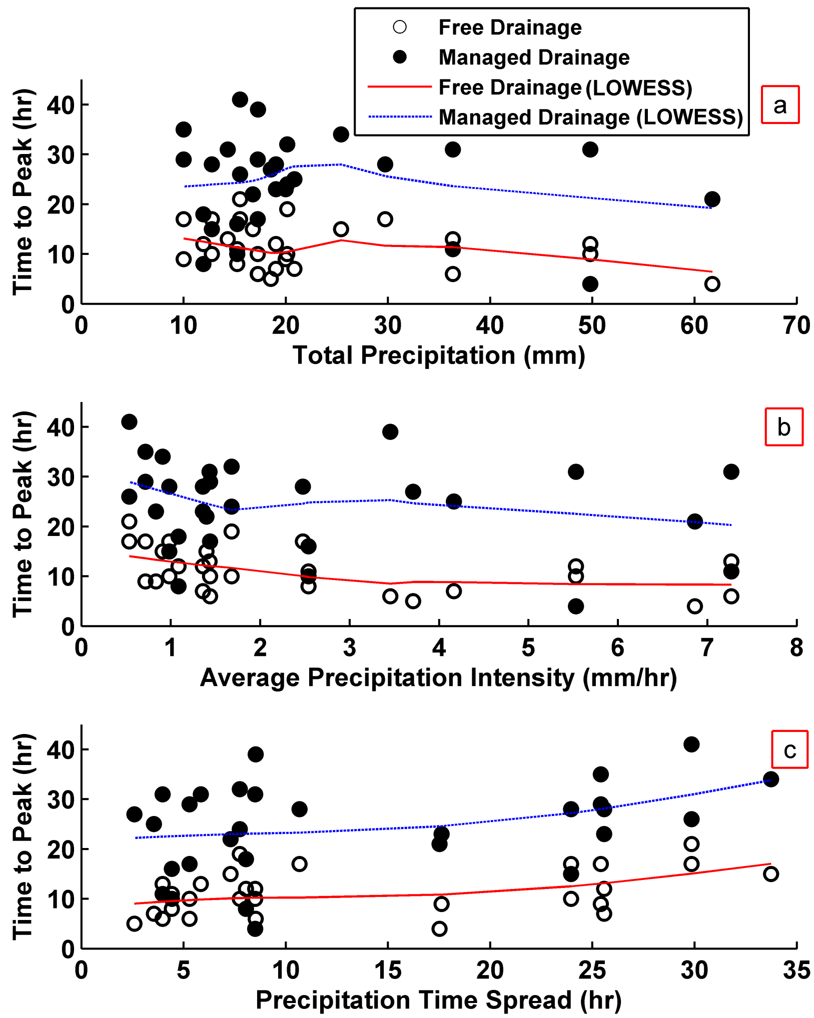


Fig. 3.15. Event time to peak of managed and free draining quadrants versus a) total precipitation, b) average precipitation intensity, and c) precipitation time spread.

Correlation analysis based on Kendall's tau rank correlation coefficient confirm the observation that total precipitation depth does not influence the time to peak of drain flow in both managed and free draining quadrants (table 3.10). In free quadrants, there is a statistically significant negative correlation between the average precipitation intensity and the time to peak, and a statistically significant positive correlation between both the precipitation time spread and the hours of precipitation, and time to peak. In contrast to what has been observed with peak flows, the time to peak decreases with higher average precipitation intensities that can maximize infiltration rate thus leading to a decrease of the time to peak in the resulting drainage hydrograph. Moreover, the more precipitation is spread over the course of the drainage event the longer it takes for the drain hydrograph to reach its peak. All correlation results in the managed quadrants are statistically insignificant; a reason for this might be that the complex interaction between different board heights, the variability in antecedent conditions, and the effect of various precipitation characteristics can mask the behavior of the time to peak in managed quadrants (figure 3.16).

Table 3.10.
Kendall's τ for rank correlation of precipitation characteristics, event duration, and antecedent conditions with the time to peak in managed and free quadrants.

Metric	Managed Time to Peak		Free Time to Peak	
	τ	p Value	τ	p Value
Total Precipitation	0.03	0.84	-0.14	0.33
Average Precipitation Intensity	-0.17	0.22	-0.34	0.01
Precipitation Time Spread	0.22	0.10	0.28	0.04
Hours of Precipitation	0.20	0.14	0.38	0.01
Event Duration	0.30	0.13	0.21	0.12
Antecedent soil column moisture	-0.18	0.18	-0.26	0.05
Antecedent water table height	0.21	0.15	-0.10	0.49

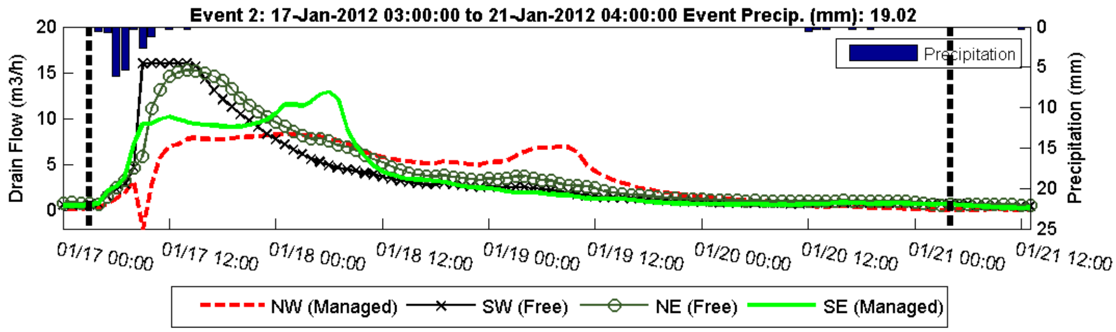


Fig. 3.16. Example of how management results in a delayed time to peak in drainage hydrographs.

3.2.4.2 Effect of antecedent conditions on the time to peak

Scatter plots of time to peak versus antecedent soil moisture for all quadrants do not show the presence of a relation between the two variables (figure 3.17). An important consideration is that all events that were examined in this study occurred between October and June, a period in which variability in the column soil moisture is low (figure 2.11). Accordingly no comparison can be made to studies that have highlighted the seasonal effect (mainly summer versus winter) of antecedent conditions on the lag time of the system.

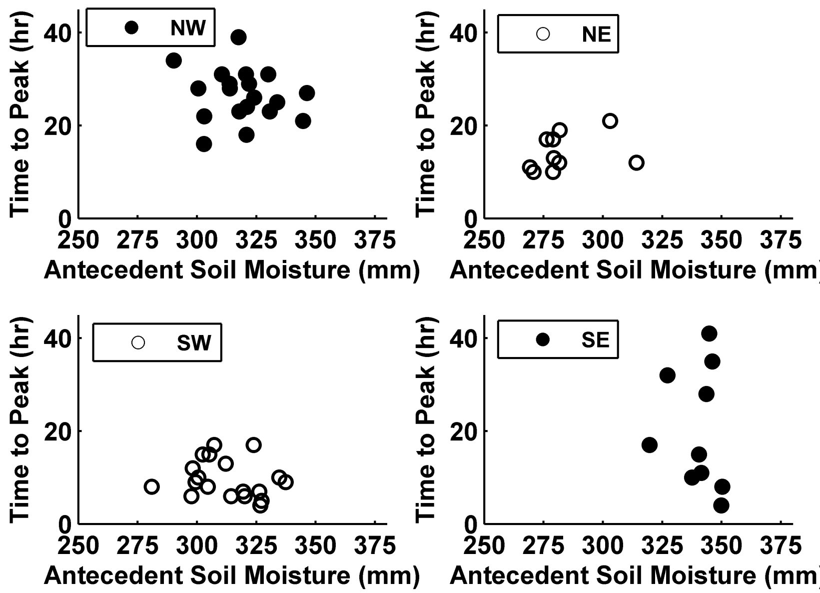


Fig. 3.17. Event time to peak of managed and free draining quadrants versus antecedent soil moisture

3.2.4.3 Event increase in the time to peak

In the 10 events in which drainage data for all quadrants is available, the average event increase in the time to peak between the average time to peak of the free draining quadrant and the average time to peak of the managed quadrants is 98% ± 52%. If the event increase in time to peak between the NW and SW from the remaining 9 events, in which the NW and SE quadrant data is missing, is to be averaged with the 10 events in which data from all quadrants is available then the increase in the time to peak averages 168%. This increase of 70% in the average time to peak comes as a result of the SW quadrant having a generally lower time to peak than it's NE counterpart. Figure 3.16 illustrates how drainage water management flattens out the drainage hydrograph such that the peak flow is pushed back.

To sum up, the time to peak in free draining quadrants decreased with higher average precipitation intensity and increase with higher precipitation time spread.

The insignificant statistical correlations between the time to peak and the hydrologic characteristics in managed quadrants were attributed to the presence of control structures, and antecedent conditions that can attenuate time to peak and mask the effect of independent variable.

3.2.5 Overland flow and surface ponding

3.2.5.1 Effect of precipitation characteristics on the maximum water table position

Figure 3.18 shows that the water table rises above the soil surface in the managed quadrants across the full range of precipitation characteristics. Correlation of the maximum water table and precipitation time spread (table 3.11) agrees with the observation on precipitation time spread and drainage volumes (section 3.2.2.1). The precipitation with the maximum water table shows two different results in managed and free draining quadrants. The positive correlation between the maximum water table and the total precipitation in the free quadrant can be expected. While in managed quadrants, there was no statistically significant correlation between the total precipitation and the maximum water table. Since the water table in the managed quadrants is controlled by the boards and not the water input to the system then a bivariate correlation between the two variables might not be detected with such a small dataset.

The maximum water table height in managed quadrants is positively correlated with the antecedent water table height. However, a negative correlation is observed with maximum water height and the antecedent soil moisture, which is contrary to what can be expected. Figure 3.19 illustrates that the antecedent soil moisture in each of the managed quadrants operates in a different range. When the maximum water table height of the two managed quadrants are plotted together versus their corresponding antecedent soil moisture they show a monotonically decreasing relation.

On the other hand, when each maximum water table height and antecedent soil moisture pair is examined individually, it appears that the maximum water table increases as the antecedent soil moisture increases (figure 3.19). This highlights the role of antecedent conditions and the board height in the structure on the maximum water table in managed quadrants.

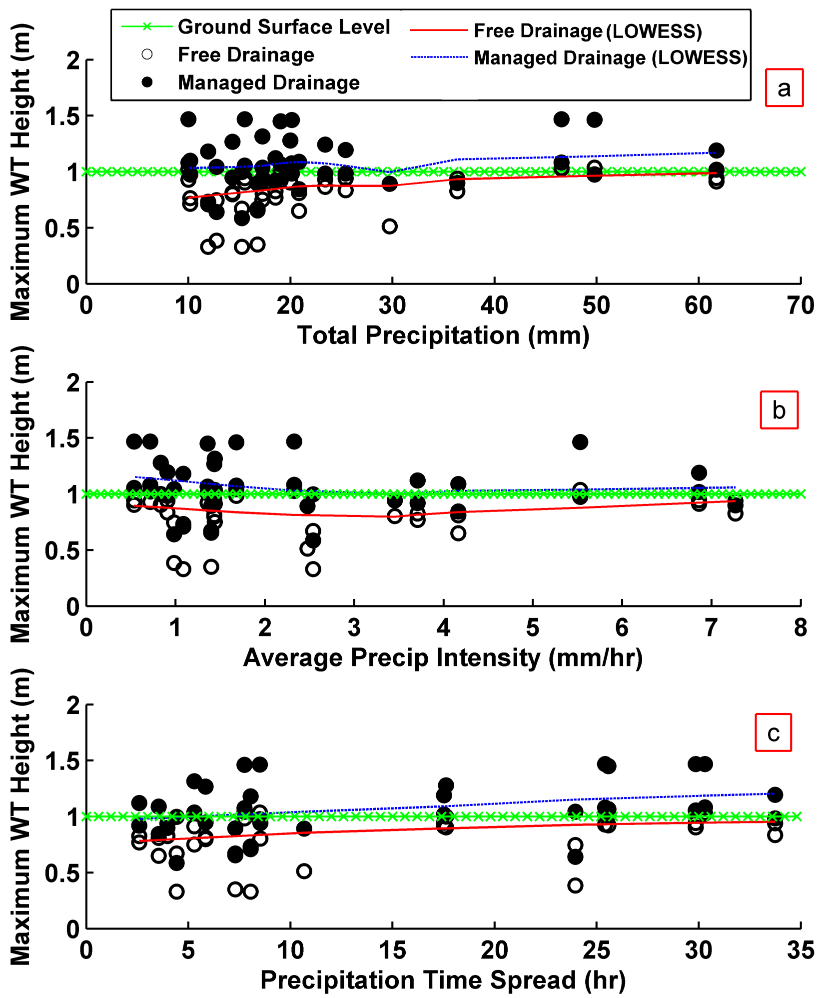


Fig. 3.18. Maximum event water table height of managed and free draining quadrants versus a) total precipitation, b) average precipitation intensity, and c) precipitation time spread.

Table 3.11.
Kendall's τ for rank correlation of precipitation characteristics, event duration, and antecedent conditions with maximum water table height in managed and free quadrants.

Metric	Managed Max. Water Table		Free Max. Water Table	
	τ	p Value	τ	p Value
Total Precipitation	0.08	0.48	0.36	0.00
Average Precipitation Intensity	-0.13	0.29	0.03	0.81
Precipitation Time Spread	0.25	0.03	0.28	0.02
Hours of Precipitation	0.26	0.03	0.21	0.09
Event Duration	0.34	0.00	0.48	0.00
Antecedent soil column moisture	-0.25	0.02	0.18	0.10
Antecedent water table height	0.42	0.00	0.18	0.11

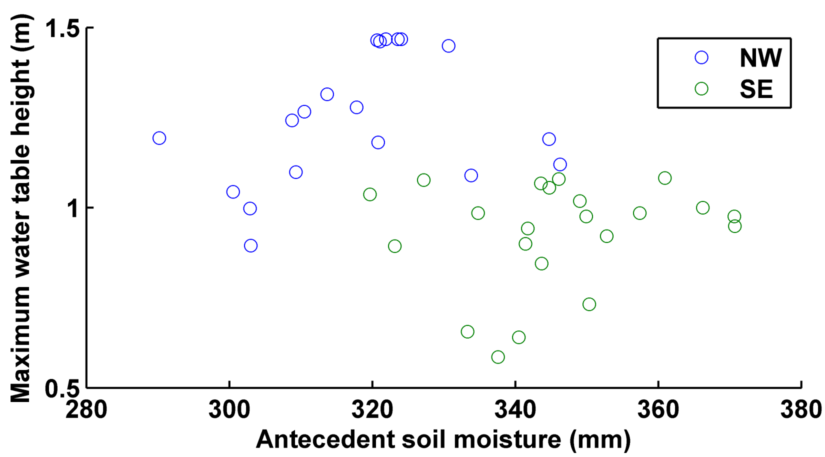


Fig. 3.19. Maximum event water table height of the two managed quadrants versus their corresponding antecedent soil moisture.

3.2.5.2 Infiltration Excess Overland Flow

The finding that the average precipitation intensity was not correlated with drainage volume (section 3.2.2.1) might suggest that the higher average precipitation intensities exceeded the infiltration rate, thus promoting an increase in Hortonian overland flow generation (Robinson et al., 1999; Nearing et al., 2005; Dunkerley, 2012; Wei et al., 2014). A scatter plot of the drainage to precipitation ratio versus the average precipitation intensity (figure3.20 a) shows that the drainage to precipitation ratio decreases with increasing average precipitation intensity, indicating that high average precipitation intensities result in less drainage and more overland flow. Kendall's Tau test for rank correlation indicates that there is a significant negative correlation ($p<0.01$) between the average precipitation intensity and the drainage to precipitation ratio in free draining (τ =-0.46) and managed quadrants (τ =-0.53).

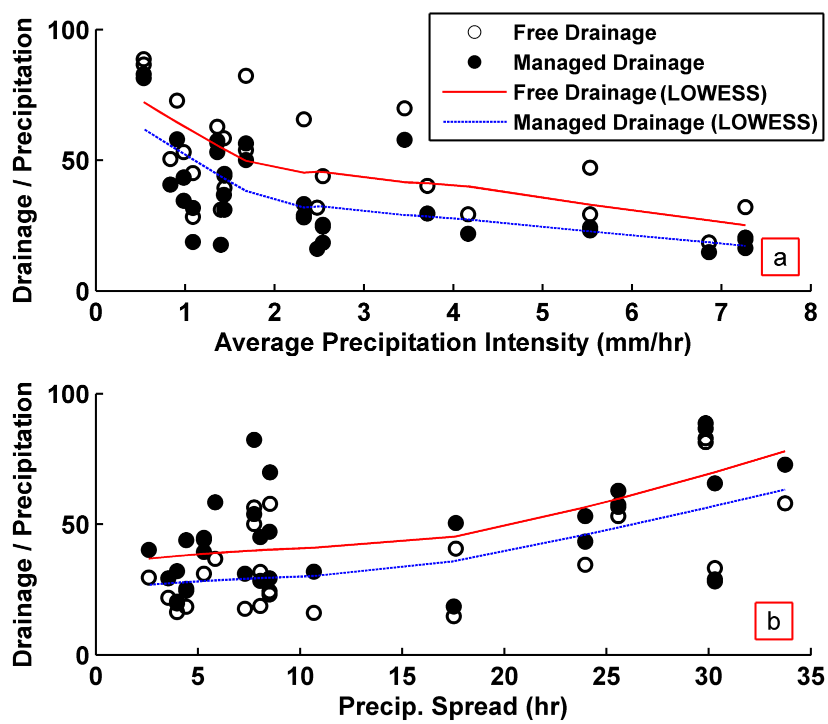


Fig. 3.20. Event drainage to precipitation ratio of managed and free draining quadrants versus a) the average precipitation intensity and b) the precipitation time spread.

