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Hydraulic Conductivity, Infiltration, and Runoff from No-till and Tilled Cropland

Jessica H. Deck
University of Nebraska-Lincoln, jhdeck@huskers.unl.edu

HYDRAULIC CONDUCTIVITY, INFILTRATION, AND RUNOFF FROM NO-TILL AND TILLED CROPLAND

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Jessica H. Deck

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Jessica H. Deck, M.S.

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Advisor: Dean E. Eisenhauer

Infiltration and runoff are important processes that affect the efficiency of center pivot irrigation systems. No-till planting systems potentially influence the hydraulic properties of soils and the soil surface conditions. The result of long-term use of no-till could be higher infiltration and lower runoff from rainfall and irrigation.

This potential was investigated in Nebraska on two center pivot irrigated sites; Fillmore County and Phelps County, one furrow irrigated site; South Central Agriculture Laboratory (SCAL), and one dryland site; Rogers Farm. Paired treatments were used at each location, one that was no-till planted and one that used two to three operations per year for seed-bed preparation and cultivation. Operations were consistent for at least seven years on all fields before experiments were conducted.

In 2008-2010 runoff was monitored during the cropping season at the center pivot irrigated sites. During this time interval, hydraulic conductivity tests were performed at all sites. Cumulative runoff data showed more runoff on tilled fields, which aligns with findings from the hydraulic conductivity from these fields. Surface satiated hydraulic conductivity was significantly higher for no-till at the center pivot irrigated sites with 6.2 cm h^{-1} and 8.2 cm h^{-1} measured for no-till and 3.9 cm h^{-1} and 2.8 cm h^{-1} for tilled. However, the dryland corn had significantly higher hydraulic conductivity on the tilled

plot (46.3 cm h^{-1}) compared to the no-till (8.3 cm h^{-1}) plot. This discrepancy may be due to soil shrinkage causing surface cracks. Overall, no-till fields had higher hydraulic conductivity and lower runoff.

Using 2010 gathered rainfall data from the center pivot irrigated sites, satiated hydraulic conductivity was predicted using four models: Crust Factor, ROSETTA, Water Erosion Prediction Project (WEPP), and Soil Water Characteristics tool (SWC). The hydraulic conductivity values were compared to both rainfall and irrigation runoff using the Green and Ampt equation. WEPP had the smallest percent bias (28%). The model over predicted runoff at the no-till field at Phelps County. No model predicted an optimal satiated hydraulic conductivity for all fields.

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CHAPTER 1: HYDRAULIC CONDUCTIVITY AND RUNOFF OF TILLED AND NO-TILL CROPLAND

1.1 Introduction

The potential for runoff from irrigation and rainfall is linked to management practices (Pagliai et al., 2004; Green et al., 2003), peak application rate of the center pivot system (Dillon, 1972), and the physical properties within a field (Strudley et al., 2008). The field's soil hydrology illustrates how efficiently water is utilized during an irrigation or rainfall event. Satiated hydraulic conductivity, influenced by the soil's characteristics, describes the ability of soil to transmit water under near saturated conditions (ASABE, 2007). Increasing the rate at which soil absorbs water results in more water available to meet crop needs and less water lost through runoff. Hydraulic conductivity is highly variable and dependent on field characteristics and management practices. Understanding the factors that influence hydraulic conductivity in agricultural fields may illustrate a potential to decrease runoff.

Conservation tillage is one management practice that can influence the characteristics of the field and increase infiltration of water into the soil. Differences in the surface characteristics, e.g., increasing organic matter, may decrease the amount of runoff that occurs from rainfall (Mielke et al., 1986), and may reduce the need for irrigation (DeBoer et al., 1992).

One type of conservation tillage is no-till planting. No-till planting, defined as minimal disturbance of the soil surface by placing the seed directly into the soil without disruption of the surface residue, and tillage, the breaking of the structure of soil surface by cultivation (ASABE, 2007), are different management practices that can affect infiltration and runoff rates. Studies have investigated the potential for no-till planting to increase hydraulic conductivity and infiltration. The following factors have been linked to the benefits of no-till.

No-till fields may have higher hydraulic conductivity due to the undisturbed macropore network connected to the surface. Macropores are defined as soil pores greater than 1.0 mm (Luxmoore, 1981), which conduct water near saturated conditions (Watson and Luxmoore, 1986). An increase in macropores at the soil's surface would correspond to an increase of water into the soil (Edwards et al. 1979). The presence of macropores has been investigated in many studies. Blevins et al. (1983) and Logsdon (1990) found tillage breaks apart the soil surface structure and, as a result, disrupts the flow into the macropores. Azooz and Arshad (1996) studied silt loam and sandy loam soils with conventional tillage and no-till treatments. The higher observed infiltration in no-till was attributed to a greater number of macropores.

Another impact of no-till may be minimal surface sealing. As drops from rain or sprinkler irrigation hit the soil, aggregates on the surface break down, forming a seal and reducing the hydraulic conductivity of the soil (Tebrugge and During, 1999; Ela et al., 1992; Duley, 1939). This effect can be reduced by crop residue. After removing residue from the soil, Bradford and Huang (1994) found a drop in hydraulic conductivity from 7.0 to 5.9 cm h^{-1} in no-till fields. The drop between no-till fields with residue and tilled fields with no residue was greater (7.0 to 3.9 cm h^{-1}). Surface sealing may also be prevented by certain characteristics of the soil's surface. No-till fields keep the surface soil structure intact, which can lead to stable aggregates. Stronger aggregates have been found in no-till due to the undisturbed surface (Packer et al., 1992). An increase in greater organic matter, shown plausible in research performed by Arshad et al. (1990), has also lead to reduced surface sealing (McIntyre, 1958).

Lastly, increased storage created through surface roughness from residue may increase the storage that must be filled before runoff occurs (Onstad, 1984). No-till fields are described as having 55-75% residue cover in corn and 40-60% in soybean, while tilled fields have 30-60% residue left from a corn crop and 20-40% from soybean (USDA NRCS, 1992). Steichen (1984) investigated surface roughness and found as surface residue increased, infiltration increased. The increase in residue could therefore decrease the runoff measured on a field (Gilley et al., 1986).

These characteristics are potential results of no-till planting, all which may increase hydraulic conductivity and reduce runoff. Although higher infiltration rates have been linked with no-till systems, studies have reported mixed findings when measuring and comparing the hydraulic conductivity of tilled and no-till fields. Hydraulic conductivity values have been shown to be time varying throughout the cropping months. Mapa et al. (1986) found an increase of hydraulic conductivity once tillage occurred. Starr (1990) observed the difference between tilled and no-till hydraulic conductivity to be variable throughout the season. Another factor that changes with time is the moisture content. Initial moisture content and time between runoff events has been shown to be a factor in tilled and no-till runoff as well. Isensee et al.

(1993) found that events less than six days since the last runoff result in higher runoff in no-till.

Not only is there variability throughout a season, but also within a field. Ankeny et al. (1990), Culley et al. (1987), Freese (1993), and Buczko et al. (2006) found untrafficked rows had higher conductivity in the tilled field.

When investigating the impact of no-till on water savings, findings have been varied. Blanco-Canqui et al. (2004) and Gregorich et al. (1993) found no difference in hydraulic conductivity between tilled and no-till fields. Mielke et al. (1986) noticed higher infiltration rates into the tilled fields, and Heard et al. (1988) found texture was a more significant factor in the value of hydraulic conductivity than tillage treatment. Shipitalo and Edwards (1993) found 36% more infiltration with no-till fields.

The main objective of this research is to quantify the satiated hydraulic conductivity and runoff on center pivot irrigated, long-term no-till systems. Two supplementary objectives include:

1. Determine the effect of slot, ridge, and disk planting on the satiated hydraulic conductivity in a furrow irrigated field and measure satiated hydraulic conductivity on dryland tilled and no-till plots.
2. Investigate factors that may increase the satiated hydraulic conductivity and decrease runoff.