Figures 3.21 a and b illustrate events 2 and 21 that had, respectively, a low (1.35 mm/hr) and higher (3.7 mm/hr) average precipitation intensity, and a comparable precipitation depth. Event 2 had a precipitation depth of 19.0 mm and a resulting drainage volume of 10.9 mm and 10.8 mm, respectively in the NW and SW quadrants.

Event 21 had a precipitation depth of 18.5 mm and a resulting drainage volume of 5.5 mm and 7.4 mm in the NW and SW quadrants. The SW quadrant of the two events had a similar antecedent soil moisture (326.5 mm), while in the NW quadrant event 21 had a 15 mm higher antecedent soil moisture than event 2. Even though there was some difference in the antecedent soil moisture in the NW quadrant, this comparison highlights how a higher average precipitation intensity resulted in a lower drainage volume and thus a likely increase in overland flow.

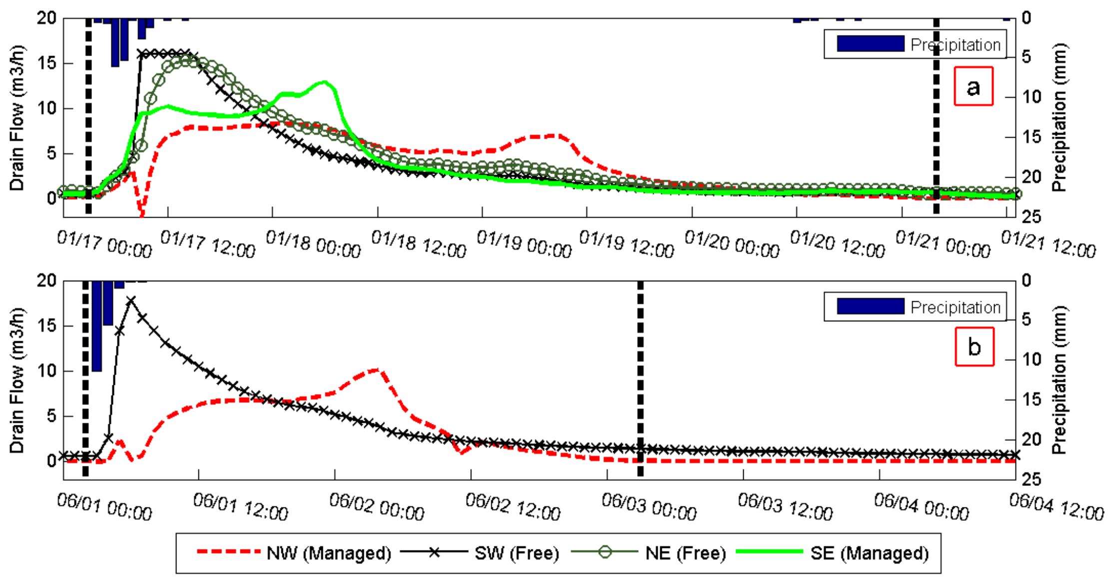


Fig. 3.21. Two events that had a high and low average precipitation intensities: (a) event 2 had an average precipitation intensity of 1.35 mm/hr while (b) event 21 had an average precipitation intensity of 3.70 mm/hr.

3.2.5.2.1. Scatter plot of change between the maximum and antecedent soil moisture versus precipitation as an indication of infiltration excess

For a better understanding of how infiltration excess occurs on Field W, scatter plots of the change between the maximum and antecedent soil moisture versus precipitation in each quadrant were examined (figure 3.22). In all quadrants, the difference between the maximum soil moisture and the antecedent soil moisture was greater than the total precipitation depth. A number of reasons can result in such discrepancies. The soil moisture sensors might be reading high soil moisture values because they lie in areas in which macropores are predominant. Another reason might be that integrating the soil moisture readings at five depths into column soil moisture is not representative of the true moisture in the soil profile. It is also likely that there is a problem of undercatch in the precipitation measurement that could be investigated. The spatial representativeness of one nest of soil moisture sensors in each quadrant can be also be put to question.

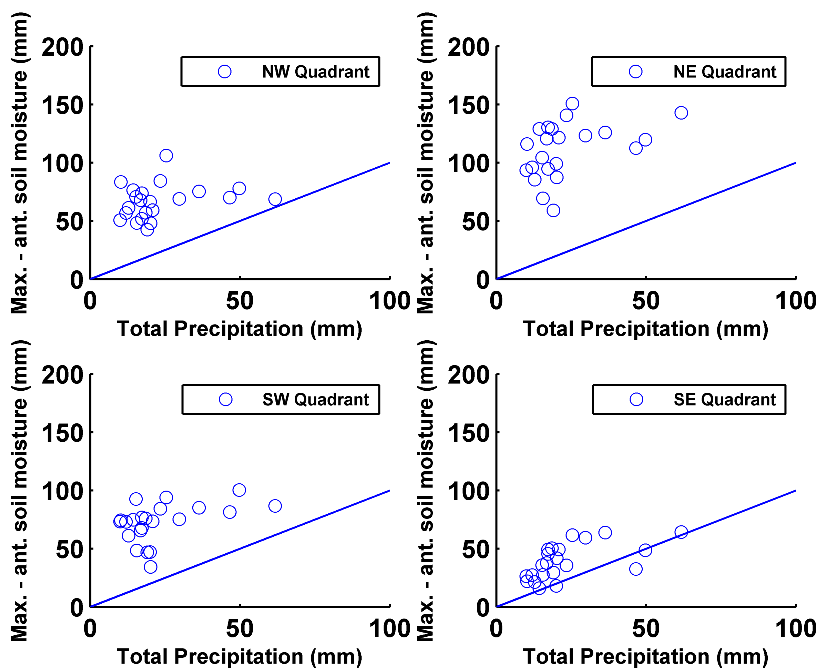


Fig. 3.22. Scatter plots of change between the maximum and antecedent soil moisture versus precipitation. The lines show a one to one slope and a y intercept of zero.

3.2.5.3 Saturation Excess Overland Flow

In the 22 events that were examined, the maximum height of the water table as recorded by the water level sensors inside observation wells in managed quadrants generally rose above ground surface while the maximum height of the water table in free quadrants stayed mostly below the ground surface (figure 3.23). The maximum height of the water table does not appear to influence the peak drain flow in the managed quadrants while the opposite is observed in free quadrants. It appears that the higher the maximum water table is in free quadrants the higher the peak flow becomes. After that the maximum water table height in free quadrants reaches the level of the ground surface the peak flow keeps increasing without any increase in the maximum water table height.

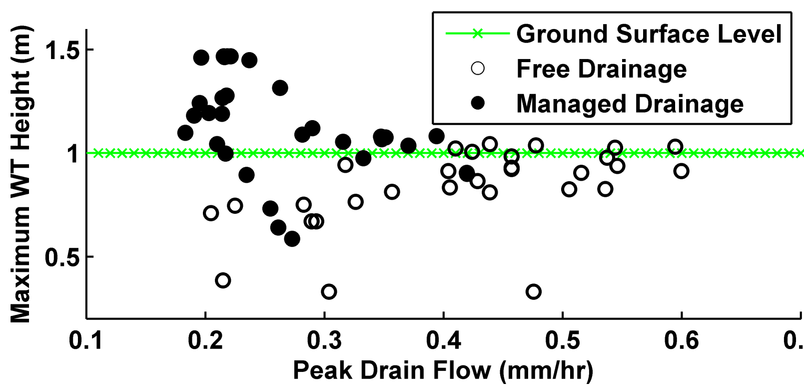


Fig. 3.23. Scatter plot of peak flow versus the event maximum water table height.

During the 22 events the managed quadrants had a total of 529 hours of water table being above the ground surface versus a total of 105 hours for the free draining quadrants (table 3.12). Such an observation, though not a direct measurement of ground surface ponding indicates that managed subsurface drainage leads to an increase of the variable. A further examination of the hours of ponding and the average precipitation intensity reveals that the events that had surface ponding occur mostly when the average precipitation intensity is low (figure 3.24 a and b). These events correspond to events that have, in general, a high drainage to precipitation ratio (figure 3.20 a) and a high precipitation time spread (figure 3.20 b) that correlates with greater drainage volumes, which leads to the conclusion that this ponding is a result of saturation excess.

Table 3.12.
Hours of water table being above ground surface for all events in each quadrant.

Event	Hours of water table being above surface			
Quadrant	NW (Managed)	SE (Managed)	NE (Free)	SW (Free)
1	0	0	0	0
2	40	20	9	0
3	51	28	14	0
4	58	27	0	0
5	21	14	0	0
6	26	27	16	8
7	0	0	0	0
8	54	20	21	7
9	0	0	0	0
10	57	5	23	7
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	2	0	0	0
16	16	12	0	0
17	0	22	0	0
18	0	19	0	0
19	0	7	0	0
20	0	0	0	0
21	0	0	0	0
22	0	5	0	0
Total	325	206	83	22

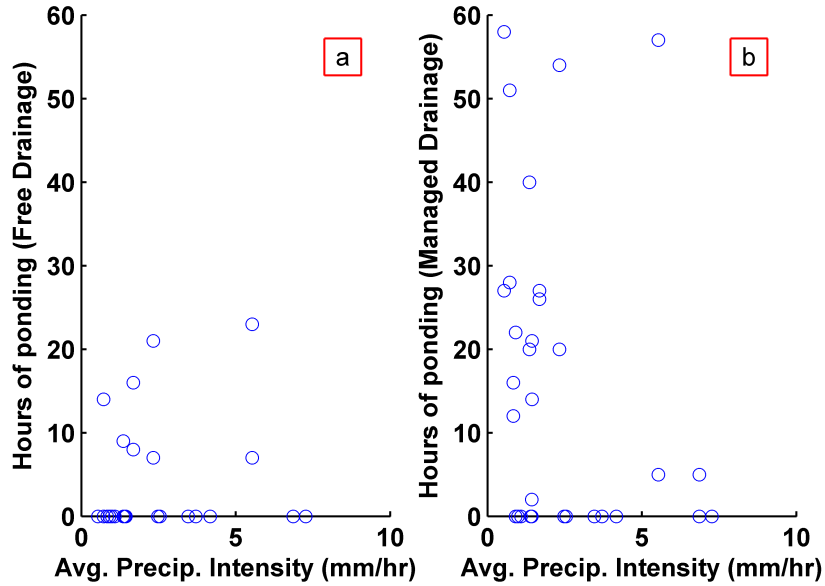


Fig. 3.24. Hours of ponding of a) free and b) managed quadrants versus the average precipitation intensity.

In this discussion the effect of precipitation characteristics on the maximum water table height, and the mechanisms of overland flow and ponding were analyzed. The water table reached the ground surface across all ranges of precipitation characteristics. Higher precipitation intensities decreased the drainage to precipitation ratio which suggests overland flow on both managed and free draining quadrants. If such infiltration excess overland flow occurred, it could affect the entire area, filling depressions and generating runoff leaving the field. Saturation excess ponding (and possibly overland flow) occurred mostly in managed quadrants and in events that have low average precipitation intensities, and high precipitation time spreads. In such events, the two managed quadrants had more hours of water table being above the ground surface than the free draining quadrants. Since observation wells are used as indicators of ponding, it may also be the case that events that have low average precipitation intensities are generating infiltration excess runoff from high points in the field that flows into lower points where the observation well is locating thus contributing to the observed ponding. Accordingly, the mechanisms of infiltration excess overland flow and saturation excess overland flow exist but cannot be exactly distinguished. This generally agrees with field observations of Gaynor et al. (2002) and Drury et al. (2009) in which they noted that managed drainage increases runoff. Such a behavior of the system has implications on water quality that need to be accounted for as surface runoff generally has a lower N and higher phosphorous concentration than drain water. Studies on the water quality aspects of drainage water management consider such implications in their nutrient accounting.

3.3 References

Drury, C., Tan, C., Reynolds, W., Welacky, T., Oloya, T., and Gaynor, J. (2009). Managing tile drainage, subirrigation, and nitrogen fertilization to enhance crop yields and reduce nitrate loss. *Journal of environmental quality*, 38(3):1193–1204.

Dunkerley, D. (2012). Effects of rainfall intensity fluctuations on infiltration and runoff: rainfall simulation on dryland soils, fowlers gap, australia. *Hydrological Processes*, 26(15):2211–2224.

G. M. Bonnin, D. Martin, B. Lin, T. Parzybok, M. Yekta, and D. Riley, NOAA, National Weather Service, Silver Spring, Maryland (2006 (accessed May 7, 2014)). *Precipitation-Frequency Atlas of the United States, NOAA Atlas 14, Volume 2, Version 3.0*. http://www.nws.noaa.gov/oh/hdsc/PF_documents/Atlas14_Volume2.pdf.

Gaynor, J., Tan, C., Drury, C., Welacky, T., Ng, H., and Reynolds, W. (2002). Runoff and drainage losses of atrazine, metribuzin, and metolachlor in three water management systems. *Journal of environmental quality*, 31(1):300–308.

Nearing, M., Jetten, V., Baffaut, C., Cerdan, O., Couturier, A., Hernandez, M., Bissonnais, Y. L., Nichols, M., Nunes, J., Renschler, C., Souchre, V., and van Oost, K. (2005). Modeling response of soil erosion and runoff to changes in precipitation and cover. *CATENA*, 61(23):131 – 154. Soil Erosion under Climate Change: Rates, Implications and Feedbacks Soil Erosion under Climate Change: Rates, Implications and Feedbacks.

Robinson, M., Rycroft, D., Skaggs, R., Schilfgaarde, J. v., et al. (1999). *The impact of drainage on streamflow.* American Society of Agronomy.

Wei, W., Jia, F., Yang, L., Chen, L., Zhang, H., and Yu, Y. (2014). Effects of surficial condition and rainfall intensity on runoff in a loess hilly area, china. *Journal of Hydrology*, 513(0):115 – 126.

4. CONCLUSION AND FUTURE RESEARCH

4.1 Conclusion

This purpose of this study was to gain better understanding of the hydrologic controls that regulate outflow from managed and free draining subsurface drainage systems from a monitoring site located at the Davis Purdue Agricultural Center in east central Indiana. Collected data were drainage, precipitation, water table depth, and soil moisture. The collected data required the handling, processing, and analysis in a consistent manner to ensure the reproducibility and the management of all data operations. Hydrological metrics were extracted and analyzed from 22 wet season drainage outflow events in the monitored in two free draining and two managed drainage subsurface systems. Before discussing conclusions, it is important to highlight the limitations of this study. The drainage events examined in this study are selected from the wet time of the year (with the exception of a few events in May and June) in which most of drainage events occurred and in which a better understanding of the hydrology of managed and free draining subsurface drainage systems is important to understanding water quality implications. Doing an event analysis does not capture the entire flow record, and some percentage of the flow is not included. This percentage of flow that is not captured is greater in free drainage than in managed drainage. This field was not designed to be hydrologically isolated and there might be run-on or runoff that was not measured. The study resulted with the following conclusions:

1. Throughout the events, drainage volume and peak flows in managed subsurface drainage systems were respectively 22% ± 12% and 29% ± 16% lower than in free draining subsurface drainage systems, and time to peak in managed subsur-

face drainage systems was 98% ± 52% higher than in free draining subsurface drainage systems.

2. Analysis focused on understanding how multiple factors affect variability in drainage characteristics. Precipitation characteristics played a major role in determining the drainage volume in managed and free draining quadrants. Higher total precipitation and precipitation time spread promote more infiltration throughout the course of the event and thus greater drainage volumes in managed and free draining systems, while the average precipitation intensity did not greatly affect drainage volumes.

3. Peak flows in free draining quadrants were positively correlated with higher precipitation and average precipitation intensity. In managed quadrants, the antecedent soil moisture appears to play a more important role in affecting peak flows than precipitation characteristics.

4. The time to peak in the free draining quadrants decreases with higher average precipitation intensity and increases with higher precipitation time spread. No significant correlations were found between the time to peak and hydrologic characteristics in the managed quadrants, this was attributed to the presence of control structures, and their interplay with antecedent conditions that add further complexity to the system thus masking the behavior of single independent variables.

5. The analysis of the mechanisms of infiltration excess overland flow and saturation excess overland flow in the managed and free draining quadrants showed that the two mechanisms took place. As the average precipitation intensity increases the runoff potential increases on both managed and free draining quadrants. Saturation excess ponding and possibly overland flow occurs as a result in events that have a low average precipitation intensity, and a high precipitation time spread. Field observations indicate that saturation excess overland flow is

more pronounced in managed quadrants that have their water tables rise higher than the water table of the free draining quadrants. During all the events, the two managed quadrants had a total of 529 hours of water table being above the ground surface versus a total of 105 hours for the free draining quadrants.

4.2 Suggested future research

Several areas of future research became evident as the work that is presented in this thesis was being conducted:

1. The addition of more drainage events to this event dataset can help in acquiring a more comprehensive event dataset that covers the full range of all possible combinations of precipitation characteristics and antecedent conditions to provide more conclusive results.

2. The event hydrological data and the understanding of the hydrology of the managed and free draining subsurface drainage systems at Field W from this study can be used to better inform the analysis of nitrate concentrations from water quality samples that are collected from the site. Valuable insight on the effect of drainage water management on water quality can be potentially gained by examining the nitrate concentrations before, during, and after events across various precipitation characteristics, and antecedent conditions.