1.2 Methods

To determine the effect of no-till planting on infiltration and runoff, center pivot irrigated tilled and no-till fields were studied in Nebraska. Satiated hydraulic conductivity data were compared to the measured runoff events under rainfall and center pivot irrigation. Secondly, factors that may influence infiltration, such as residue, depressional storage, macropores, and aggregate stability were investigated.

Supplementing center pivot irrigated field data, hydraulic conductivity measurements were performed on furrow irrigated fields. Experiments took place in rotational corn (corn/soybean rotated) during the corn year and in continuous corn. In addition to the furrow irrigated site, a dryland site was also included in the study. Hydraulic conductivity tests were performed on tilled and no-till sections. Experiments took place in soybean and in corn.

1.2.1 Field data

Study areas included two center pivot irrigated sites, one furrow irrigated site, and one dryland site in Nebraska. The first center pivot site is located in Fillmore County in southeast Nebraska. The study area contains Crete silty clay loam soil (USDA NRCS, 2010) with a slope of 1.0%. Fillmore County center pivots have Nelson R3000 Rotators and Sprayheads. The second site is located in south central Nebraska in Phelps County. This site includes fields with Holdrege silt loam soil (USDA NRCS, 2010) and a measured slope of 0.4%. In Phelps County, Valley Sprayheads are installed at the no-till site and Nelson Sprayheads at the tilled site. Center pivot characteristics are shown in Table 1.1.

Table 1.1. Center pivot characteristics. R = distance to sprinkler; R_s = system length; W_r = wetted radius, D_a = depth applied.

Site	Plot	Span	R, m	Q, L/s	D_a, cm	R_s, m	W_r, m	Field size, ha
Fillmore County	No-till	3	123	37.9	2.5	392	9.8	48
		5	219					
		7	343					
	Tilled	3	145	48.9	2.5	395	8.5	49
		5	251					
		7	341					
Phelps County	No-till	7	359	50.5	2.5	395	6.2	49
	Tilled	7	355	50.5	2.5	397	8.5	49

Each center pivot site contains two fields cropped with a corn/soybean rotation. All the fields were in soybean in 2008. The two fields for each site included one tilled field that was tilled once in the spring, before planting, and one practicing long term, continuous no-till. The no-till and tilled fields at each site were paired to match in planting date, corn hybrid and soybean cultivar, location for similarities in weather, land slope, and soil type. Soil properties for each field are shown in Table 1.2.

In 2009, a rolling stalk chopper was employed in place of pre-planting tillage in the tilled field at Fillmore County and Fillmore County no-till field used a strip tillage system. After planting, Fillmore tilled field was only partially cultivated due to the corn being too tall. Other than these discrepancies, tillage operations have been consistent for at least seven years. The final year, 2010, both no-till fields used true no- till planting and the tilled fields were tilled in the spring before planting and once in July.

Roger's Memorial Farm is a research farm operated by the University of Nebraska-Lincoln. The farm is located in southeast Nebraska in Lancaster County. The soil is Aksarben silty clay loam with a slope of 6-11% (USDA NRCS, 2010). The site includes two dryland plots, one in corn and one in soybean. Each plot has three sections of no-till and three sections of tilled. Each section measures 9.1 m by 22.9 m. There were a total of twelve sections included in this research; all were corn/soybean rotated. Tillage systems have been continuous since 1981.

Table 1.2. The soil properties at each site. ρ_b is the bulk density and h_f is the wetting front pressure head. Subtillage indicates measurements taken below the tillage layer (approximately 15 cm)

Site	Plot	Slope, %	Sand, %		Clay, %		Organic Matter, %		h_f, cm		ρ_b, g cm^{-3}		θ_s, cm^{3}cm^{-3}	
			Surface	Subtillage	Surface	Subtillage	Surface	Subtillage	Surface	Subtillage	Surface	Subtillage	Surface	Subtillage
Fillmore	No-till	1.0	22.3	20.4	24.2	24.3	3.2	3.1	35.9	40.6	1.19	1.25	0.50	0.48
County		(0.1)	(2.3)	(3.0)	(4.9)	(4.8)	(0.3)	(0.3)	(4.2)	(5.0)	(0.05)	(0.04)	(0.02)	(0.01)
	Tilled	0.9	19.8	19.0	21.3	21.3	3.2	3.0	28.1	36.4	1.09	1.23	0.61	0.59
		(0.2)	(1.7)	(2.1)	(2.1)	(2.8)	(0.5)	(0.4)	(1.2)	(3.8)	(0.07)	(0.14)	(0.14)	(0.19)
Phelps	No-till	0.2	21.6	21.1	21.3	20.7	3.4	3.0	29.5	34.7	1.15	1.25	0.51	0.48
County		(0.0)	(3.1)	(3.3)	(1.8)	(2.5)	(0.1)	(0.1)	(3.7)	(2.6)	(0.02)	(0.01)	(0.01)	(0.00)
	Tilled	0.5	25.7	24.6	18.8	20.7	3.5	3.2	23.9	28.5	1.10	1.21	0.52	0.49
		(0.1)	(2.1)	(2.3)	(1.1)	(1.4)	(0.2)	(0.4)	(0.6)	(3.9)	0.00	(0.09)	(0.00)	(0.03)
Rogers	No-till	6-11*	18.8	17.3	28.3	34.3	3.7	3.1	29.4	47.4	1.05	1.22	0.54	0.49
Farm Corn			(3.6)	(2.1)	(4.3)	(3.2)	(0.6)	(0.1)	(6.6)	(10.2)	(0.08)	(0.08)	(0.03)	(0.03)
	Tilled	6-11	17.2	17.8	30.0	30.8	3.4	3.3	28.2	30.9	0.99	1.05	0.56	0.54
			(2.0)	(2.2)	(3.6)	(3.9)	(0.2)	(0.1)	(4.1)	(4.5)	(0.05)	(0.06)	(0.02)	(0.02)
Rogers	No-till	6-11	19.7	17.7	26.0	29.7	4.0	3.1	31.8	39.2	1.12	1.18	0.52	0.50
Farm			(2.2)	(2.0)	(2.0)	(4.2)	(0.6)	(0.5)	(8.7)	(6.8)	(0.11)	(0.07)	(0.04)	(0.03)
Soybean	Tilled	6-11	16.3	15.7	26.2	26.8	3.3	3.3	34.9	42.5	1.12	1.21	0.52	0.49
			(1.5)	(1.2)	(4.3)	(2.8)	(0.1)	(0.1)	(7.9)	(8.3)	(0.14)	(0.11)	(0.05)	(0.04)
SCAL	Slot	0.4**	19.3	18.0	20.0	25.3	4.0	2.9	29.0	45.0	1.11	1.30	0.52	0.46
Rotational			(1.5)	(1.0)	(1.7)	(1.5)	(0.2)	(0.1)	(9.1)	(16.1)	(0.31)	(0.35)	(0.14)	(0.12)
	Ridge	0.4	20.3	19.7	20.7	23.7	3.5	3.0	29.7	43.7	1.14	1.32	0.51	0.45
			(1.2)	(1.5)	(0.6)	(1.2)	(0.3)	(0.4)	(3.4)	(7.1)	(0.06)	(0.07)	(0.02)	(0.03)
	Disk	0.4	19.0	18.0	20.3	24.7	3.5	2.9	26.1	42.2	1.04	1.27	0.47	0.55
			0.0	0.0	(2.1)	(2.5)	(0.3)	(0.1)	(14.9)	(7.9)	(0.36)	(0.28)	(0.12)	(0.14)
SCAL	Slot	0.4	20.7	16.7	20.3	26.3	4.6	2.9	29.4	54.9	1.14	1.37	0.50	0.44
Continuous			(4.0)	(0.6)	(2.3)	(1.2)	(0.1)	(0.1)	(6.1)	(10.9)	(0.13)	(0.09)	(0.04)	(0.03)
	Ridge	0.4	18.0	18.0	19.3	23.3	3.9	2.8	31.3	46.8	1.13	1.36	0.50	0.44
			(1.0)	(1.7)	(4.7)	(2.9)	(0.4)	(0.3)	(5.5)	(5.0)	(0.08)	(0.05)	(0.03)	(0.02)
	Disk	0.4	18.0	19.0	20.3	21.3	3.5	3.5	28.9	41.7	1.08	1.29	0.43	0.54
			(1.0)	(1.0)	(2.5)	(1.5)	(0.1)	(0.5)	(9.7)	(3.0)	(0.15)	(0.08)	(0.05)	(0.03)

* Slope from Web Soil Survey (USDA, NRCS 2010)

** Slope from past records

The South Central Agricultural Research Laboratory (SCAL) in Clay County located in south central Nebraska was the location for the furrow irrigated site. The soil is Hastings silt loam (Table 1.2) with a slope of 0.4%. At this site, one field is divided into sections of different, long-term tillage practices. The tillage had been consistent for nine years at the time when the tests were performed. Tillage practices include sections of slot, ridge, and disk treatments divided into continuous corn and corn/soybean rotation subsections. Rotational sections began in 2002. Each subsection is eight rows in width with 76 cm row spacing. Excluding the first disk plot, which has a length of 335 m, the length of all sections are 378 m. Each section repeats three times for a total of nine plots (eighteen subsections). All patches are managed the same in regards to irrigation and fertilizer applications.

In Table 1.2 the wetting front pressure head, h_f, was calculated using the following pedotranfer function (Rawls and Brakensiek, 1983):

$$h_f = \exp[6.53 - 7.326\,(0.9 \cdot \eta) + 0.00158\,(\text{Clay})^2 + 3.809\,(0.9 \cdot \eta)^2 + 0.000344\,(\text{Sand})(\text{Clay}) - 0.04989\,(\text{Sand})\,(0.9 \cdot \eta) + 0.0016\,(\text{Sand})^2\,(0.9 \cdot \eta)^2 + 0.0016\,(\text{Clay})^2\,(0.9 \cdot \eta)^2 - 0.0000136\,(\text{Sand})^2\,(\text{Clay}) - 0.00348\,(\text{Clay})^2\,(0.9 \cdot \eta) - 0.000799\,(\text{Sand})^2\,(0.9 \cdot \eta)] \quad (1.1)$$

where Sand and Clay units are % and η = porosity. Assuming 90% of porosity described field saturation, or satiation, $\theta_s = 0.9 \cdot \eta$. Porosity was calculated from the measured bulk density assuming particle density is 2.65 g cm^{-3}.

1.2.2 Runoff

Each center pivot field contained three micro runoff plots, which included a rain gage, runoff frame, gutter, sump, and pressure transducer. This configuration is shown in Figure 1.1

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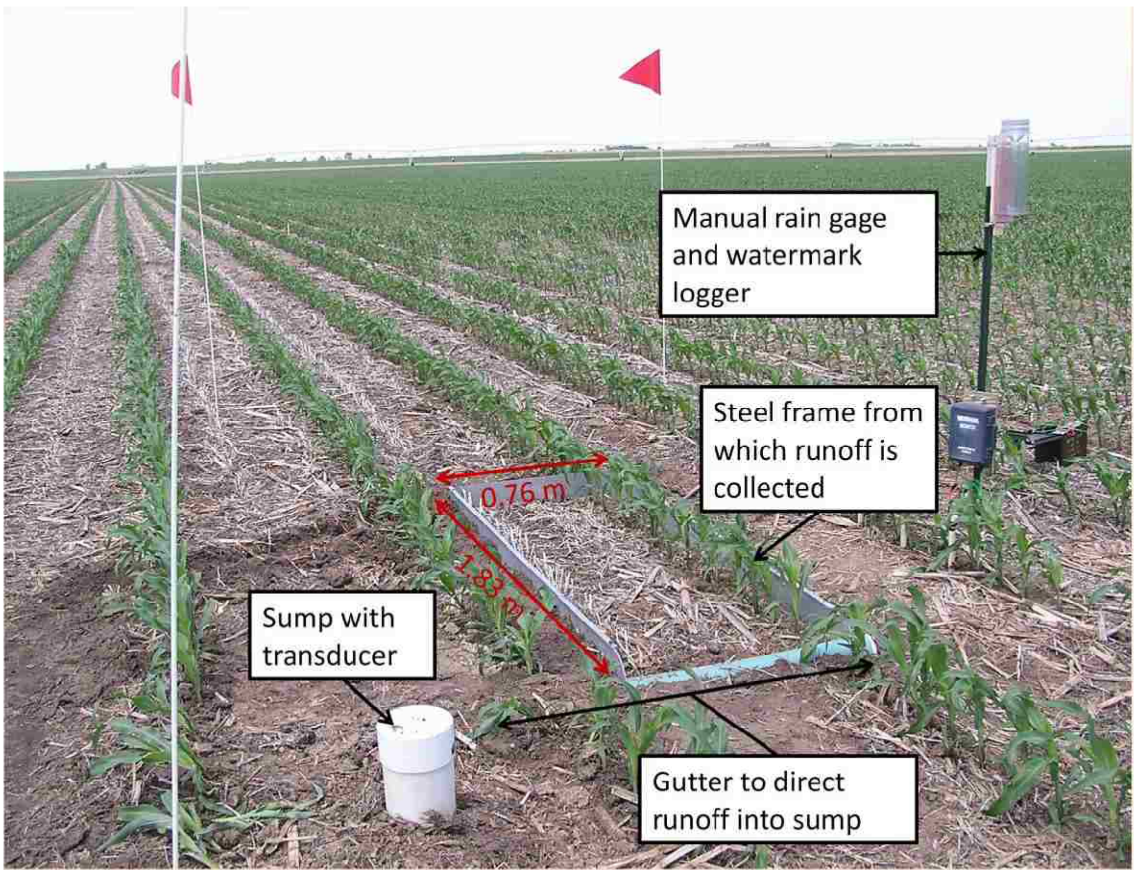

Figure 1.1. Picture of micro runoff plot equipment

At the Fillmore site, the micro runoff plots were located in spans 3, 5, and 7. At the Phelps site, all of the plots were installed in span 7. Runoff plot placement avoided unrepresentative rows, such as varying spacing on the end rows of the planter and wheel tracks. Micro runoff plots were designed based on procedures established in the National Phosphorus Research Project (Sharpley and Kleinman, 2003). The galvanized steel frames, measuring 0.76 m wide by 1.83 m long and driven into the soil 15 cm, captured a representative sample of field runoff. Runoff was caught by a 0.10 m wide gutter covering the down slope width of the frame. The gutter routed the runoff into a sump extending six feet into the ground. The gutter was exposed to the rainfall and the depth of rain received directly onto the gutter area was subtracted from the amount of runoff measured in the sump to acquire an accurate runoff from the micro runoff frame. Figure1.2 shows the difference between the sump hydrograph, which includes the depth of water from the impervious gutter, and the runoff hydrograph.