3. This analysis suggests that the managed quadrants can promote overland flow through saturation excess, but this has not been measured directly. It would be helpful to upgrade the field measurement capabilities to enable the quantification of the volume of overland flow that is flowing from each of the quadrants by surrounding each quadrant by weirs that channel runoff outside the field or alternatively devising a method that can enable the monitoring of the water quality of overland flow.

4. There appears to be an opportunity for drainage water management to be used to further increase the field storage capacity so that the field is employed as a storm water detention pond. Kemper et al. (2013) have suggested the use of subsurface drainage to increase the storage capacity of land as a cheaper alternative than basins for the detention of rural flood water. The addition of control structures to the field can be used to further increase the detention capacity of the system and decrease peak flows from subsurface drainage systems.

This study have shown that drainage water management decreased peak flows by 29% ± 16%. The 'pre-draining' of managed subsurface drainage systems before anticipated precipitation events can be studied to assess the potential of drainage water management to further reduce peak flows from the system. Moreover, a modeling study can be conducted to assess the potential of drainage water management to provide additional storage capacity and reduce peak flows on a watershed scale.

5. The addition of more observation wells and piezometers at various depths across the field can provide information on how much water is held in the quadrants. Such a study would be useful in determining lateral seepage losses in order assess the efficiency of drainage water management in increasing the water storage capacity of the field.

6. Climate change models project that future precipitation events will be more intense (Georgakakos et al., 2014). Accordingly, it is recommended to conduct a DRAINMOD study that uses projected future climate data and focuses on the effect of such intense precipitation events on managed and free draining subsurface systems in order to assess the efficiency of drainage water management in light of the changing hydro-climate.

4.3 References

Georgakakos, A., Fleming, P., Dettinger, M., Peters-Lidard, C., Richmond, T., Reckhow, K., White, K., and Yates, D. (2014). *Ch.3 Water Resources. Climate Change Impacts in the United States: The Third National Climate Assessment.* "U.S. Global Change Research Program".

Kemper, W. D., Fouss, J. L., Jaynes, D. B., Dabney, S. M., Ihde, a. M., Meyer, L. D., and Reicosky, D. C. (2013). Storm water management: Potential for lower cost and more benefits if farmers and municipalities cooperate on tile drainage. *Journal of Soil and Water Conservation*, 68(3):79A–83A.

APPENDICES

A. DATA PROCESSING SCRIPTS

A.1 Well data processing script

The 'Combine_Write_Depth_WT.m' script reads well data files, for one quadrant, stored in the Raw_Well_Data folder, adds all data to a structure array, sorts the data, fills dates with missing data gaps with NaNs , converts sensor readings that are originally height from sensor to depth of water table measured from the ground surface, and finally writes the data to a tab delimited text file and a structure array (the script does not call any functions or scripts).

Description of the comma delimited input text files:

- Header first line example: 'well3S1,3/31/2014,1:27:08 PM'
- Header second line: 'Date, Time, Feet, Volts, Pulses'
- Column description:'MM/DD/YY, HH:MM:SS, Height from sensor in feet, Voltage from Data Logger, Reading that is not required'
- One line example from the dataset: '1/16/14, 16:00:26, 4.96, 43.15, 18.43, 0'

Description of a tab delimited output text file:

- Header: 'Date&Time Water Table Depth (m) Volts'
- Column description: 'DD-MMMM-YYYY HH:MM:SS Depth Voltage'
- One line example from the dataset: 01-Jan-2013 14:28:40 0.335208 15.760000

Description of an output structure array:

- The structure array has the following fields:'Date','Time','Feet','Volt','Date_matlab'.
- The 'Date' and 'Time' fields store the date and time stamps as saved in the input text files. The 'Date_matlab' field stores the hourly date and time as a Matlab 'Datenum' number. The 'Feet' and 'Volt' fields store the depth of the water table in meters and the voltage of the data logger, respectively.

Items that may need modification when running the script:

- Start and end data of processing
- Output file name and quadrant (NW, SW, NE, or SE)
- If the depth of the water level sensors change then the code will need editing.

A.2 Soil moisture data processing scripts

A.2.1 Processing of raw soil moisture data

The 'SMT_RAW_DATA_PROC.m' script reads a tab delimited text file that contains aggregated Decagon ECH2O soil moisture, temperature, and electric conductivity data files that have been converted to a text files using the Decagon ECH2O software (one master file for each quadrant). The user inputs the master file into a folder titled 'Raw SMT Data' as well as the start date and end date of the data to be processed, the name of the output file, and the respective quadrant. The script loads the data into a Matlab structure array, converts the time stamp string into a Matlab 'DateNUM' value to be able to sort the data in a chronological order. The script inserts missing temporal data gaps into the structure, fills them with NaNs, and resorts the rows in the structure array based on the Datenum field. If the data is 2012 data, erroneous moisture and temperature readings will be deleted (i.e. data after planting). The script outputs a text file and a structure that contain an hourly soil moisture and temperature dataset. When printing the output file, this program will automatically select the hourly data from the 5 minute data by selecting every 12th index (every 12 lines of 5 minute readings represent 60 min of data given that temporal gaps have been filled and the dataset was sorted chronologically) (the script does not call any functions or scripts).

Description of the tab delimited input text files:

- Header: 'Measurement Time Port 1 5TE Moisture/Temp/EC m?/m? VWC Port 1 5TE Moisture/Temp/EC Temp ?C Port 1 5TE Moisture/Temp/EC Bulk EC dS/m Port 2 5TM Moisture/Temp m?/m? VWC Port 2 5TM Moisture/Temp Temp ?C Port 3 5TM Moisture/Temp m?/m? VWC Port 3 5TM Moisture/Temp Temp ?C Port 4 5TM Moisture/Temp m?/m? VWC Port 4 5TM Moisture/Temp Temp ?C' (note: ? represents superscripts that do not display correctly in the DECAGON data logger text output)

- Column description:'MM/DD/YY HH:MM AM/PM Port 1 VWC Port 1 Temp. Port 1 EC Port 2 VWC Port 2 Temp Port 3 VWC Port 3 Temp Port 4 VWC Port 4 Temp Port 5 VWC Port 5 Temp'

- One line example from the dataset: '02/01/13 09:00 AM 0.255 1.4 0.24 0.255 2.1 0.272 3.6 NaN NaN 0.347 5.0'

Description of tab delimited output text files:

- Header: The same header of the input text file

- Column description:'DD-MMM-YYYY HH:MM:SS Port 1 VWC Port 1 Temp. Port 1 EC Port 2 VWC Port 2 Temp Port 3 VWC Port 3 Temp Port 4 VWC Port 4 Temp Port 5 VWC Port 5 Temp'

- One line example from the dataset: '01-Feb-2013 09:00:00 0.255000 1.400000 0.240000 0.255000 2.100000 0.272000 3.600000 NaN NaN 0.347000 5.000000'

Description of an output structure array:

- The structure array has the following fields: 'Timestamp', 'Moisture_10cm', 'Temp_10cm', 'EC_10cm', 'Moisture_20cm', 'Temp_20cm', 'Moisture_40cm', 'Temp_40cm', 'Moisture_60cm', 'Temp_60cm', 'Moisture_100cm', 'Temp_100cm', 'Date_matlab'.
- The 'Timestamp' field stores time stamp that is extracted from the input text files. The 'Date_matlab' field stores the hourly date and time as a Matlab 'Datenum' number. The rest of the fields store the soil moisture, temperature, and electric conductivity data as saved in the input master text file.

Items that may need modification when running the script:

- Start and end data of processing
- Output file name and quadrant (NW, SW, NE, or SE)
- New planting dates may be added
- Code may be added to account for change in daylight saving time.

A.2.2 Calculation of column soil moisture script

The 'Soil_Filling_Column_Daily_Monthly_MasterCODE.m' script loads data structures that are generated from the 'SMT_RAW_DATA_PROC.m' script and saved in the 'Data' folder then specifies the soil moisture data gaps that are to be filled using bias correction scaling ratios that are calculated according to the filling procedure that is described in the data processing chapter. Hourly, daily average, and monthly soil moisture in the column are calculated and saved to structure arrays. The script also generates a plot of daily soil moisture average in the column of all the available soil moisture dataset. Structure arrays and tab delimited text files of all structures are saved in the folder containing the m file.

Description of a tab delimited output hourly filled text file:

- Header: The file has no header.
- Column description:'DD-MMM-YYYY HH:MM:SS Port 1 VWC Port 2 VWC Port 3 VWC Port 4 VWC Port 5 VWC'
- One line example from the dataset: '24-May-2013 05:00:00 0.329000 0.314000 0.293000 0.359000 0.327000'

Description of a tab delimited output hourly column soil moisture text file:

- Header: 'Time_Stamp NW_COL_Moisture SE_Col_Moisture NE_Col_Moisture SW_Col_Moisture'
- Column description:'DD-MMM-YYYY HH:MM:SS NW Column Soil Moisture SE Column Soil Moisture NE Column Soil Moisture SW Column Soil Moisture'
- One line example from the dataset: '23-Sep-2012 00:00:00 309.7 319.4 257.2 305.1'

Description of a tab delimited output daily average column soil moisture text file:

- Header: 'Date NW_Avg_Moisture SE_Avg_Moisture NE_Avg_Moisture SW_Avg_Moisture '
- Column description:'DD-MMM-YYYY HH:MM:SS NW Average Column Soil Moisture SE Average Column Soil Moisture NE Average Column Soil Moisture SW Average Column Soil Moisture'
- One line example from the dataset: '01-Dec-2011 15:00:00 365.3 364.2 321.4 354.8'

Description of a tab delimited output monthly average column soil moisture text file:

- Header: 'YEAR Month NW_Avg_Moisture SE_Avg_Moisture NE_Avg_Moisture SW_Avg_Moisture'
- Column description:'Year Month NW Average Column Soil Moisture SE Average Column Soil Moisture NE Average Column Soil Moisture SW Average Column Soil Moisture'
- One line example from the dataset: '2012 3 332.0 357.1 296.6 322.7'

Description of an output hourly filled structure array:

- The structure array has the same fields as the output data structures that are generated from the 'SMT_RAW_DATA_PROC.m' script. The difference is that the output structure here has its missing sensor data gaps filled.

Description of an output hourly filled column soil moisture structure array:

- The structure array has the following fields: 'Date_matlab' ,and 'Total_Moisture'.
- The 'Date_matlab' field stores the hourly date and time as a Matlab 'Datenum' number. The 'Total_Moisture' field stores the column soil moisture of the quadrant.

Description of an output daily average filled column soil moisture structure array:

- The structure array has the following fields: 'Date_matlab' ,and 'Total_Moisture'.
- The 'Date_matlab' field stores the daily date and time as a Matlab 'Datenum' number. The 'Total_Moisture' field stores the daily average column soil moisture of the quadrant.

Description of an output monthly average filled column soil moisture structure array:

- The structure array has the following fields: 'Date_matlab' ,and 'Total_Moisture'.
- The 'Date_matlab' field stores the monthly date and time as a Matlab 'Datenum' number. The 'Total_Moisture' field stores the monthly average column soil moisture of the quadrant.

Items that may need modification when running the script:

- Update the 'year' and 'monthcounter' indexes in the 'Calculate monthly totals' Matlab function that is called in the 'Soil_Filling_Column_Daily_Monthly _MasterCODE.m' script.
- The number of days to be plotted need to be changed
- New dates for data gaps to be filled may need to be added and changes in the code need to be done accordingly.

A.3 Processing of CR 1000 data script

The 'Process_DataLogger_Data.m' script reads hourly data logger files stored in the 'Raw Hourly Data Logger Data' folder (all data logger data are stored in a master file), adds it to a struct, sorts the data by time, fills dates with missing hourly data gaps with 'NaN's , resorts the structure in a chronological order after filling the time gaps with empty readings, and writes the output to a structure array and to tab delimited text files (outfile_datalogger_processed_data.txt, outfile_Tile_NetDischarge.txt, outfile_NetDischarge_mm.txt, outfile_precip_gauge.txt, outfile_Tile_DrainFBQ.txt). Pulses from the Krohne Flow meters are converted to cubic meters. For the sake of brevity and practicality only a description of data logger input text file and the output structure array is provided here (no description of output text files is provided).

Description of the comma delimited data logger input text file:

- Header (first line):'"TOA5", "DWM", "CR1000", "41062", "CR1000.Std.22", "CPU:DWM_2011revF.CR1", "6235", "Hourly"'
- Header (second line, variables stored):'"TIMESTAMP", "RECORD", "BattV_Min", "WS_ms_Max", "WS_ms_Avg", "Rain_mm_Tot", "SE_pt_Avg", "SW_pt_Avg", "NW_pt_Avg", "NE_pt_Avg"," SE_KrohneP_Tot", "SE_KrohneS_Tot", "SW_KrohneP_Tot", "SW_KrohneS_Tot", "NW_KrohneP_Tot", "NW_KrohneS_Tot", "NE_KrohneP_Tot", "NE_KrohneS_Tot"'
- Header (third line, units):'"TS", "RN", "Volts", "meters/second", "meters/second", "mm", "mV", "mV", "mV", "mV", "pulses", "pulses", "pulses", "pulses", "pulses", "pulses", "pulses", "pulses"'
- Header (fourth line, operation done by data logger): '"", "", "Min", "Max", "Avg", "Tot", "Avg", "Avg", "Avg", "Avg", "Tot", "Tot", "Tot", "Tot", "Tot", "Tot", "Tot", "Tot"'
- Column description:'Time Stamp, Record Number, Battery Minimum Voltage, Maximum Wind Speed (m/s), Average Wind Speed (m/s), Rainfall(mm), SE Pressure Transducer Average Voltage, SW Pressure Transducer Average Voltage, NW Pressure Transducer Average Voltage, NE Pressure Transducer Average Voltage, Total Forward Pulses from SE Krohne Signal Converter', Total Backward Pulses from SE Krohne Signal Converter, Total Forward Pulses from SW Krohne Signal Converter, Total Backward Pulses from SW Krohne Signal Converter, Total Forward Pulses from NW Krohne Signal Converter, Total Backward Pulses from NW Krohne Signal Converter, Total Forward Pulses from NE Krohne Signal Converter, Total Backward Pulses from NE Krohne Signal Converter'
- One line example from the dataset: '"2013-03-02 18:00:00", 6, 12.29783, 6.65, 3.835625, 0, -24.89002, 17.74564, 21.35607, 6.599538, 0, 0, 757, 0, 32, 1, 0, 0'

Description of the output structure array:

- The structure array has the following fields: 'Timestamp', 'Windspeed_ms_max', 'Rain_total', 'NE_KrohneF_Tot', 'NE_KrohneB_Tot', 'NE_KrohneQ_Tot', 'SE_KrohneF_Tot', 'SE_KrohneB_Tot', 'SE_KrohneQ_Tot', 'SW_KrohneF_Tot', 'SW_KrohneB_Tot', 'SW_KrohneQ_Tot', 'NW_KrohneF_Tot', 'NW_KrohneB_Tot', 'NW_KrohneQ_Tot', 'Date_matlab', 'NE_KrohneQ_Tot_mm', 'SE_KrohneQ_Tot_mm', 'SW_KrohneQ_Tot_mm'.
- The 'Date_matlab' field stores the hourly date and time as a Matlab 'Datenum' number. Fields that end with KrohneF_Tot, KrohneB_Tot, KrohneQ_Tot, and KrohneQ_Tot_mm store forward, backward, net flow in cubic meters, and net flow in mm, respectively. Precipitation in mm from the Field W rain gauge is stored in the Rain_total field.

Items that may need modification when running the script:

- Start and end data of processing
- Output file names
- If changes were made to the program of the Campbell Scientific CR 1000 data logger so that it outputs results differently then the changes need to be accounted for in the 'Process_DataLogger_Data.m' script.

A.4 Event hydrological metrics extraction

The 'Event_Analysis_Script.m' script takes as input from the 'Data' folder the hourly array structures that are generated from the data processing scripts (hourly column soil moisture, drainage, well depth data) as well as a precipitation data structure that is generated from the output of the two C shell scripts and C programs that are described in section 2.2.3 of the Data Processing chapter. Times that limit when events start and end are inserted into the script as Matlab 'datenum' serial date numbers and well depths are converted to height above the drain using calculations that were made in section 2.2.4.2 of the Data Processing Chapter. The script feeds the start and end data of each event as input to the 'Analyze_Single_Event.m' function that delimits the event according to the event definition and extracts from it metrics that are described in section 3.1 of Chapter 3. Event metrics are saved to a data structure named 'Metrics_Struct' that is described below and the 'Analyze_Single_Event.m' function call another function called 'PLOTTING_FUNCTION_AnalyzeEvent.m' that generates the graphs of extracted events as outputted in section B of the appendix. The script also saves the metrics of each event in a separate text file that has the event number, start and end time of the event, and on the 'All_Events_Metrics.txt' tab delimited text file that stores all event data (not described below).

List of input data structures to the script:

- Filled Column soil moisture data structure
- Drainage data structure
- Well depth data structure
- Precipitation data structure

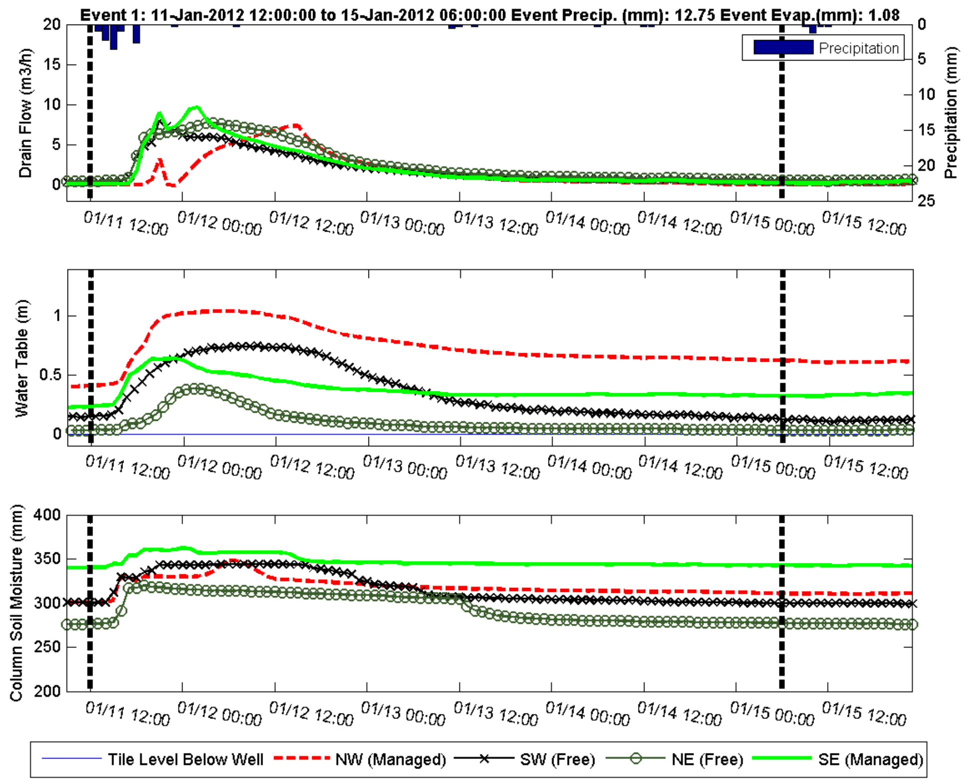
Description of the output structure array:

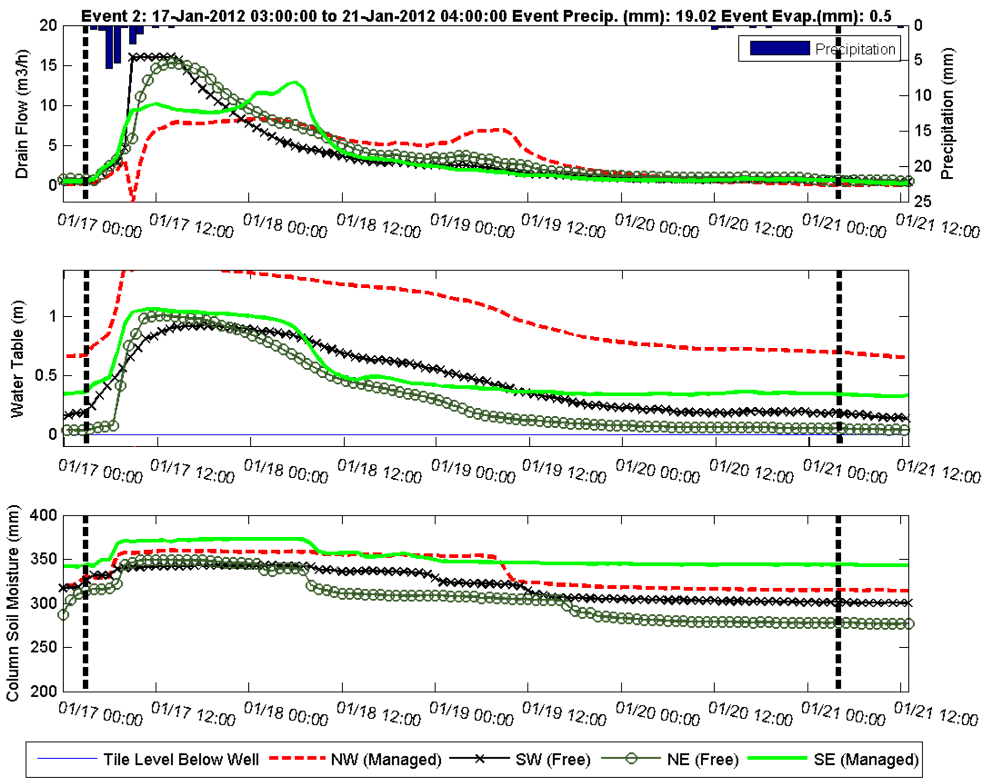
- The structure array has the following fields (only fields that were used in this study are shown): 'Quadrant', 'Event_num', 'Ev_Start_String', 'Ev_End_String', 'Ev_Start_Datenum', 'Ev_End_Datenum', 'Event_Duration', 'Tot_Precip', 'Hours_of_precip', 'Avg_precip_intensity', 'Precip_Spread', 'TotQ', 'Peak_Q', 'Time2Peak_Q', 'Pre_ev_WT', 'Post_ev_WT', 'Max_WT_Height', 'WT_atPeakFlow', 'Prevent_SoilMoist', 'Postevent_SoilMoist', 'Max_Soil_Moist', 'Q2P_Ratio'

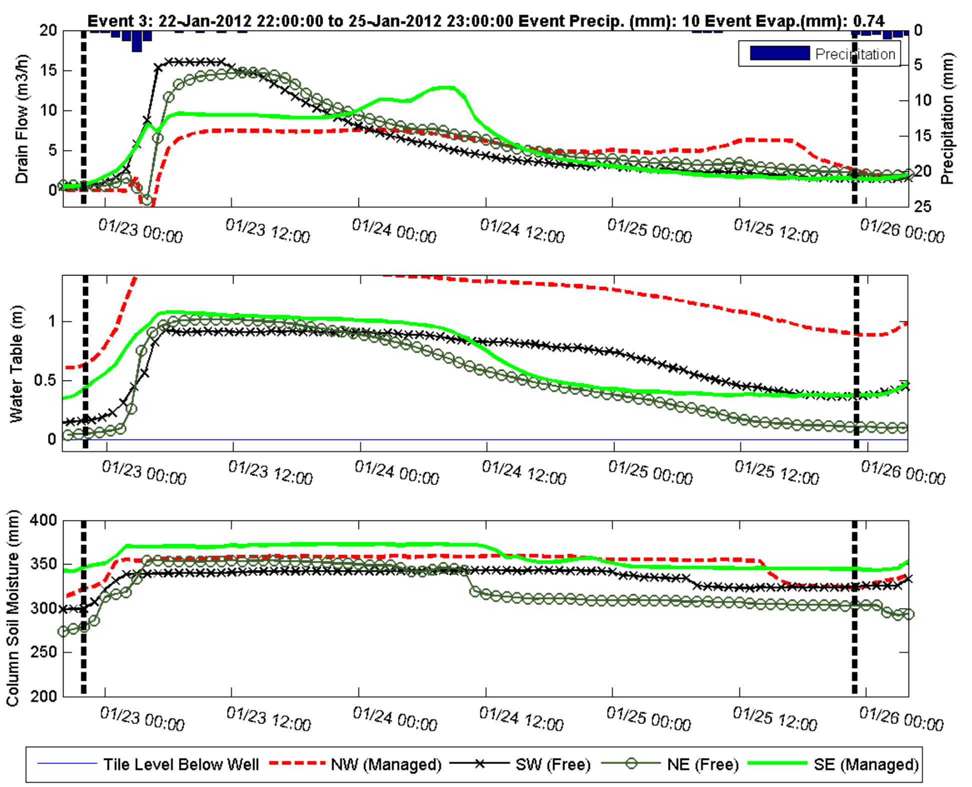
- Each entry in the structure array belongs to event data for one quadrant. Accordingly there are 88 entries in the structure array. The 'Quadrant' and 'Event_num' fields store the quadrant identifier and the event number, respectively. The start and end data of the event serial date number are stored in the 'Ev_Start_Datenum' and 'Ev_End_Datenum' fields and their corresponding date strings are stored in the 'Ev_Start_String', and 'Ev_End_String' fields. The rest of the field and their corresponding metrics are shown in the following table:

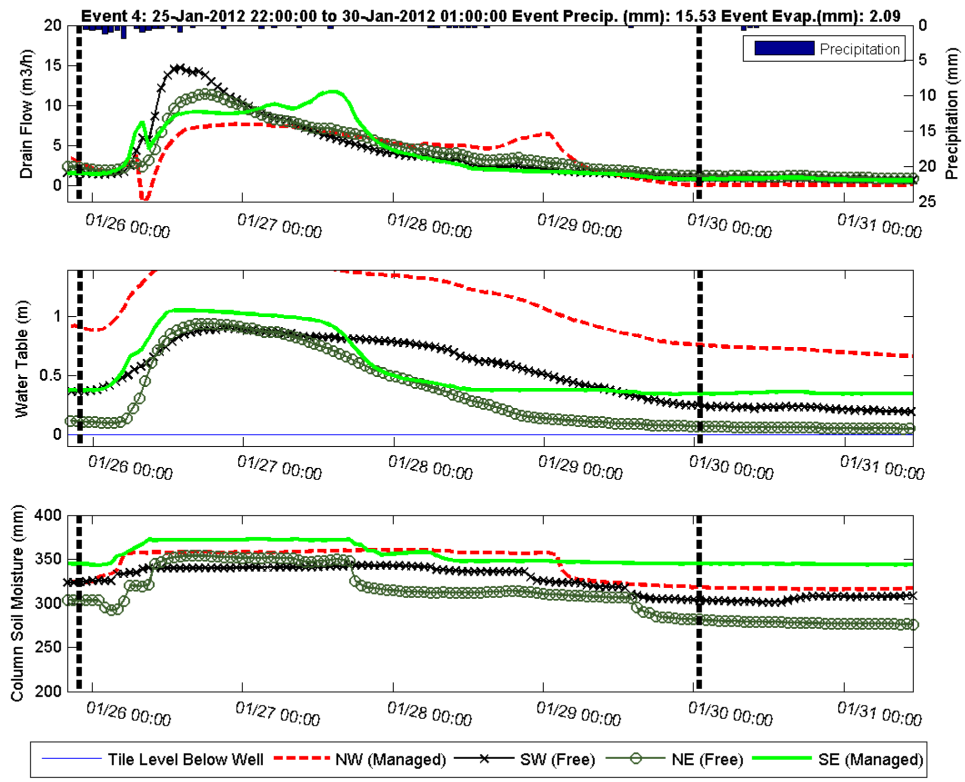
Field	**Metric**
'Event_Duration'	Event duration
'Tot_Precip'	Total precipitation depth
'Hours_of_precip'	Hours of precipitation
'Avg_precip_intensity'	Average precipitation intensity
'Precip_Spread'	Precipitation time spread
'TotQ'	Total drainage volume
'Peak_Q'	Peak drainage flow
'Time2Peak_Q'	Time to peak
'Pre_ev_WT'	Antecedent water table height
'Post_ev_WT'	Post event water table height
'Max_WT_Height'	Maximum water table height
'Prevent_SoilMoist'	Antecedent soil moisture
'Postevent_SoilMoist'	Post event soil moisture
'Max_Soil_Moist'	Maximum soil moisture
'Q2P_Ratio'	Drainage to precipitation ratio

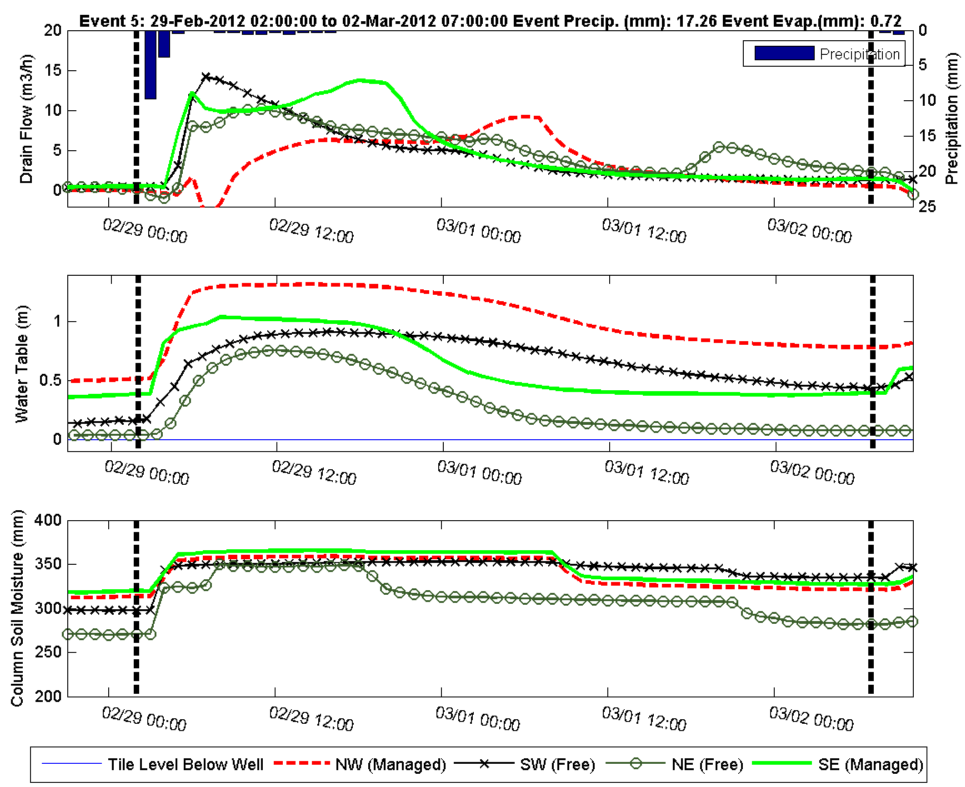
B. GRAPHS OF EXTRACTED EVENTS

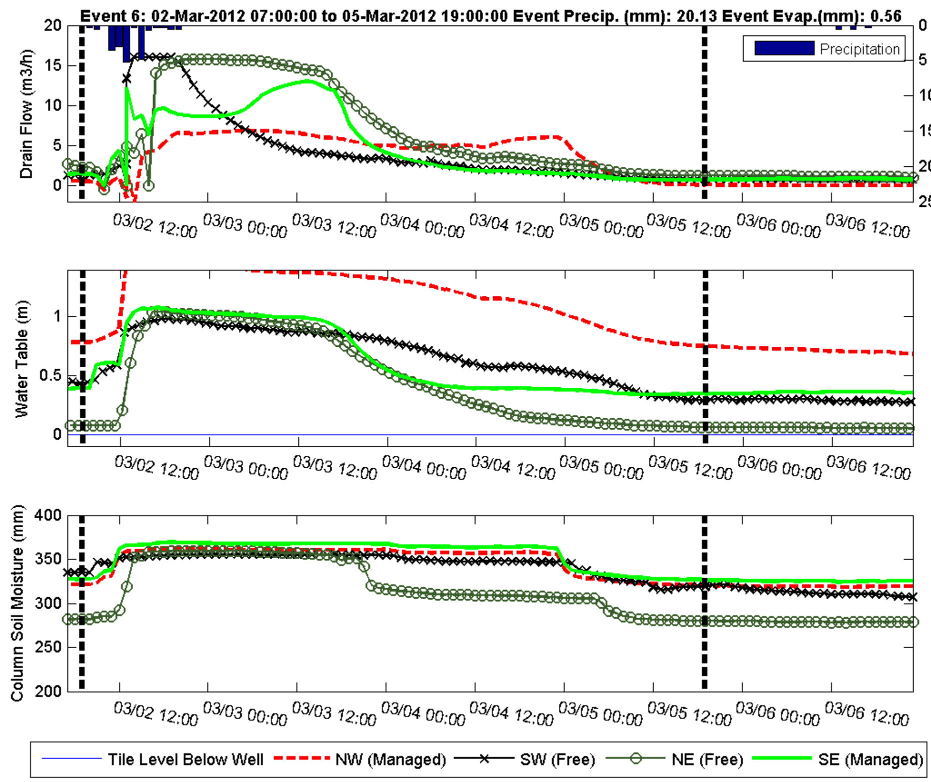



Event 2: 17-Jan-2012 03:00:00 to 21-Jan-2012 04:00:00 Event Precip. (mm): 19.02 Event Evap.(mm): 0.5
Drain Flow (m3/h)
Precipitation (mm)
Precipitation
Water Table (m)
Column Soil Moisture (mm)
01/17 00:00
01/17 12:00
01/18 00:00
01/18 12:00
01/19 00:00
01/19 12:00
01/20 00:00
01/20 12:00
01/21 00:00
01/21 12:00
Tile Level Below Well
NW (Managed)
SW (Free)
NE (Free)
SE (Managed)