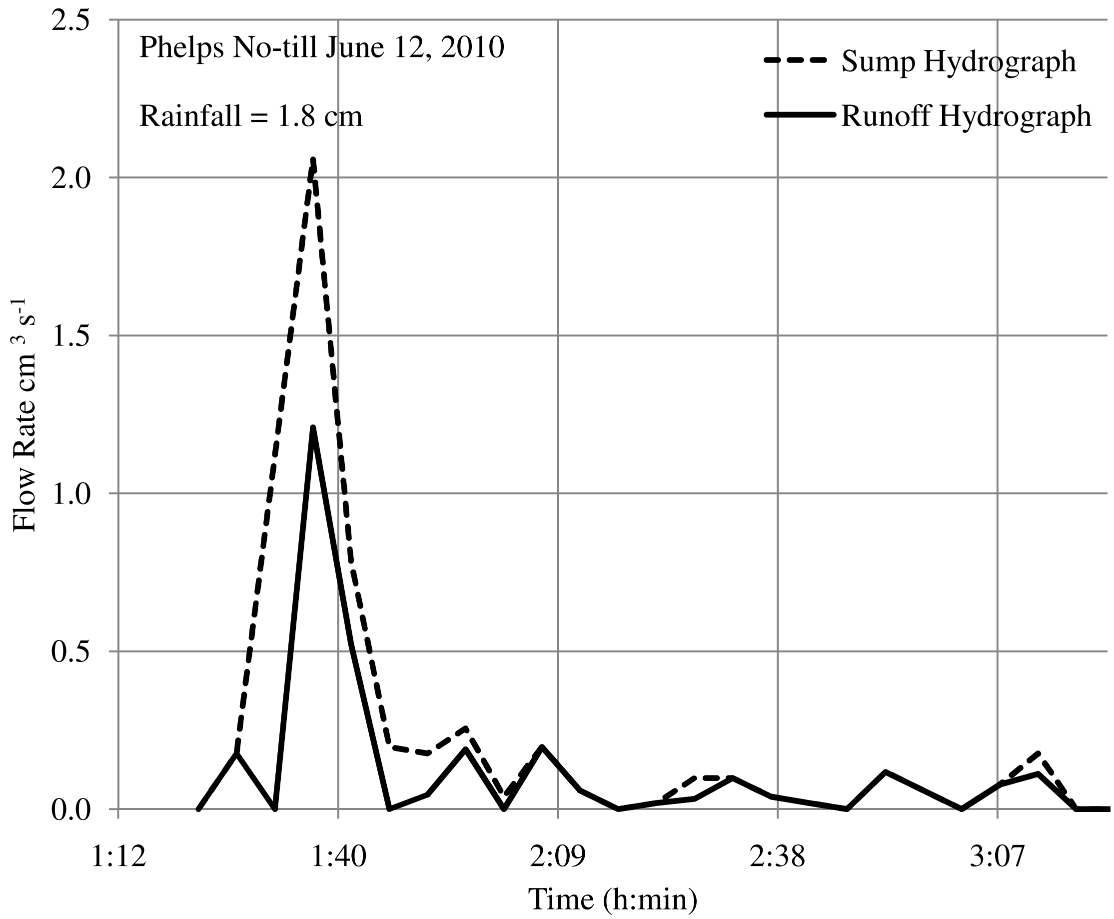

Figure 1.2. Hydrographs observed in sump and then converted to runoff from subtracting rainfall hitting impervious gutter and being directed into the sump

Water in the sump was monitored using a pressure transducer hanging approximately five centimeters above the base of the sump. The HOBO Onset U20 Water Level USB Logger recorded the change in water level during an event due to pressure changes with a resolution of 0.21 cm. Water level data were recorded every five minutes during the summer and adjusted for barometric pressure changes occurring throughout the day. Runoff was assumed to be immediate from the end of the frame to the sump and no routing method was considered. Data downloaded from the pressure transducer were used to calculate the amount of runoff that occurred from within the frame during each rainfall or irrigation event. To accommodate large and numerous events, a 12 volt operated, 2.84 $m^3 h^{-1}$ Johnson Pump Model 2270 was installed to remove water from the sump.

Monitoring runoff began in 2008 at Fillmore County in soybean. Instrumentation was installed in August and removed in late September. In 2009 and 2010, runoff events in late-May through September were monitored at the Fillmore County and Phelps County sites.

1.2.3 Satiated hydraulic conductivity

Modification of Smith's infiltration testing procedure (1999) was used to measure hydraulic conductivity. Single ring infiltration tests were performed at the center pivot irrigated sites close to the three runoff plots in each field in late June to early July 2009. Locations were chosen 1.5 m upslope of the three micro runoff frames, in three consecutive rows, where there had been minimal foot traffic. The tests performed in the two fields at each site were completed within two days, without any rain or irrigation occurring between time intervals. Eight tests were performed at each plot for a total of twenty-four tests per field.

Rogers Farm hydraulic conductivity tests were performed in early July 2009. Tests were executed on both rotational soybean and corn. Four tests were performed in each section for a total of 48 tests. In early June 2010, single ring infiltration tests were executed at the furrow irrigated site, SCAL. In each strip, eight conductivity tests were performed for the rotational corn and continuous corn for a total of 144 tests. Again, the tests were performed in two consecutive days on dry soil without any rain between days.

Hydraulic conductivity was measured on the soil surface and in the subtillage layer, defined as the soil immediately below the tillage layer. To measure infiltration of water into the soil's surface, the test areas were prepared by removing loose residue while being cautious not to disturb the surface. Surface residue partially buried in the soil within the perimeter of the ring was left in place. Residue extending beyond the border of the test area was cut before the ring was driven into the soil so as not to create a gap between the metal rim and soil where water could penetrate.

Randomly, half the sites were chosen for subtillage infiltration measurement. The loose, cultivated layer, approximately 15 cm depending on the cultivator, was removed from the tilled field. The depth of the soil layer removed on the no-till fields was 80% of that removed on the corresponding tilled field to account for a higher bulk density in the no-till surface layer. The test areas with the surface layer removed were vacuumed to avoid obstruction to water pathways by removing loose dirt that may have been displaced from digging.

A 14.88 cm diameter ring was driven into the ground 15 cm. A coffee filter was then set in the infiltration ring before water was added to minimize surface disturbance. For each plot, the temperature of water was documented to account for changes in viscosity, then 285 mL of tap water, equivalent to 1.64 cm of depth, was added into the ring and the filter was gently removed. The time was recorded for half the surface to be free from water. If time exceeded three minutes, water was removed with a syringe until half the soil was free from water ponding. Both time and the volume of water removed were recorded.

The inverse form of the Green and Ampt infiltration equation (Green and Ampt, 1911) was used to calculate field satiated hydraulic conductivity, K_s, and is given by:

$$K_s = 1/t\ [F - h_f \Delta\theta \ln (1+F/ (h_f \Delta \theta))] \quad (1.2)$$

in which t = time for water to infiltrate; F = cumulative infiltration; h_f = wetting front pressure head; $\Delta\theta$ = change in moisture content. Wetting front pressure head was calculated using Rawls and Brakensiek (1983) pedotransfer function. At the time of the field infiltration test, a 136 cm^3 soil sample next to the ring was taken to determine bulk density and initial water content. The length of the bulk density core was 6 cm. A sample for lab hydraulic conductivity was also taken randomly from a quarter of the test areas.

1.2.4 Lab experiments

Satiated hydraulic conductivity was measured in the lab using the falling head method (Klute, 1986). Tests were performed on undisturbed samples collected from the matching layer where the corresponding field conductivity test was performed. The location of collection was immediately upslope from the field test. The samples were used to verify field methods.

To collect lab samples, a core sampler was driven into the ground 7 cm. The sample ring was 3 cm in length. The soil was left in the ring during the test to keep the core intact. A 25 cm acrylic tube was fastened to the metal ring sample using a rubber seal. However, the soil/ring seam was occasionally loose, increasing the conductivity erroneously. Samples were soaked in tap water for 12 hours to satiate the core and eliminate most of the air in the pores. After the conductivity test was performed, the samples were dried to obtain bulk density. Subsamples of the core were used for lab analysis of percent sand, clay, and organic matter.

1.2.5 Depressional storage, surface seal, and aggregates

Random roughness is a measure of the variation in height of the surface depressions, due to soil relief and surface residue, and relates to the depth of water that can be stored on the surface. Random roughness was determined using the Saleh chain method (Saleh, 1993). A 1.0 m roller chain (ANSI 35 riv.type) was carefully positioned on the ground, parallel to the row, hugging residue and surface contours. The reduced length was measured. The roughness of the field was determined using Saleh's chain method equation for random roughness.

$$RR = (1 - L_2 / L_1)100 \qquad (1.3)$$

where RR = random roughness, L_1 = the length of the chain, L_2 = the adjusted length of the chain when draped over depressions and residue on the ground.

Once ponding occurs, the water begins to pool in depressions on the surface and is referred to as the depressional storage. From the random roughness, depressional storage was calculated by Equation 1.3 developed by Onstad (1987).

$$DS = 0.112 \cdot RR + 0.031 \cdot RR^2 - 0.012 \cdot RR \cdot S \qquad (1.4)$$

where DS = depressional storage in centimeters, RR = random roughness in centimeters, and S = percent slope.

In 2009, residue was counted on eight random locations on the fields. In 2010, residue was counted within the runoff frames. Every tenth of a foot, hits or misses were counted (a hit being a piece of residue larger than 0.5 cm) on the diagonals of each frame, and percent residue was calculated. The furrow irrigated field residue was counted in 2010, upslope from the ring conductivity tests.

Aggregate stability was investigated at the center pivot sites. Lab procedures were conducted based on the study done by Kemper and Koch (1966). Approximately forty grams of soil was taken from the soil surface. Twelve samples were taken from each center pivot irrigated field and eight samples from each clay center subplot. The samples were air dried for twelve hours. The soil was then sieved through a 2 mm and then 1 mm sieve. The aggregates were the portion of the soil that went through the 2 mm sieve, but not the 1 mm sieve. The sample was misted with water so air pockets would not form when placed into water. Then the soil was placed on a 250 μm sieve, immersed into water, and then removed from water. The pulsing of inundation took place for three minutes at a rate of 35 submerges per minute. Samples were dried and weighed and the process is repeated with a dispersing solution, hexameta-phosphate. The dispersing solution broke apart all aggregates so the sand and residue can be weighed and subtracted from the stable aggregates.

1.2.6 Macropores

Macropores were quantified in each field through image analysis. An 8.6 cm diameter soil sampler was used to collect soil cores directly below the tillage layer, to a depth of approximately 6.5 cm, for both sites. The core was flipped over and the picture was taken on the underside of the excavated core at each infiltration test area. Pores greater than 1.0 mm were considered macropores (Luxmoore, 1981). The pores at the bottom of the tillage layer were assumed to be connected with surface. Using the picture, pores were counted within each sample and the diameter was measured. Each pore was assumed circular. The total area of macropores was found and compared to the area sampled.

1.3 Results and Discussion

1.3.1 Measured hydraulic conductivity

Hydraulic conductivity data are presented in Table 1.3 and displayed in Figure 1.4. Fillmore County, Phelps County, and SCAL have a texture of silt loam. Surface and subtillage hydraulic conductivity values fall in line with values reported in other references for silt loam such as Rawls et al. (1993). However, the rotational disk plot in SCAL was in the upper range provided. The Rogers Farm site, which has a texture of silty clay loam, had high surface and subtillage hydraulic conductivity values when compared to those reported for silty clay loam by Rawls et al. (1993). At Fillmore County, the no-till field had a geometric mean surface hydraulic conductivity of 6.2 cm $h^{-1}$and the tilled field had a value of 3.9 cm h^{-1}. Phelps County followed the same trend as Fillmore County with a no-till hydraulic conductivity geometric mean of 8.21 cm h^{-1} and the tilled hydraulic conductivity geometric mean of 2.82 cm h^{-1}. Rogers Farm corn had higher hydraulic conductivity in the tilled plot (46.3 cm h^{-1}) than the no-till (8.3 cm h^{-1}). Rogers Farm soybean measured a hydraulic conductivity of 16.4 cm h^{-1} for no-till and 11.3 cm h^{-1} for the tilled. SCAL slot, ridge, and disk treatments were found to have surface conductivities of 8.9 cm h^{-1}, 4.6 cm h^{-1}, and 22.1 cm h^{-1}, respectively, for the rotational corn and 4.5 cm h^{-1}, 2.8 cm h^{-1}, and 8.7cm h^{-1} for the slot, ridge, and disk treatments in continuous corn.

Table 1.3. Geometric means of satiated hydraulic conductivity in no-till and tilled fields for field tests. Twelve tests were conducted per plot for Fillmore County, Phelps County, and SCAL. Six tests were run for each value in Rogers Farm.

			Geometric Mean (mean ± 1 standard deviation)*	
Site	Plot	Date	Surface K_s, cm h^{-1}	Subtillage K_s, cm h^{-1}
Fillmore County	No-till	22-Jun-09	6.18	0.88
Rotational Corn			(2.10-18.22)	(0.15-5.37)
	Tilled**	22-Jun-09	3.89	1.03
			(1.44-10.49)	(0.56-1.88)
Phelps County	No-till	23-Jun-09	8.21	1.27
Rotational Corn			(3.47-19.44)	(0.61-2.62)
	Tilled	23-Jun-09	2.82	1.42
			(1.26-6.30)	(0.75-2.67)
Rogers Farm	No-till	7,8-July-09	8.25	13.08
Rotational Corn			(1.39-49.00)	(5.21-32.84)
	Tilled	7,8-July-09	46.29	19.83
			(26.28-81.52)	(11.23-34.99)
Rogers Farm	No-till	7,8-July-09	16.35	4.94
Rotational Soybean			(4.03-66.36)	(1.25-19.45)
	Tilled	7,8-July-09	11.3	15.26
			(1.85-68.98)	(1.90-122.57)
SCAL	Slot	10-Jun-10	8.89	1.94
Rotational Corn			(1.26-18.55)	(1.08-2.49)
	Ridge	10-Jun-10	4.64	1.39
			(2.57-8.39)	(0.74-2.64)
	Disk	11-Jun-10	22.13	1.04
			(11.08-44.20)	(0.44-2.50)
SCAL	Slot	10-Jun-10	4.48	0.94
Continuous Corn			(1.26-18.55)	(0.57-1.53)
	Ridge	10-Jun-10	2.81	0.84
			(0.90-8.77)	(0.47-1.49
	Disk	11-Jun-10	8.74	0.54
			(2.31-33.04)	(0.21-1.40)

$* \text{ mean } \pm \text{ standard deviation } = 10^{[\log_{10}(\bar{y}) + \log_{10}(s_y)]}$

** Only eight tests are included for Fillmore County tilled

The high surface hydraulic conductivity values measured in the field were also present in the lab tests as shown in the plot of lab versus field graph in Figure 1.3. The lab test had higher hydraulic conductivity values. The lab data illustrated the field methods were sufficient. The geometric mean of field measured satiated hydraulic conductivity over the geometric mean of the lab satiated hydraulic conductivity was 0.29 for surface measurements and 0.54 for the values in the subtillage layer, indicating field values were slightly higher.

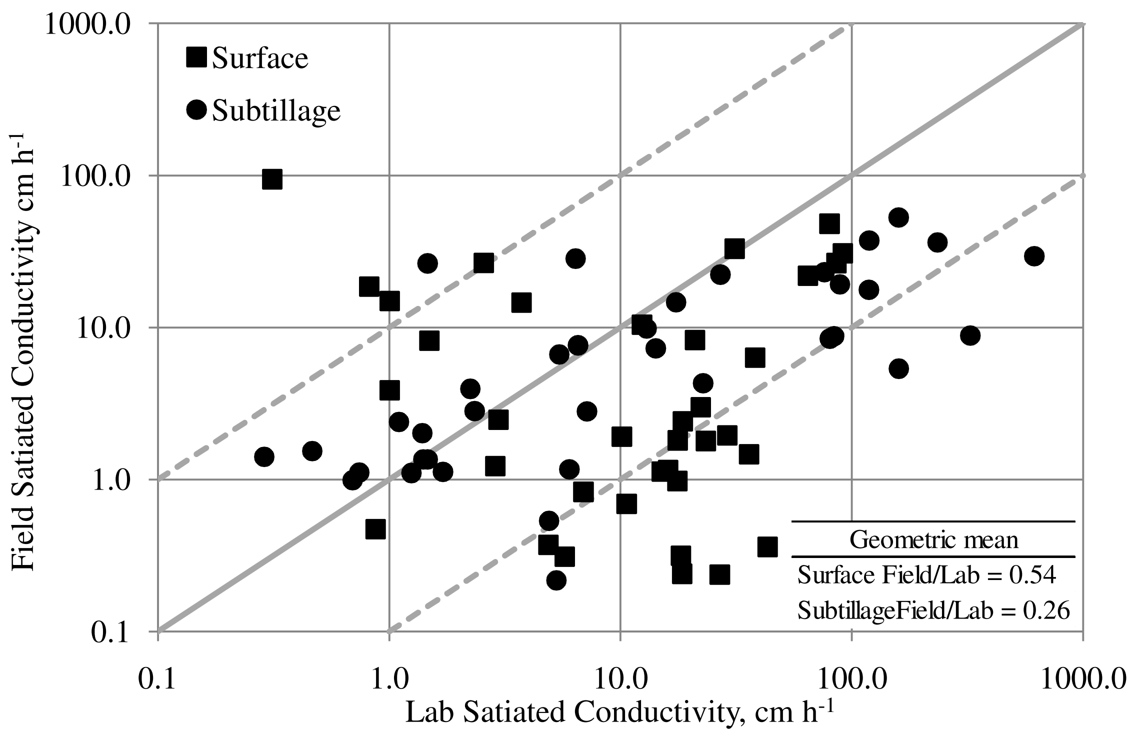

Figure 1.3. Field vs. lab satiated hydraulic conductivity for surface and subtillage layers