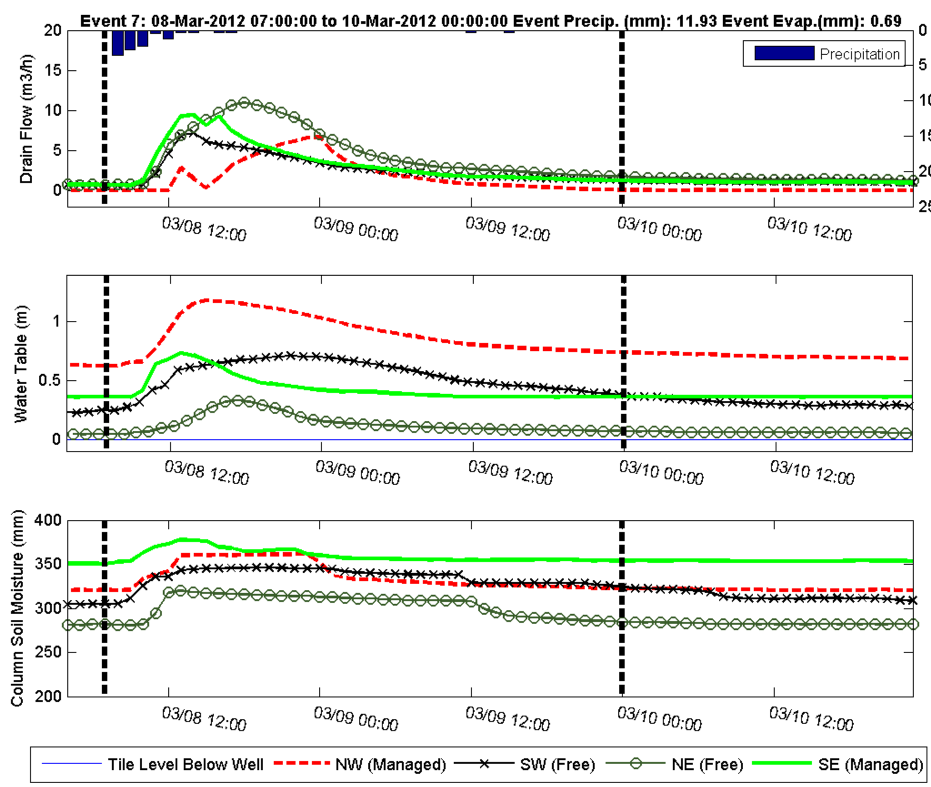

Event 3: 22-Jan-2012 22:00:00 to 25-Jan-2012 23:00:00 Event Precip. (mm): 10 Event Evap.(mm): 0.74
Drain Flow (m3/h)
Precipitation (mm)
Precipitation
Water Table (m)
Column Soil Moisture (mm)
01/23 00:00
01/23 12:00
01/24 00:00
01/24 12:00
01/25 00:00
01/25 12:00
01/26 00:00
Tile Level Below Well
NW (Managed)
SW (Free)
NE (Free)
SE (Managed)


Event 4: 25-Jan-2012 22:00:00 to 30-Jan-2012 01:00:00 Event Precip. (mm): 15.53 Event Evap.(mm): 2.09
Drain Flow (m3/h)
Precipitation (mm)
Precipitation
Water Table (m)
Column Soil Moisture (mm)
01/26 00:00
01/27 00:00
01/28 00:00
01/29 00:00
01/30 00:00
01/31 00:00
Tile Level Below Well
NW (Managed)
SW (Free)
NE (Free)
SE (Managed)

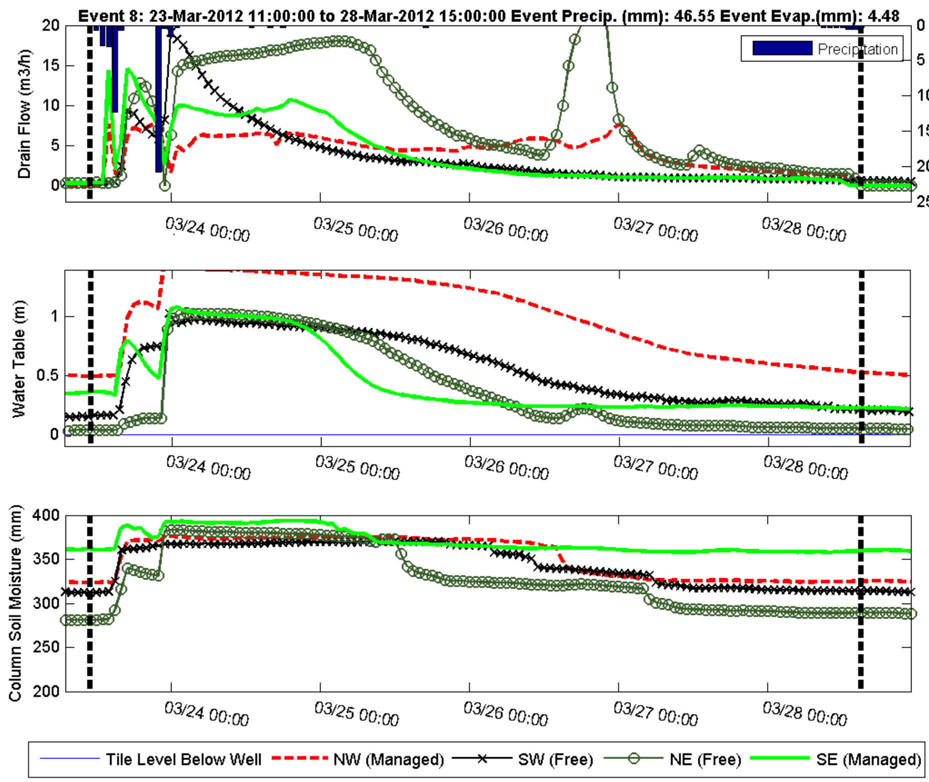

Event 5: 29-Feb-2012 02:00:00 to 02-Mar-2012 07:00:00 Event Precip. (mm): 17.26 Event Evap.(mm): 0.72
Drain Flow (m3/h)
Precipitation (mm)
Precipitation
Water Table (m)
Column Soil Moisture (mm)
02/29 00:00
02/29 12:00
03/01 00:00
03/01 12:00
03/02 00:00
Tile Level Below Well
NW (Managed)
SW (Free)
NE (Free)
SE (Managed)

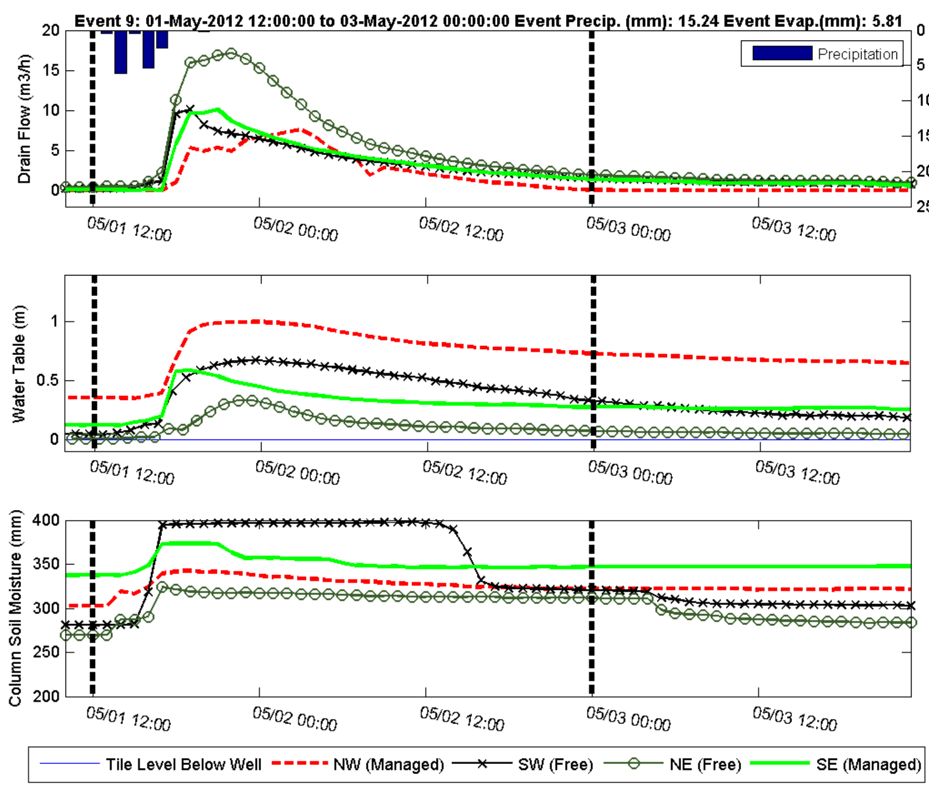


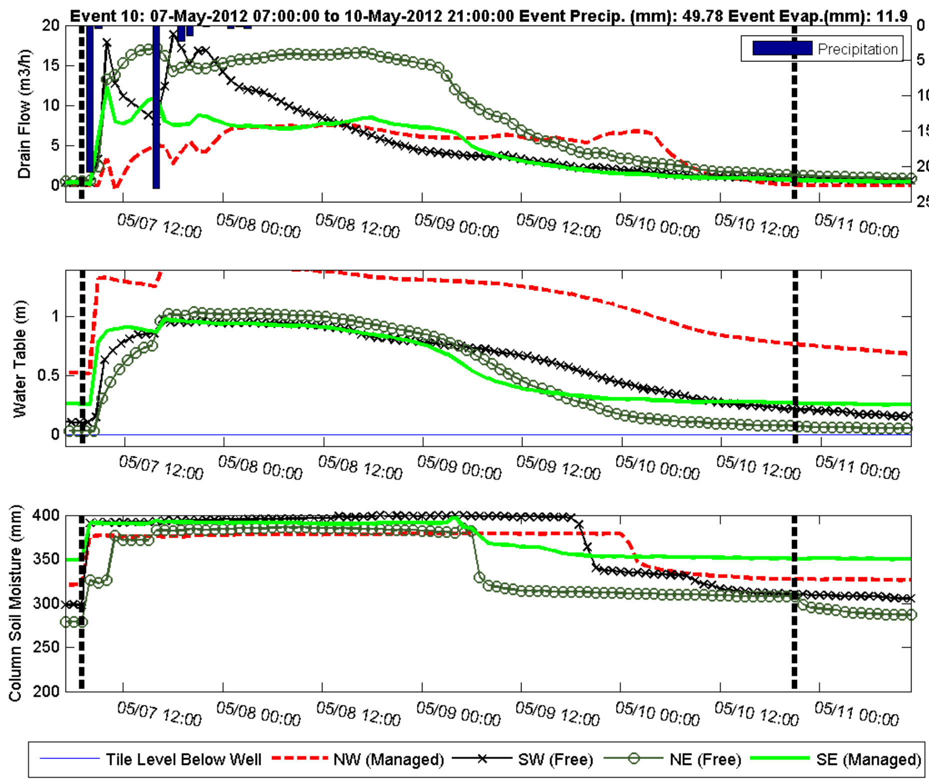
Event 6: 02-Mar-2012 07:00:00 to 05-Mar-2012 19:00:00 Event Precip. (mm): 20.13 Event Evap.(mm): 0.56
Drain Flow (m3/h)
Precipitation (mm)
Precipitation
Water Table (m)
Column Soil Moisture (mm)
03/02 12:00
03/03 00:00
03/03 12:00
03/04 00:00
03/04 12:00
03/05 00:00
03/05 12:00
03/06 00:00
03/06 12:00
Tile Level Below Well
NW (Managed)
SW (Free)
NE (Free)
SE (Managed)



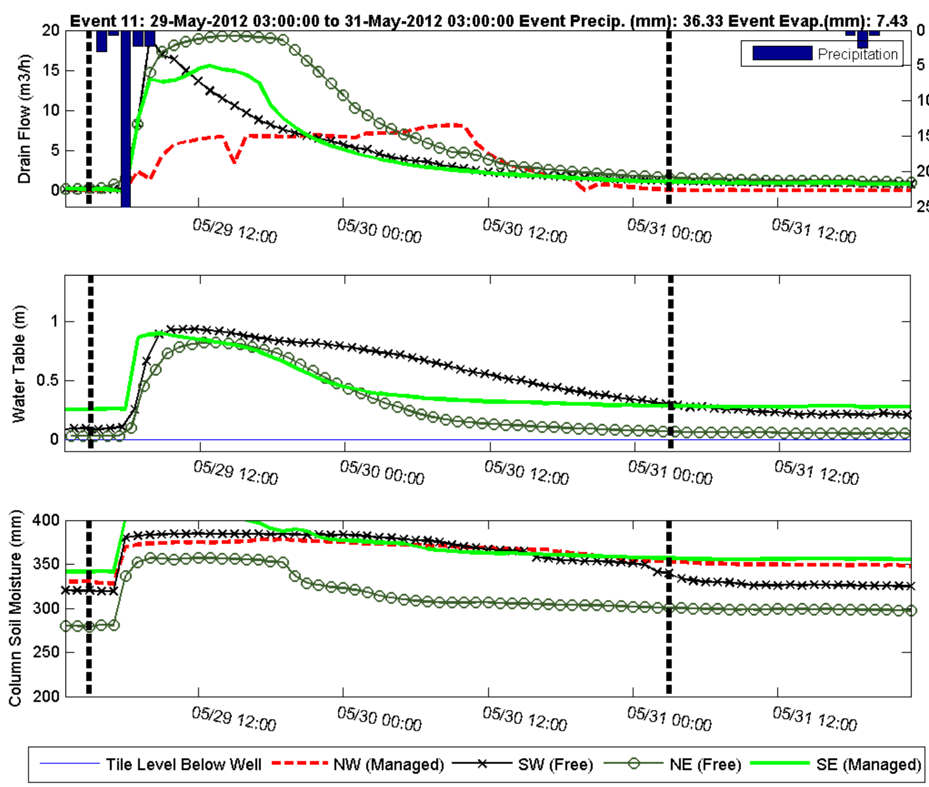
Event 7: 08-Mar-2012 07:00:00 to 10-Mar-2012 00:00:00 Event Precip. (mm): 11.93 Event Evap.(mm): 0.69
Drain Flow (m3/h)
Precipitation (mm)
Precipitation
Water Table (m)
Column Soil Moisture (mm)
03/08 12:00
03/09 00:00
03/09 12:00
03/10 00:00
03/10 12:00
Tile Level Below Well
NW (Managed)
SW (Free)
NE (Free)
SE (Managed)


Event 8: 23-Mar-2012 11:00:00 to 28-Mar-2012 15:00:00 Event Precip. (mm): 46.55 Event Evap.(mm): 4.48
Drain Flow (m3/h)
Precipitation (mm)
Precipitation
03/24 00:00
03/25 00:00
03/26 00:00
03/27 00:00
03/28 00:00
Water Table (m)
Column Soil Moisture (mm)
Tile Level Below Well
NW (Managed)
SW (Free)
NE (Free)
SE (Managed)

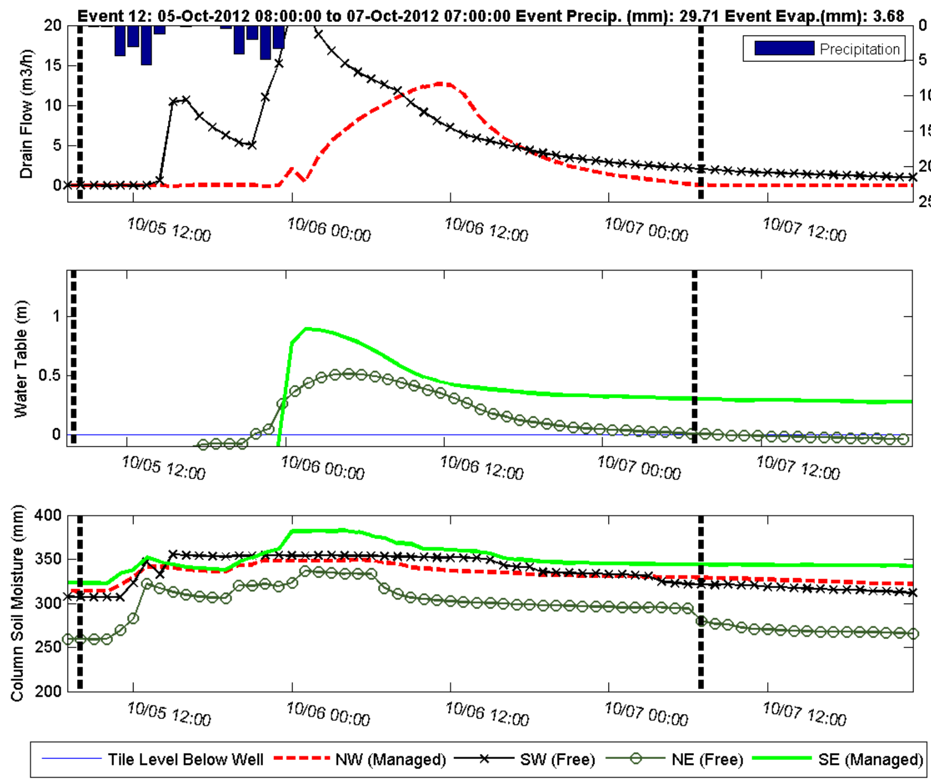

Event 9: 01-May-2012 12:00:00 to 03-May-2012 00:00:00 Event Precip. (mm): 15.24 Event Evap.(mm): 5.81
Drain Flow (m3/h)
Precipitation (mm)
Precipitation
05/01 12:00
05/02 00:00
05/02 12:00
05/03 00:00
05/03 12:00
Water Table (m)
Column Soil Moisture (mm)
Tile Level Below Well
NW (Managed)
SW (Free)
NE (Free)
SE (Managed)