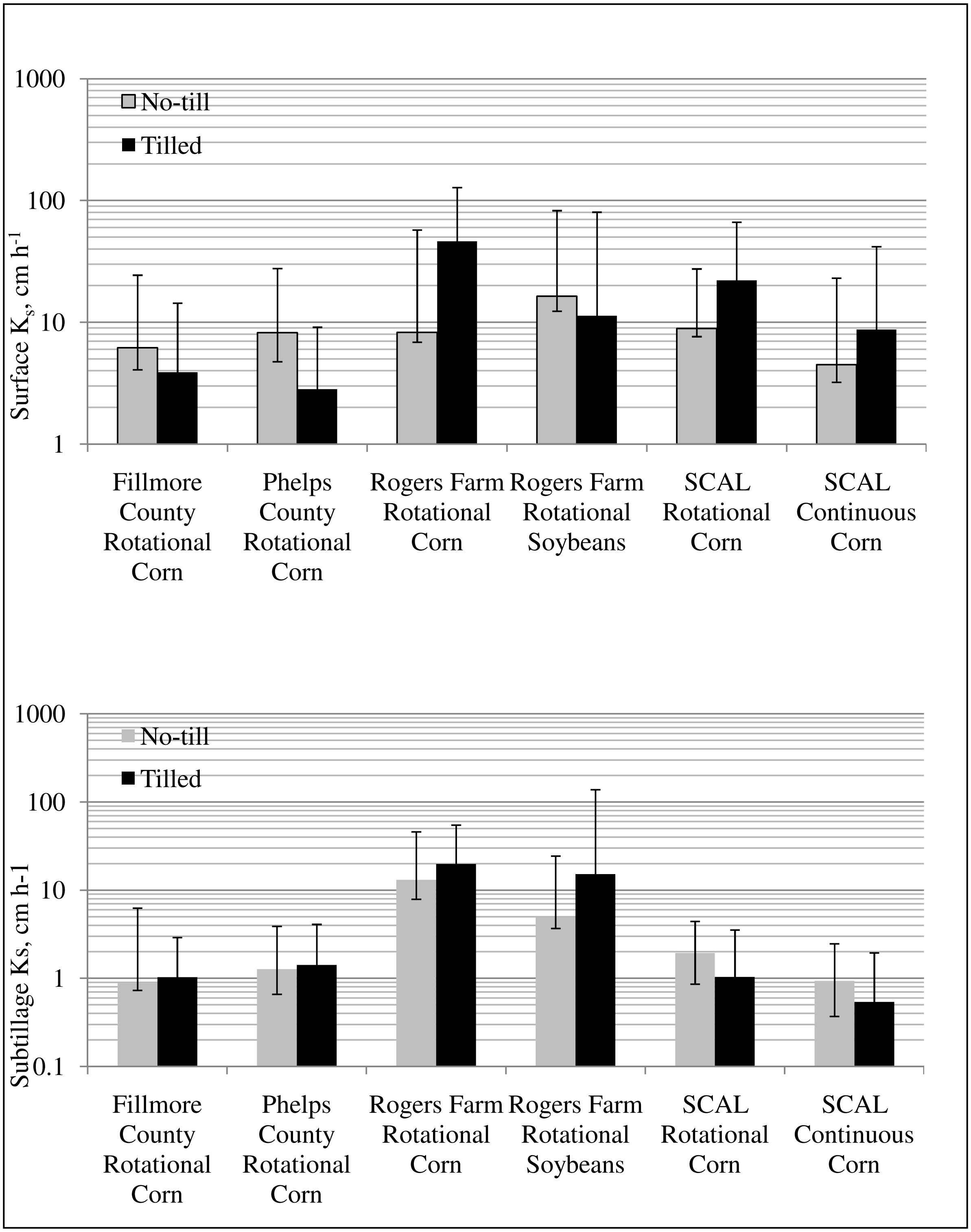

Figure 1.4 Surface and subtillage hydraulic conductivity for tilled and no-till plots. Error bars indicate standard deviation

Analysis of variance was performed for the satiated hydraulic conductivity (Table 1.4). More detailed results are presented in Appendix A. Statistical difference ($P < 0.10$) existed between surface hydraulic conductivities in Phelps County and in Fillmore County, with no-till values being higher. At the furrow irrigation site, SCAL, a significant difference was found in the rotational corn among each variation for slot, ridge, and disk treatment surface hydraulic conductivities. In continuous corn at SCAL, only ridge and disk were significantly different. Disk had the highest hydraulic conductivity. The tilled field was significantly higher in Rogers Farm corn than the no-till measurements. The Rogers Farm soybean measurements had no trend. The only subtillage hydraulic conductivity comparison that was different was the disk versus slot treatments in SCAL, indicating differences in soil from no-till systems that affect hydraulic conductivity are within the tillage (surface) layer of the soil.

Table 1.4. Two-way analysis of variance of satiated hydraulic conductivity (Holm-Sidak method). Statistically significant if P < 0.10.

Site	Comparisons for factor	Comparison	Unadjusted P	Different
Fillmore County	Tillage Treatment within Surface	Tilled vs. No-till	0.028	Yes
	Tillage Treatment within Subtillage	Tilled vs. No-till	0.112	No
Phelps County	Tillage Treatment within Surface	Tilled vs. No-till	0.001	Yes
	Tillage Treatment within Subtillage	Tilled vs. No-till	0.713	No
Rogers Farm Corn	Tillage Treatment within Surface	Tilled vs. No-till	0.012	Yes
	Tillage Treatment within Subtillage	Tilled vs. No-till	0.512	No
Rogers Farm Soybean	Tillage Treatment within Surface	Tilled vs. No-till	0.709	No
	Tillage Treatment within Subtillage	Tilled vs. No-till	0.262	No
SCAL Rotation	Tillage Treatment within Surface	Disk vs. Ridge	<0.001	Yes
	Tillage Treatment within Surface	Disk vs. Slot	0.001	Yes
	Tillage Treatment within Surface	Slot vs. Ridge	0.029	Yes
	Tillage Treatment within Subtillage	Disk vs. Ridge	0.115	No
	Tillage Treatment within Subtillage	Disk vs. Slot	0.023	Yes
	Tillage Treatment within Subtillage	Slot vs. Ridge	0.446	No
SCAL Continuous	Tillage Treatment within Surface	Disk vs. Ridge	0.008	Yes
	Tillage Treatment within Surface	Disk vs. Slot	0.163	No
	Tillage Treatment within Surface	Slot vs. Ridge	0.191	No
	Tillage Treatment within Subtillage	Disk vs. Ridge	0.42	No
	Tillage Treatment within Subtillage	Disk vs. Slot	0.197	No
	Tillage Treatment within Subtillage	Slot vs. Ridge	0.624	No

Texture was investigated as a possible influence on hydraulic conductivity results. The no-till field at Fillmore County had significantly higher clay content, with P = 0.035. At Phelps County, the tilled field had a significantly higher percentage of sand than no-till. Since at the other two sites the tillage treatment variations were located within the same field, no differences were found in texture. Two models were used to determined hydraulic conductivity based on the surface properties of the soil. ROSETTA (Schaap et al., 2001) is a model for predicting hydraulic conductivity with an input of percent sand, silt, and clay and bulk density. The Soil Water Characteristics tool (Saxton and Rawls 2006), which is a model that uses pedotransfer functions, requires an input of percent sand, clay, and organic matter and bulk density. The results are shown in Table 1.5. Based on texture differences, hydraulic conductivity should be higher in the tilled fields at Phelps County and Fillmore County, confirming higher hydraulic conductivity in no-till fields was not due to the percent sand and clay.

Table 1.5. Texture, organic matter, and bulk density predicted satiated hydraulic conductivity using Soil Water Characteristics tool (SWC) and ROSETTA. Measured

Site	Plot	K_s, cm h^{-1}		
		Measured Subtillage (mean ± 1 standard deviation)*	SWC	ROSETTA
Fillmore County	No-till	0.88 (0.15-5.37)	1.32	1.55
	Tilled	0.67 (0.27-1.67)	1.41	7.24
Phelps County	No-till	1.27 (0.61-2.62)	1.48	1.76
	Tilled	1.42 (0.75-2.67)	1.67	2.99

* mean ± standard deviation = $10^{[\log_{10}(\bar{y}) + \log_{10}(s_y)]}$

Data from the tilled field in Fillmore County were collected ten days after cultivation. The ground was wet when cultivation took place, resulting in a very cloddy surface. Only one of the spans where the experiments were conducted was cultivated because the corn was high. Minimal rainfall (<1.27 cm) occurred between the cultivation of the single plot and testing; therefore, no surface seal was expected to form. The data from this span were excluded in the above analysis, and are given below (Table 1.6). The excluded June cultivated plot at Fillmore County tilled had significantly higher measured hydraulic conductivity values than the other two plots in the tilled field.

Table 1.6. Geometric mean K_s span 3 data for tilled field in the above Fillmore County analysis; there were 4 of replications of the test. The data were not used in analysis in Tables 1.3 -1.5.

		Geometric Mean (mean ± 1 standard deviation)*	
Site	Plot	Surface K_s, cm h^{-1}	Subtillage K_s, cm h^{-1}
Fillmore County	Tilled Span 3	43.9	0.29
		(31.3-61.6)	(0.12-0.67)

* $\text{mean} \pm \text{standard deviation} = 10^{[\log_{10}\bar{y} + \log_{10}s_y)]}$

The value for the surface satiated conductivity conducted in cracked soil at Fillmore County tilled resembles the magnitude of hydraulic conductivity for the Rogers Farm Corn tilled plot value. It is possible the high values observed at Rogers Farm are the result of dried soil that has cracked due to high clay content (29%). Moisture deficit was highest during the tests run at Rogers Farm ($\Delta\theta = 0.30$) and cracks were observed in the corn tilled field at Rogers Farm. SCAL disked plot may have been high due to the low bulk density (Table 1.2). Measurement of hydraulic conductivity recently after tillage can increase the bulk density, and therefore the hydraulic conductivity. This study assumed satiated hydraulic conductivity was constant with time although shown in other studies to be highly variable throughout the cropping season (Starr, 1990 and Gantzer and Blake, 1987). Tillage systems may have a positive effect on infiltration immediately after tillage, before reconsolidation and surface sealing has taken place. Therefore, our infiltration results may be influenced by the time of measurement.

1.3.2 Runoff

At the center pivot sites, 55 irrigation and rainfall runoff events were captured during the crop seasons from 2008-2010. An example runoff hydrograph from one of the runoff events is shown in Figure 1.5.

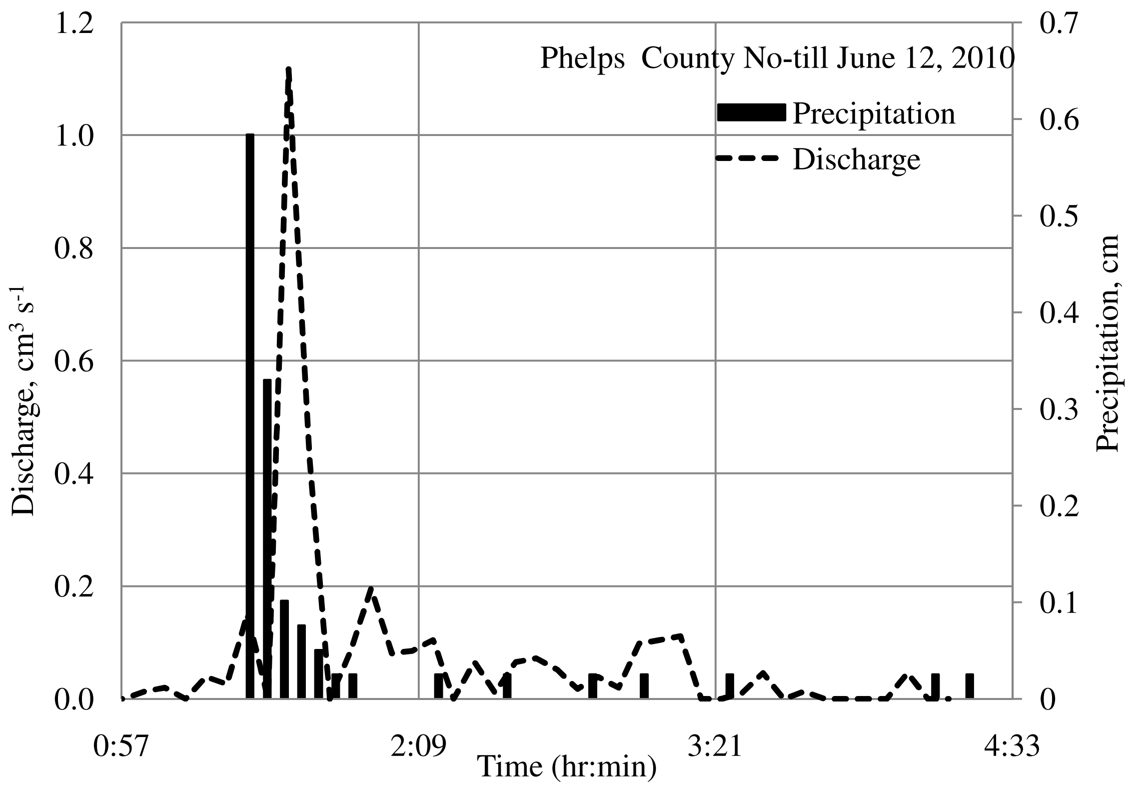

Figure 1.5. Example runoff hydrograph and rainfall hyetograph of an observed runoff event. Total precipitation = 1.78 cm

Forty-three pairs of the events (both tilled and no-till) were the result of rainfall and 12 individual events were monitored irrigation events. Figures 1.6 and 1.7 display cumulative rainfall runoff over the monitored seasons. Events shown do no encompass the total runoff events that occurred during the time frame. These are events with complete data from both no-till and tilled fields and ones with questionable or incomplete data were excluded.

At the sites, the two fields are located within 1.5 km, so rainfall depths were similar at both fields. For the no-till field in Fillmore County, 7.2 cm of runoff was observed. During these same events, 9.3 cm cumulative runoff was obtained from the tilled field in Fillmore County. The cumulative rainfall was 38.1 cm for no-till and 40.1 cm for tilled. Runoff vales at this site were not significantly different, so a conclusion could not be drawn. Rainfall totals for events included in the graph at Phelps County were 58.8 cm for no-till and 62.7 cm for tilled. Cumulative amounts of runoff were 6.4 cm for no-till and 14.6 cm for tilled in Phelps County. These values were significantly different.