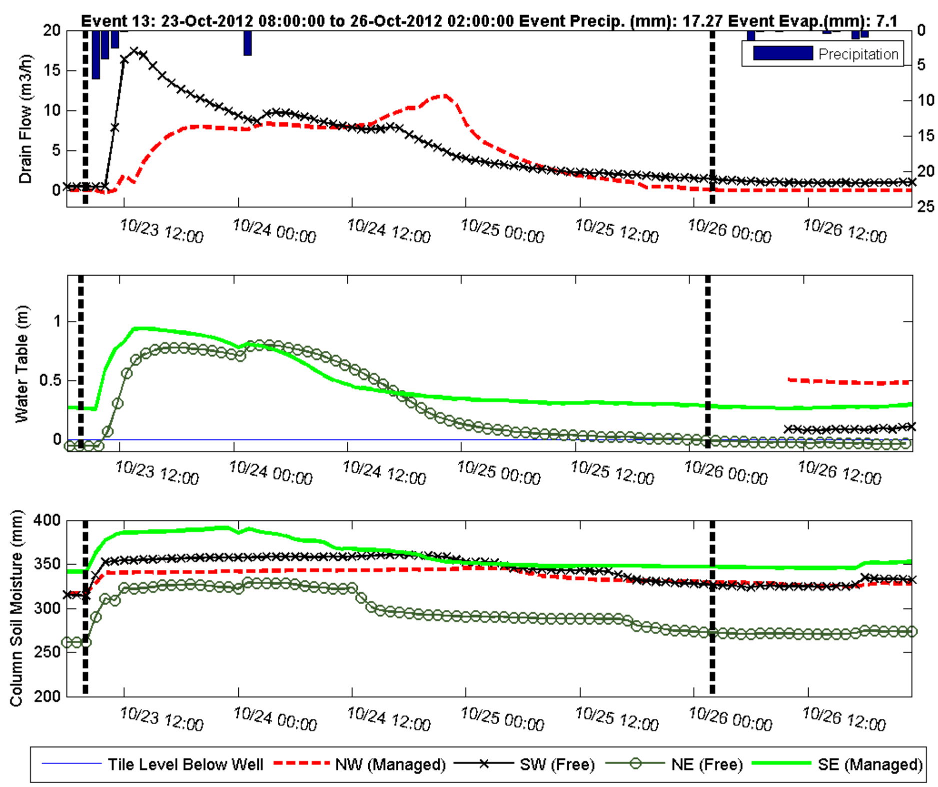


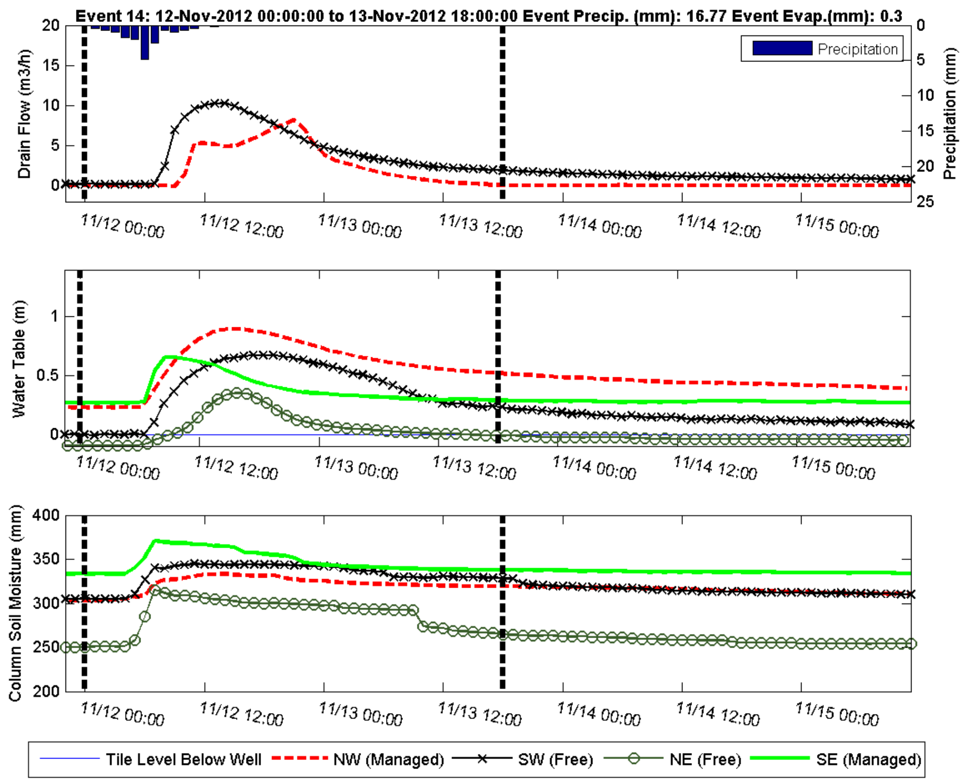
Event 10: 07-May-2012 07:00:00 to 10-May-2012 21:00:00 Event Precip. (mm): 49.78 Event Evap.(mm): 11.9
Drain Flow (m3/h)
Precipitation (mm)
Precipitation
Water Table (m)
Column Soil Moisture (mm)
05/07 12:00
05/08 00:00
05/08 12:00
05/09 00:00
05/09 12:00
05/10 00:00
05/10 12:00
05/11 00:00
Tile Level Below Well
NW (Managed)
SW (Free)
NE (Free)
SE (Managed)

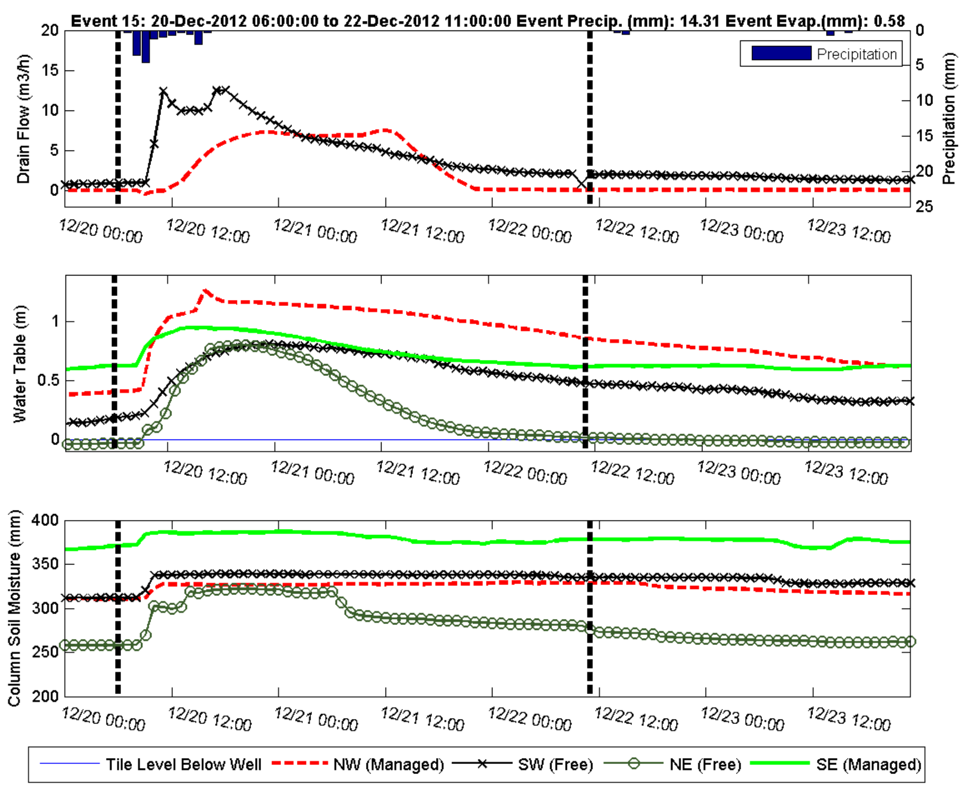


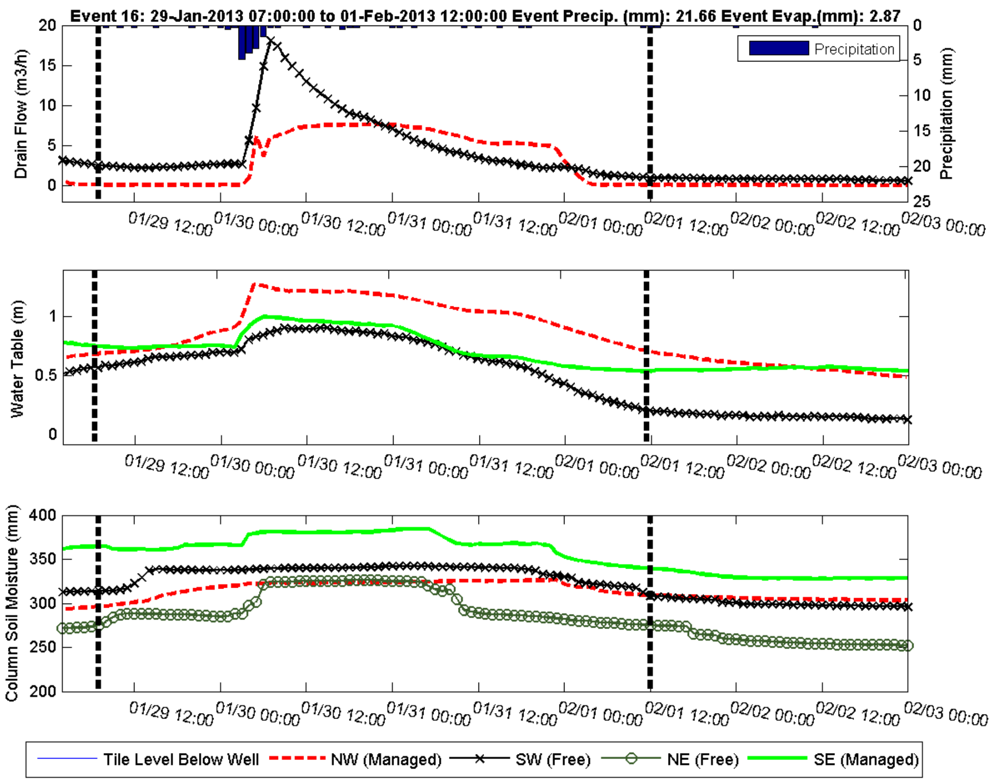
Event 11: 29-May-2012 03:00:00 to 31-May-2012 03:00:00 Event Precip. (mm): 36.33 Event Evap.(mm): 7.43
Drain Flow (m3/h)
Precipitation (mm)
Precipitation
Water Table (m)
Column Soil Moisture (mm)
05/29 12:00
05/30 00:00
05/30 12:00
05/31 00:00
05/31 12:00
Tile Level Below Well
NW (Managed)
SW (Free)
NE (Free)
SE (Managed)


Event 12: 05-Oct-2012 08:00:00 to 07-Oct-2012 07:00:00 Event Precip. (mm): 29.71 Event Evap.(mm): 3.68
Precipitation
Drain Flow (m3/h)
Precipitation (mm)
Water Table (m)
Column Soil Moisture (mm)
10/05 12:00
10/06 00:00
10/06 12:00
10/07 00:00
10/07 12:00
Tile Level Below Well
NW (Managed)
SW (Free)
NE (Free)
SE (Managed)

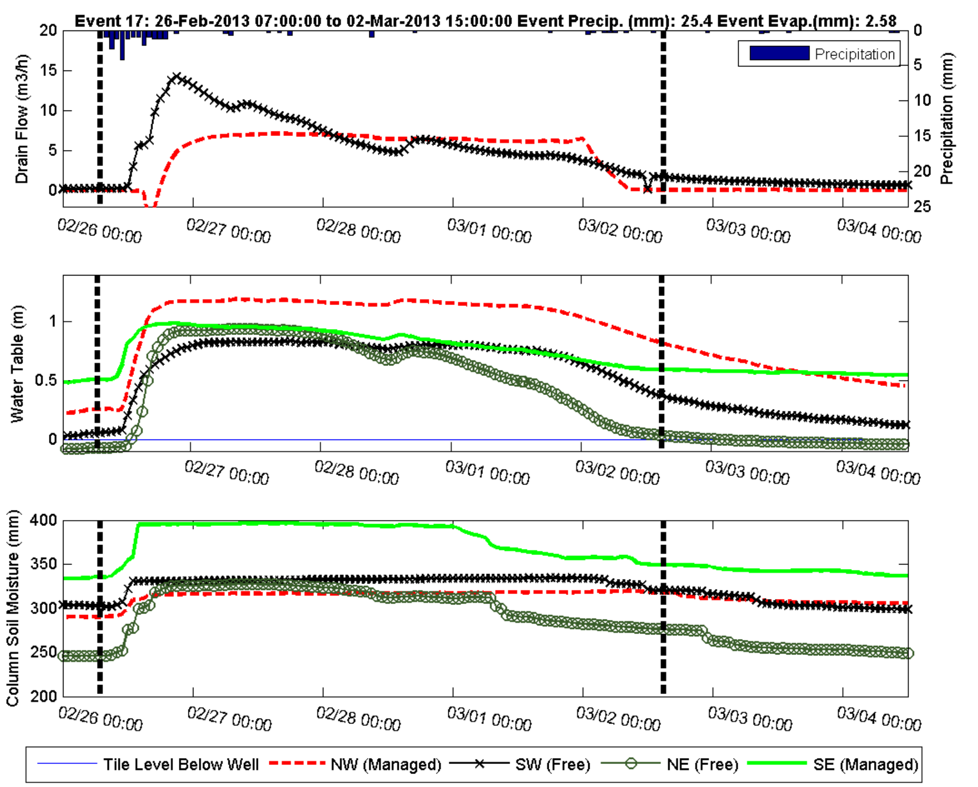

Event 13: 23-Oct-2012 08:00:00 to 26-Oct-2012 02:00:00 Event Precip. (mm): 17.27 Event Evap.(mm): 7.1
Precipitation
Drain Flow (m3/h)
Precipitation (mm)
Water Table (m)
Column Soil Moisture (mm)
10/23 12:00
10/24 00:00
10/24 12:00
10/25 00:00
10/25 12:00
10/26 00:00
10/26 12:00
Tile Level Below Well
NW (Managed)
SW (Free)
NE (Free)
SE (Managed)


Event 14: 12-Nov-2012 00:00:00 to 13-Nov-2012 18:00:00 Event Precip. (mm): 16.77 Event Evap.(mm): 0.3
Drain Flow (m3/h)
Precipitation (mm)
Precipitation
Water Table (m)
Column Soil Moisture (mm)
11/12 00:00
11/12 12:00
11/13 00:00
11/13 12:00
11/14 00:00
11/14 12:00
11/15 00:00
Tile Level Below Well
NW (Managed)
SW (Free)
NE (Free)
SE (Managed)

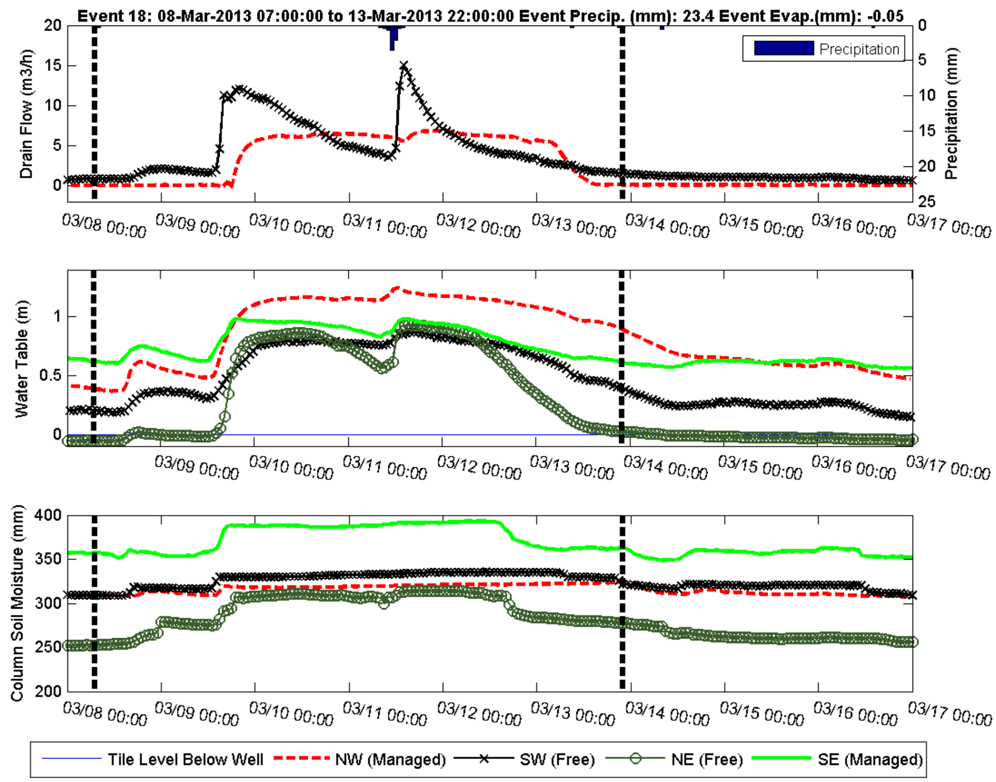

Event 15: 20-Dec-2012 06:00:00 to 22-Dec-2012 11:00:00 Event Precip. (mm): 14.31 Event Evap.(mm): 0.58
Drain Flow (m3/h)
Precipitation (mm)
Precipitation
Water Table (m)
Column Soil Moisture (mm)
12/20 00:00
12/20 12:00
12/21 00:00
12/21 12:00
12/22 00:00
12/22 12:00
12/23 00:00
12/23 12:00
Tile Level Below Well
NW (Managed)
SW (Free)
NE (Free)
SE (Managed)

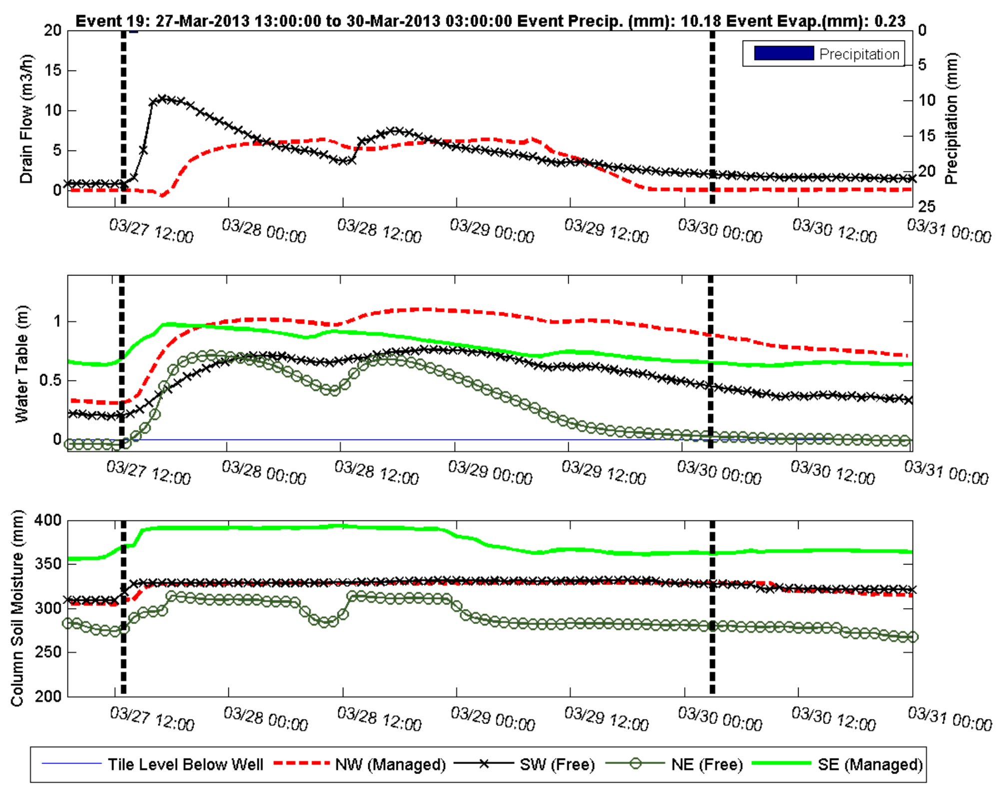


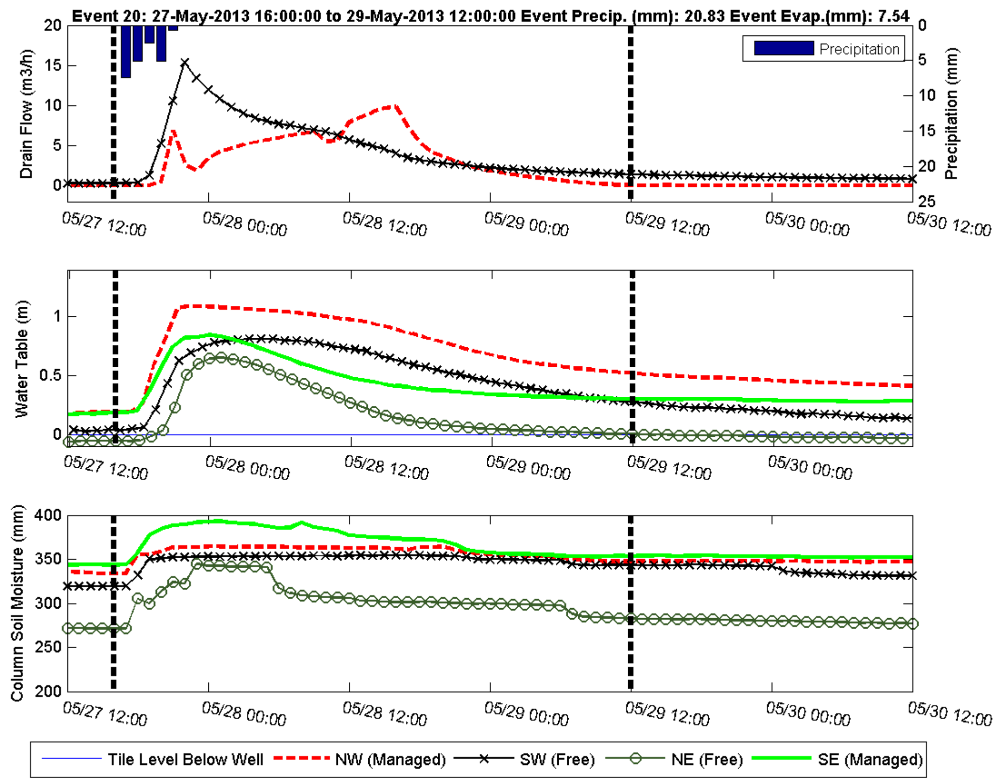
Event 16: 29-Jan-2013 07:00:00 to 01-Feb-2013 12:00:00 Event Precip. (mm): 21.66 Event Evap.(mm): 2.87
Precipitation
Drain Flow (m3/h)
Precipitation (mm)
Water Table (m)
Column Soil Moisture (mm)
01/29 12:00
01/30 00:00
01/30 12:00
01/31 00:00
01/31 12:00
02/01 00:00
02/01 12:00
02/02 00:00
02/02 12:00
02/03 00:00
Tile Level Below Well
NW (Managed)
SW (Free)
NE (Free)
SE (Managed)



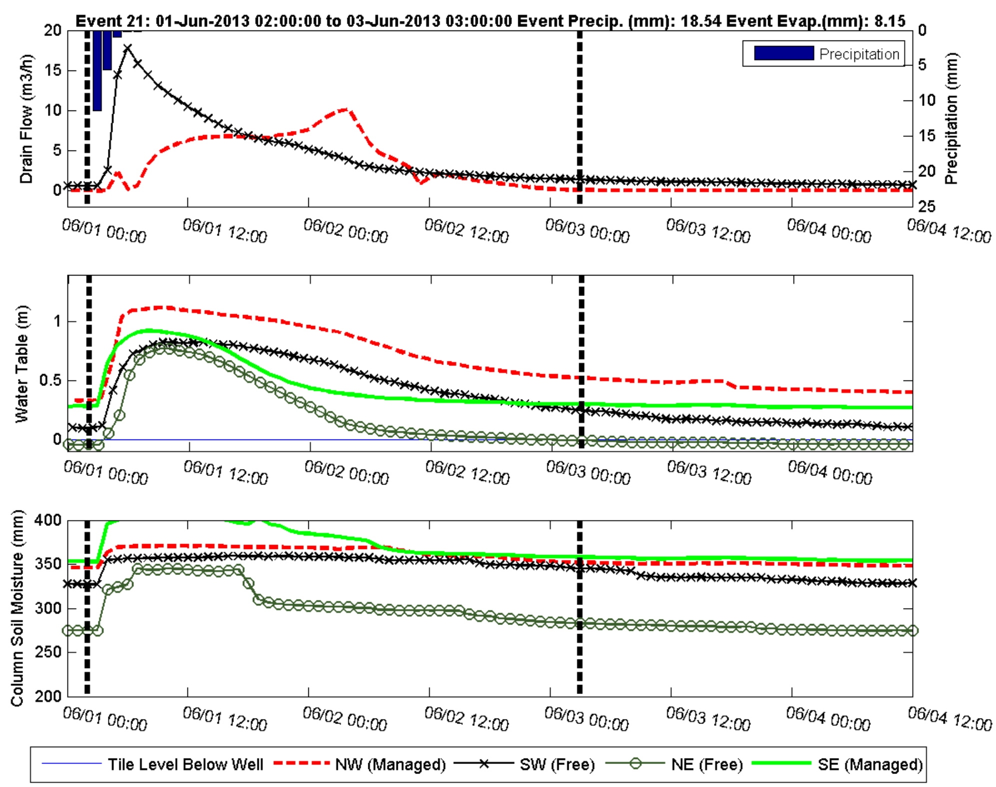
Event 17: 26-Feb-2013 07:00:00 to 02-Mar-2013 15:00:00 Event Precip. (mm): 25.4 Event Evap.(mm): 2.58
Precipitation
Drain Flow (m3/h)
Precipitation (mm)
Water Table (m)
Column Soil Moisture (mm)
02/26 00:00
02/27 00:00
02/28 00:00
03/01 00:00
03/02 00:00
03/03 00:00
03/04 00:00
Tile Level Below Well
NW (Managed)
SW (Free)
NE (Free)
SE (Managed)


Event 18: 08-Mar-2013 07:00:00 to 13-Mar-2013 22:00:00 Event Precip. (mm): 23.4 Event Evap.(mm): -0.05
Drain Flow (m3/h)
Precipitation (mm)
Precipitation
Water Table (m)
Column Soil Moisture (mm)
03/08 00:00
03/09 00:00
03/10 00:00
03/11 00:00
03/12 00:00
03/13 00:00
03/14 00:00
03/15 00:00
03/16 00:00
03/17 00:00
Tile Level Below Well
NW (Managed)
SW (Free)
NE (Free)
SE (Managed)

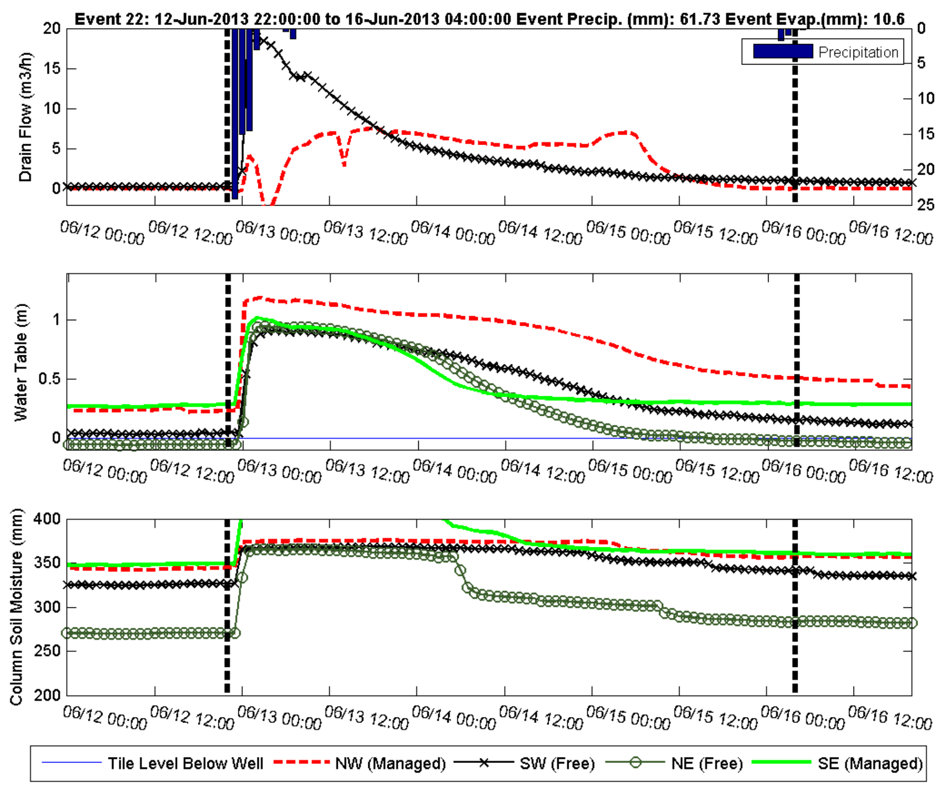

Event 19: 27-Mar-2013 13:00:00 to 30-Mar-2013 03:00:00 Event Precip. (mm): 10.18 Event Evap.(mm): 0.23
Drain Flow (m3/h)
Precipitation (mm)
Precipitation
Water Table (m)
Column Soil Moisture (mm)
03/27 12:00
03/28 00:00
03/28 12:00
03/29 00:00
03/29 12:00
03/30 00:00
03/30 12:00
03/31 00:00
Tile Level Below Well
NW (Managed)
SW (Free)
NE (Free)
SE (Managed)



Event 20: 27-May-2013 16:00:00 to 29-May-2013 12:00:00 Event Precip. (mm): 20.83 Event Evap.(mm): 7.54
Precipitation
Drain Flow (m3/h)
Precipitation (mm)
Water Table (m)
Column Soil Moisture (mm)
05/27 12:00
05/28 00:00
05/28 12:00
05/29 00:00
05/29 12:00
05/30 00:00
05/30 12:00
Tile Level Below Well
NW (Managed)
SW (Free)
NE (Free)
SE (Managed)



Event 21: 01-Jun-2013 02:00:00 to 03-Jun-2013 03:00:00 Event Precip. (mm): 18.54 Event Evap.(mm): 8.15
Precipitation
Drain Flow (m3/h)
Precipitation (mm)
Water Table (m)
Column Soil Moisture (mm)
06/01 00:00
06/01 12:00
06/02 00:00
06/02 12:00
06/03 00:00
06/03 12:00
06/04 00:00
06/04 12:00
Tile Level Below Well
NW (Managed)
SW (Free)
NE (Free)
SE (Managed)



Event 22: 12-Jun-2013 22:00:00 to 16-Jun-2013 04:00:00 Event Precip. (mm): 61.73 Event Evap.(mm): 10.6
Drain Flow (m3/h)
Precipitation (mm)
Precipitation
Water Table (m)
Column Soil Moisture (mm)
06/12 00:00
06/12 12:00
06/13 00:00
06/13 12:00
06/14 00:00
06/14 12:00
06/15 00:00
06/15 12:00
06/16 00:00
06/16 12:00
Tile Level Below Well
NW (Managed)
SW (Free)
NE (Free)
SE (Managed)

C. EVENT DATA

Event Number	1			
Start Time	1/11/2012 12:00			
End Time	1/15/2012 6:00			
Event Duration (hrs)	91			
Total Precipitation (mm)	12.7			
Hours of Precipitation (hrs)	13			
Average Precipitation Intensity (mm/hr)	1			
Precipitation Time Spread (hr)	24			
Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	154.2	193.8	244.0	204.3
Peak Flow (m^3/hr)	7.3	7.9	7.7	9.7
Time to peak (hrs)	28	10	17	15
Antecedent Water Table Height (m)	0.41	0.15	0.03	0.24
Post Event Water Table Height (m)	0.62	0.12	0.03	0.32
Maximum Water Table Height (m)	1.04	0.75	0.39	0.64
Antecedent Soil Moisture (mm)	300.5	300.5	276.3	340.5
Post Event Soil Moisture (mm)	310.7	299.8	276.6	343.0
Event Change in Soil Moisture (mm)	10.2	-0.8	0.3	2.6
Drainage to Precipitation Ratio (mm/mm)	0.35	0.43	0.53	0.43

Event Number	2			
Start Time	1/17/2012 3:00			
End Time	1/21/2012 4:00			
Event Duration (hrs)	98			
Total Precipitation (mm)	19			
Hours of Precipitation (hrs)	14			
Average Precipitation Intensity (mm/hr)	1.4			
Precipitation Time Spread (hr)	25.6			
Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	382.7	377.5	430.4	373.7
Peak Flow (m^3/hr)	8.3	16.0	15.3	12.9
Time to peak (hrs)	23	7	12	28
Antecedent Water Table Height (m)	0.75	0.24	0.04	0.43
Post Event Water Table Height (m)	0.69	0.17	0.05	0.34
Maximum Water Table Height (m)	1.45	0.92	1.01	1.07
Antecedent Soil Moisture (mm)	330.7	326.2	314.2	343.6
Post Event Soil Moisture (mm)	314.4	301.2	277.4	343.4
Event Change in Soil Moisture (mm)	-16.2	-25.0	-36.8	-0.1
Drainage to Precipitation Ratio (mm/mm)	0.57	0.57	0.63	0.53

Event Number	3			
Start Time	1/22/2012 22:00			
End Time	1/25/2012 23:00			
Event Duration (hrs)	74			
Total Precipitation (mm)	10			
Hours of Precipitation (hrs)	14			
Average Precipitation Intensity (mm/hr)	0.7			
Precipitation Time Spread (hr)	25.4			
Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	394.3	445.6	472.7	440.3
Peak Flow (m^3/hr)	7.5	16.0	14.8	12.9
Time to peak (hrs)	29	9	17	35
Antecedent Water Table Height (m)	0.68	0.16	0.05	0.50
Post Event Water Table Height (m)	0.88	0.37	0.10	0.37
Maximum Water Table Height (m)	1.47	0.93	1.02	1.08
Antecedent Soil Moisture (mm)	321.9	299.4	279.0	346.1
Post Event Soil Moisture (mm)	323.7	324.5	303.1	344.4
Event Change in Soil Moisture (mm)	1.8	25.1	24.2	-1.7
Drainage to Precipitation Ratio (mm/mm)	1.13	1.27	1.31	1.19

Event Number	4			
Start Time	1/25/2012 22:00			
End Time	1/30/2012 1:00			
Event Duration (hrs)	100			
Total Precipitation (mm)	15.5			
Hours of Precipitation (hrs)	29			
Average Precipitation Intensity (mm/hr)	0.5			
Precipitation Time Spread (hr)	29.9			
Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	442.5	481.8	484.1	476.6
Peak Flow (m^3/hr)	7.6	14.7	11.4	11.7
Time to peak (hrs)	26	17	21	41
Antecedent Water Table Height (m)	0.89	0.37	0.11	0.37
Post Event Water Table Height (m)	0.76	0.24	0.07	0.35
Maximum Water Table Height (m)	1.47	0.90	0.94	1.06
Antecedent Soil Moisture (mm)	324.0	323.9	303.0	344.7
Post Event Soil Moisture (mm)	317.8	303.4	281.6	344.8
Event Change in Soil Moisture (mm)	-6.2	-20.5	-21.4	0.1
Drainage to Precipitation Ratio (mm/mm)	0.81	0.89	0.87	0.83

Event Number	5			
Start Time	2/29/2012 2:00			
End Time	3/2/2012 7:00			
Event Duration (hrs)	54			
Total Precipitation (mm)	17.3			
Hours of Precipitation (hrs)	12			
Average Precipitation Intensity (mm/hr)	1.4			
Precipitation Time Spread (hr)	5.3			
Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	187.7	238.2	274.3	286.0
Peak Flow (m^3/hr)	9.2	14.1	10.2	13.7
Time to peak (hrs)	29	6	10	17
Antecedent Water Table Height (m)	0.52	0.17	0.04	0.38
Post Event Water Table Height (m)	0.78	0.44	0.07	0.39
Maximum Water Table Height (m)	1.32	0.91	0.75	1.04
Antecedent Soil Moisture (mm)	313.7	297.6	270.8	319.7
Post Event Soil Moisture (mm)	321.1	334.6	281.7	327.2
Event Change in Soil Moisture (mm)	7.4	37.0	10.9	7.5
Drainage to Precipitation Ratio (mm/mm)	0.31	0.39	0.44	0.45

Event Number	6			
Start Time	3/2/2012 7:00			
End Time	3/5/2012 19:00			
Event Duration (hrs)	86			
Total Precipitation (mm)	20.1			
Hours of Precipitation (hrs)	12			
Average Precipitation Intensity (mm/hr)	1.7			
Precipitation Time Spread (hr)	7.7			
Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	352.9	380.1	596.7	420.8
Peak Flow (m^3/hr)	6.9	16.0	15.8	13.0
Time to peak (hrs)	24	10	19	32
Antecedent Water Table Height (m)	0.78	0.44	0.07	0.39
Post Event Water Table Height (m)	0.75	0.29	0.06	0.35
Maximum Water Table Height (m)	1.46	0.98	1.04	1.08
Antecedent Soil Moisture (mm)	321.1	334.6	281.7	327.2
Post Event Soil Moisture (mm)	320.2	318.9	279.9	326.3
Event Change in Soil Moisture (mm)	-0.9	-15.7	-1.8	-0.9
Drainage to Precipitation Ratio (mm/mm)	0.50	0.54	0.82	0.56

Event Number	7			
Start Time	3/8/2012 7:00			
End Time	3/10/2012 0:00			
Event Duration (hrs)	42			
Total Precipitation (mm)	11.9			
Hours of Precipitation (hrs)	11			
Average Precipitation Intensity (mm/hr)	1.1			
Precipitation Time Spread (hr)	8			
Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	78.4	118.3	193.9	140.2
Peak Flow (m^3/hr)	6.7	7.2	10.9	9.4
Time to peak (hrs)	18	8	12	8
Antecedent Water Table Height (m)	0.63	0.24	0.04	0.36
Post Event Water Table Height (m)	0.74	0.37	0.07	0.36
Maximum Water Table Height (m)	1.18	0.71	0.33	0.73
Antecedent Soil Moisture (mm)	320.8	304.6	281.6	350.3
Post Event Soil Moisture (mm)	322.7	323.9	284.5	353.9
Event Change in Soil Moisture (mm)	1.9	19.4	2.9	3.6
Drainage to Precipitation Ratio (mm/mm)	0.19	0.28	0.45	0.32

Event Number	8			
Start Time	3/23/2012 11:00			
End Time	3/28/2012 15:00			
Event Duration (hrs)	125			
Total Precipitation (mm)	46.6			
Hours of Precipitation (hrs)	20			
Average Precipitation Intensity (mm/hr)	2.3			
Precipitation Time Spread (hr)	30.3			
Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	542.0	458.4	1099.8	499.0
Peak Flow (m^3/hr)	7.7	19.0	21.4	14.6
Time to peak (hrs)	12	14	82	7
Antecedent Water Table Height (m)	0.50	0.16	0.03	0.36
Post Event Water Table Height (m)	0.52	0.21	0.04	0.22
Maximum Water Table Height (m)	1.47	1.03	1.03	1.08
Antecedent Soil Moisture (mm)	323.6	312.2	281.2	360.9
Post Event Soil Moisture (mm)	325.0	314.1	289.2	359.5
Event Change in Soil Moisture (mm)	1.4	1.9	8.0	-1.4
Drainage to Precipitation Ratio (mm/mm)	0.33	0.28	0.66	0.29

Event Number	9			
Start Time	5/1/2012 12:00			
End Time	5/3/2012 0:00			
Event Duration (hrs)	37			
Total Precipitation (mm)	15.2			
Hours of Precipitation (hrs)	6			
Average Precipitation Intensity (mm/hr)	2.5			
Precipitation Time Spread (hr)	4.4			
Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	98.7	134.9	241.2	138.9
Peak Flow (m^3/hr)	7.6	10.1	17.1	10.1
Time to peak (hrs)	16	8	11	10
Antecedent Water Table Height (m)	0.35	0.04	0.01	0.12
Post Event Water Table Height (m)	0.73	0.32	0.07	0.27
Maximum Water Table Height (m)	1.00	0.67	0.33	0.59
Antecedent Soil Moisture (mm)	302.9	280.9	269.3	337.6
Post Event Soil Moisture (mm)	321.7	320.5	311.4	346.9
Event Change in Soil Moisture (mm)	18.8	39.6	42.1	9.3
Drainage to Precipitation Ratio (mm/mm)	0.19	0.25	0.44	0.25

Event Number	10			
Start Time	5/7/2012 7:00			
End Time	5/10/2012 21:00			
Event Duration (hrs)	87			
Total Precipitation (mm)	49.8			
Hours of Precipitation (hrs)	9			
Average Precipitation Intensity (mm/hr)	5.5			
Precipitation Time Spread (hr)	8.5			
Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	424.6	510.3	845.3	427.1
Peak Flow (m^3/hr)	7.6	18.8	17.2	12.3
Time to peak (hrs)	31	12	10	4
Antecedent Water Table Height (m)	0.52	0.10	0.03	0.25
Post Event Water Table Height (m)	0.76	0.21	0.07	0.26
Maximum Water Table Height (m)	1.46	0.98	1.04	0.98
Antecedent Soil Moisture (mm)	320.7	298.2	278.9	349.9
Post Event Soil Moisture (mm)	326.9	309.7	307.7	350.5
Event Change in Soil Moisture (mm)	6.3	11.5	28.7	0.6
Drainage to Precipitation Ratio (mm/mm)	0.24	0.29	0.47	0.23

Event Number	11			
Start Time	5/29/2012 3:00			
End Time	5/31/2012 3:00			
Event Duration (hrs)	49			
Total Precipitation (mm)	36.3			
Hours of Precipitation (hrs)	5			
Average Precipitation Intensity (mm/hr)	7.3			
Precipitation Time Spread (hr)	4			
Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	209.0	259.6	419.6	265.0
Peak Flow (m^3/hr)	8.1	19.1	19.3	15.5
Time to peak (hrs)	31	6	13	11
Antecedent Water Table Height (m)	-	0.08	0.03	0.26
Post Event Water Table Height (m)	-	0.29	0.07	0.28
Maximum Water Table Height (m)	-	0.94	0.83	0.90
Antecedent Soil Moisture (mm)	330.0	320.1	279.3	341.4
Post Event Soil Moisture (mm)	353.0	339.6	300.3	356.9
Event Change in Soil Moisture (mm)	22.9	19.5	21.1	15.5
Drainage to Precipitation Ratio (mm/mm)	0.16	0.20	0.32	0.20

Event Number	12			
Start Time	10/5/2012 8:00			
End Time	10/7/2012 7:00			
Event Duration (hrs)	48			
Total Precipitation (mm)	29.7			
Hours of Precipitation (hrs)	12			
Average Precipitation Intensity (mm/hr)	2.5			
Precipitation Time Spread (hr)	10.7			
Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	167.5	331.3	-	-
Peak Flow (m^3/hr)	12.6	22.3	-	-
Time to peak (hrs)	28	17	1	1
Antecedent Water Table Height (m)	-	-	-0.34	-1.15
Post Event Water Table Height (m)	-	-	0.00	0.30
Maximum Water Table Height (m)	-	-	0.51	0.89
Antecedent Soil Moisture (mm)	313.8	307.2	259.4	323.1
Post Event Soil Moisture (mm)	329.0	321.4	280.0	344.0
Event Change in Soil Moisture (mm)	15.3	14.2	20.6	20.9
Drainage to Precipitation Ratio (mm/mm)	0.16	0.32	-	-

Event Number	13			
Start Time	10/23/2012 8:00			
End Time	10/26/2012 2:00			
Event Duration (hrs)	67			
Total Precipitation (mm)	17.3			
Hours of Precipitation (hrs)	5			
Average Precipitation Intensity (mm/hr)	3.5			
Precipitation Time Spread (hr)	8.5			
Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	349.4	422.6	-	-
Peak Flow (m^3/hr)	11.8	17.4	-	-
Time to peak (hrs)	39	6	1	1
Antecedent Water Table Height (m)	-	-	-0.06	0.26
Post Event Water Table Height (m)	-	-	-0.01	0.28
Maximum Water Table Height (m)	-	-	0.80	0.94
Antecedent Soil Moisture (mm)	317.5	314.3	260.9	341.8
Post Event Soil Moisture (mm)	329.6	326.3	272.4	347.0
Event Change in Soil Moisture (mm)	12.1	12.0	11.5	5.3
Drainage to Precipitation Ratio (mm/mm)	0.58	0.70	-	-

Event Number	14			
Start Time	11/12/2012 0:00			
End Time	11/13/2012 18:00			
Event Duration (hrs)	43			
Total Precipitation (mm)	16.8			
Hours of Precipitation (hrs)	12			
Average Precipitation Intensity (mm/hr)	1.4			
Precipitation Time Spread (hr)	7.3			
Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	103.9	182.6	-	-
Peak Flow (m^3/hr)	8.2	10.3	-	-
Time to peak (hrs)	22	15	1	1
Antecedent Water Table Height (m)	0.23	0.00	-0.10	0.27
Post Event Water Table Height (m)	0.52	0.23	-0.01	0.29
Maximum Water Table Height (m)	0.89	0.67	0.35	0.66
Antecedent Soil Moisture (mm)	303.0	305.2	250.3	333.3
Post Event Soil Moisture (mm)	319.3	328.4	264.9	338.0
Event Change in Soil Moisture (mm)	16.4	23.1	14.7	4.7
Drainage to Precipitation Ratio (mm/mm)	0.18	0.31	-	-

Event Number	15			
Start Time	12/20/2012 6:00			
End Time	12/22/2012 11:00			
Event Duration (hrs)	54			
Total Precipitation (mm)	14.3			
Hours of Precipitation (hrs)	10			
Average Precipitation Intensity (mm/hr)	1.4			
Precipitation Time Spread (hr)	5.8			
Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	184.1	292.7	-	-
Peak Flow (m^3/hr)	7.5	12.5	-	-
Time to peak (hrs)	31	13	1	1
Antecedent Water Table Height (m)	0.40	0.18	-0.03	0.63
Post Event Water Table Height (m)	0.86	0.47	0.01	0.62
Maximum Water Table Height (m)	1.27	0.81	0.80	0.95
Antecedent Soil Moisture (mm)	310.5	312.1	258.0	370.7
Post Event Soil Moisture (mm)	328.6	335.4	275.9	378.2
Event Change in Soil Moisture (mm)	18.1	23.4	17.9	7.5
Drainage to Precipitation Ratio (mm/mm)	0.37	0.58	-	-

Event Number	16			
Start Time	1/29/2013 7:00			
End Time	2/1/2013 12:00			
Event Duration (hrs)	78			
Total Precipitation (mm)	21.7			
Hours of Precipitation (hrs)	30			
Average Precipitation Intensity (mm/hr)	0.7			
Precipitation Time Spread (hr)	29.6			
Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	285.8	390.4	-	-
Peak Flow (m^3/hr)	7.6	18.0	-	-
Time to peak (hrs)	39	25	1	1
Antecedent Water Table Height (m)	0.68	0.57	-	0.75
Post Event Water Table Height (m)	0.71	0.20	-	0.54
Maximum Water Table Height (m)	1.28	0.90	-	1.00
Antecedent Soil Moisture (mm)	296.8	313.8	275.0	364.7
Post Event Soil Moisture (mm)	309.1	308.4	275.0	338.7
Event Change in Soil Moisture (mm)	12.3	-5.4	0.0	-25.9
Drainage to Precipitation Ratio (mm/mm)	0.38	0.51	-	-

Event Number	17			
Start Time	2/26/2013 7:00			
End Time	3/2/2013 15:00			
Event Duration (hrs)	105			
Total Precipitation (mm)	25.4			
Hours of Precipitation (hrs)	28			
Average Precipitation Intensity (mm/hr)	0.9			
Precipitation Time Spread (hr)	33.7			
Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	516.3	647.5	-	-
Peak Flow (m^3/hr)	7.1	14.2	-	-
Time to peak (hrs)	34	15	1	1
Antecedent Water Table Height (m)	0.25	0.05	-0.07	0.51
Post Event Water Table Height (m)	0.81	0.36	0.03	0.59
Maximum Water Table Height (m)	1.19	0.83	0.94	0.99
Antecedent Soil Moisture (mm)	290.2	302.4	245.5	334.8
Post Event Soil Moisture (mm)	317.4	320.0	275.8	349.3
Event Change in Soil Moisture (mm)	27.2	17.6	30.3	14.5
Drainage to Precipitation Ratio (mm/mm)	0.58	0.73	-	-

Event Number	18			
Start Time	3/8/2013 7:00			
End Time	3/13/2013 22:00			
Event Duration (hrs)	136			
Total Precipitation (mm)	23.4			
Hours of Precipitation (hrs)	10			
Average Precipitation Intensity (mm/hr)	2.3			
Precipitation Time Spread (hr)	80.3			
Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	518.4	676.8	-	-
Peak Flow (m^3/hr)	6.8	15.0	-	-
Time to peak (hrs)	89	80	1	1
Antecedent Water Table Height (m)	0.38	0.20	-0.05	0.62
Post Event Water Table Height (m)	0.88	0.38	0.02	0.61
Maximum Water Table Height (m)	1.24	0.87	0.93	0.99
Antecedent Soil Moisture (mm)	308.8	308.8	252.4	357.4
Post Event Soil Moisture (mm)	322.1	321.6	277.8	362.4
Event Change in Soil Moisture (mm)	13.4	12.8	25.4	5.0
Drainage to Precipitation Ratio (mm/mm)	0.63	0.83	-	-

Event Number	19			
Start Time	3/27/2013 13:00			
End Time	3/30/2013 3:00			
Event Duration (hrs)	63			
Total Precipitation (mm)	10.2			
Hours of Precipitation (hrs)	1			
Average Precipitation Intensity (mm/hr)	10.2			
Precipitation Time Spread (hr)	2			
Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	250.7	329.8	-	-
Peak Flow (m^3/hr)	6.4	11.4	-	-
Time to peak (hrs)	44	5	1	1
Antecedent Water Table Height (m)	0.32	0.22	-0.03	0.70
Post Event Water Table Height (m)	0.88	0.44	0.02	0.65
Maximum Water Table Height (m)	1.10	0.76	0.71	0.98
Antecedent Soil Moisture (mm)	309.3	318.4	276.7	370.6
Post Event Soil Moisture (mm)	327.9	327.5	280.1	362.3
Event Change in Soil Moisture (mm)	18.6	9.1	3.4	-8.3
Drainage to Precipitation Ratio (mm/mm)	0.70	0.93	-	-

Event Number	20
Start Time	5/27/2013 16:00
End Time	5/29/2013 12:00
Event Duration (hrs)	45
Total Precipitation (mm)	20.8
Hours of Precipitation (hrs)	5
Average Precipitation Intensity (mm/hr)	4.2
Precipitation Time Spread (hr)	3.5

Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	159.9	213.9	-	-
Peak Flow (m^3/hr)	9.8	15.4	-	-
Time to peak (hrs)	25	7	1	1
Antecedent Water Table Height (m)	0.19	0.03	-0.06	0.19
Post Event Water Table Height (m)	0.52	0.27	0.00	0.30
Maximum Water Table Height (m)	1.09	0.81	0.65	0.84
Antecedent Soil Moisture (mm)	333.8	319.4	271.5	343.7
Post Event Soil Moisture (mm)	347.7	343.5	282.9	353.4
Event Change in Soil Moisture (mm)	13.9	24.1	11.4	9.7
Drainage to Precipitation Ratio (mm/mm)	0.22	0.29	-	-

Event Number	21
Start Time	6/1/2013 2:00
End Time	6/3/2013 3:00
Event Duration (hrs)	50
Total Precipitation (mm)	18.5
Hours of Precipitation (hrs)	5
Average Precipitation Intensity (mm/hr)	3.7
Precipitation Time Spread (hr)	2.6

Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	192.0	260.7	-	-
Peak Flow (m^3/hr)	10.1	17.7	-	-
Time to peak (hrs)	27	5	1	1
Antecedent Water Table Height (m)	0.33	0.10	-0.05	0.28
Post Event Water Table Height (m)	0.52	0.24	-0.01	0.30
Maximum Water Table Height (m)	1.12	0.83	0.77	0.92
Antecedent Soil Moisture (mm)	346.3	327.1	274.3	352.8
Post Event Soil Moisture (mm)	352.0	345.4	282.9	358.0
Event Change in Soil Moisture (mm)	5.8	18.2	8.6	5.2
Drainage to Precipitation Ratio (mm/mm)	0.30	0.40	-	-

Event Number	22			
Start Time	6/12/2013 22:00			
End Time	6/16/2013 4:00			
Event Duration (hrs)	79			
Total Precipitation (mm)	61.7			
Hours of Precipitation (hrs)	9			
Average Precipitation Intensity (mm/hr)	6.9			
Precipitation Time Spread (hr)	17.5			
Quadrant	**NW**	**SW**	**NE**	**SE**
Total Drainage Volume (m^3)	320.6	401.8	-	-
Peak Flow (m^3/hr)	7.5	21.0	-	-
Time to peak (hrs)	21	4	1	1
Antecedent Water Table Height (m)	0.23	0.05	-0.06	0.28
Post Event Water Table Height (m)	0.51	0.15	-0.03	0.29
Maximum Water Table Height (m)	1.19	0.91	0.95	1.02
Antecedent Soil Moisture (mm)	344.7	326.7	270.6	349.0
Post Event Soil Moisture (mm)	356.9	342.0	283.4	360.9
Event Change in Soil Moisture (mm)	12.3	15.3	12.8	11.9
Drainage to Precipitation Ratio (mm/mm)	0.15	0.19	-	-