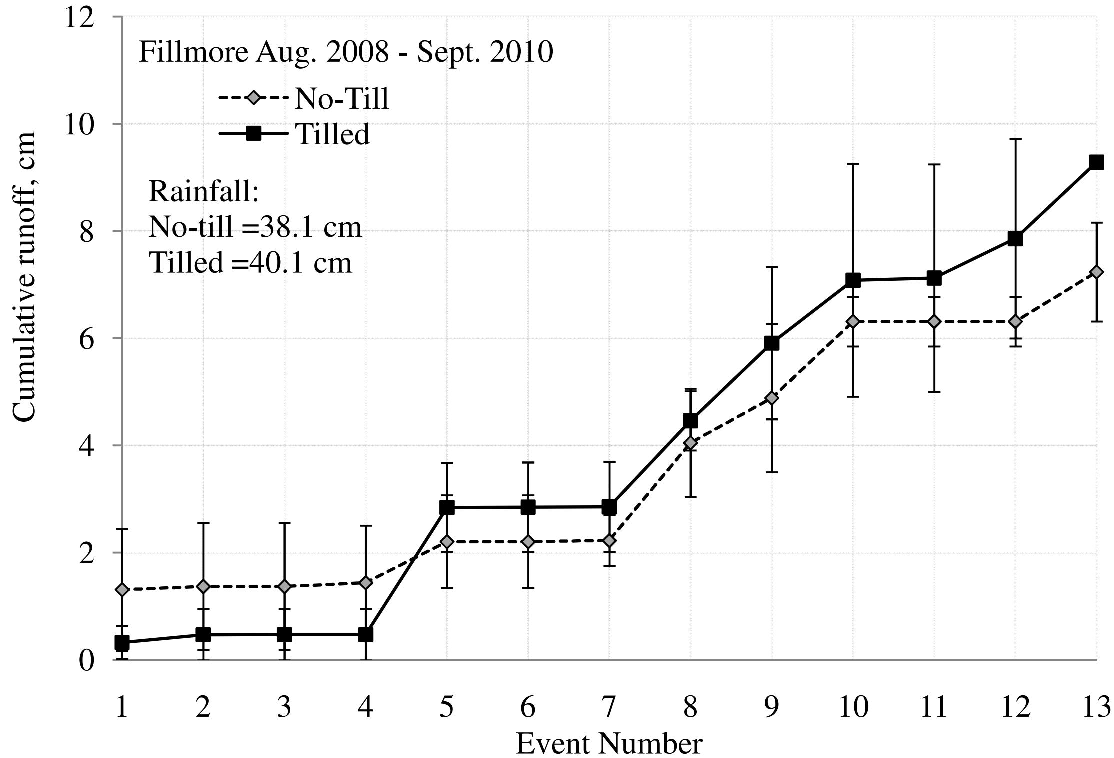

Figure 1.6. Growing season cumulative runoff with standard deviation error bars from rainfall events during Fillmore County cropping seasons 2008-2010

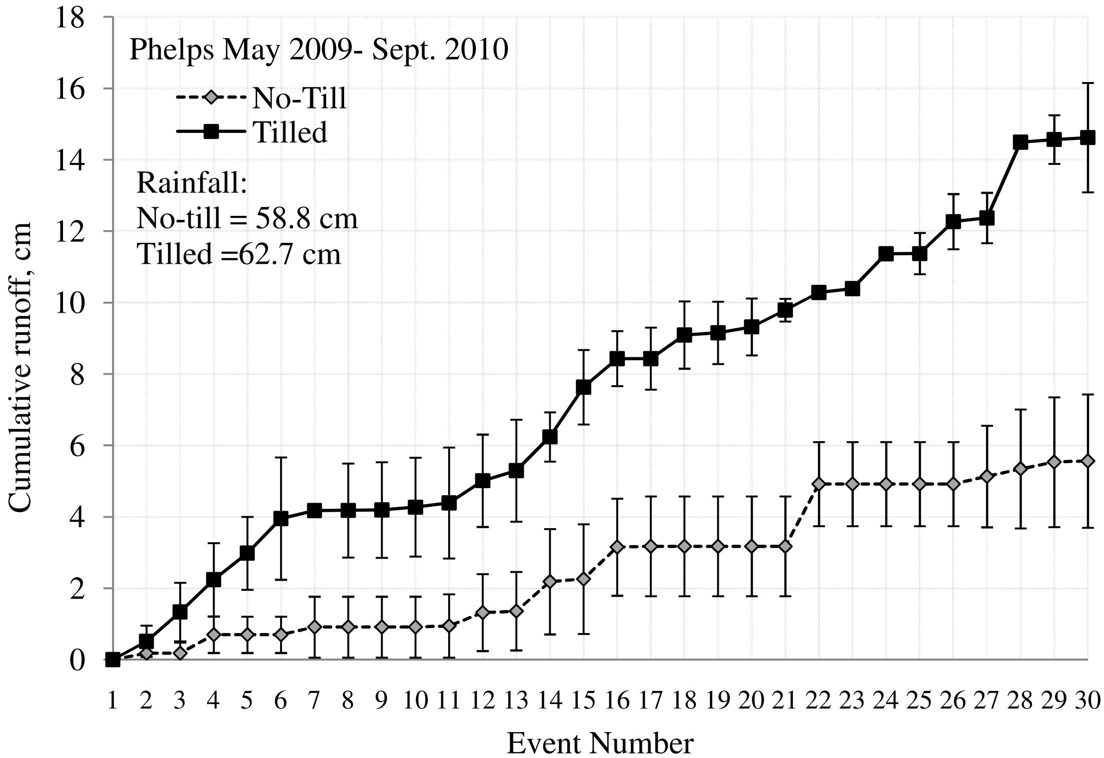

Figure 1.7. Growing season cumulative runoff with standard deviation error bars from rainfall events during Phelps County cropping seasons 2008-2010

Few irrigation events were captured due to incomplete rain data in 2009 since a rain gauge was not installed in the field. In Fillmore County average irrigation runoff was 14.9% for tilled and 1.7% for no-till for six and three monitored events respectively. In Phelps County tilled 52.0% of irrigation water ran off compared with 38% runoff from no-till. Two events were recorded to have runoff from no-till and one irrigation runoff event from tilled (Table 1.7).

Table 1.7. Irrigation events and the corresponding runoff depths

Site	Field	Year	Day-Month	Irrigation, cm	Runoff, cm
Fillmore County	No-till	2010	4-Aug	2.74	0.02
			10-Aug	2.74	0.03
			20-Aug	3.12	0.10
	Tilled	2008	8/27-8/28	3.41	0.45
		2009	28-Jun	1.81	0.05
			7-Jul	2.08	0.34
			5-Aug	2.08	0.89
		2010	6-Aug	3.18	0.47
			12-Aug	3.33	0.17
Phelps County	No-till	2009	11-Aug	2.54	0.15
		2010	13-Jun	2.18	0.83
	Tilled	2009	21-Jul	2.29	1.20

1.3.3 Surface seal, storage, and aggregates

To explore reasons for variations in hydraulic conductivity between tilled and no-till, surface sealing, depressional storage, aggregate stability, and residue were investigated. The amount of water storage per field was determined by calculating depressional storage. The results of depressional storage are shown in Table1.8. Depressional storage was calculated assuming residue is a barrier that can retain pools of water and therefore reduce runoff. No-tilled fields had a depressional storage of about 0.13 cm while tilled fields were in the 0.02-0.03 cm range. Depressional storage reduces runoff because soil depressions must be filled before runoff occurs. The storage is a result of soil microrelief and residue, which can retain a significant amount of water after ponding occurs. Therefore, more residue and soil depressions would decrease the amount of runoff. From a one-way analysis of variance, Fillmore County no-till depressional storage was significantly larger than tilled (P = 0.002). Phelps County no-till also had significantly more depressional storage than tilled (P = <0.001).

Residue slows down the water velocity and protects the ground from rain impaction. In 2009, residue measurements constituted about 20% cover for tilled fields. No-till fields differed. Fillmore County, when the no-till field utilized strip till, had 65% residue and Phelps retained 82% of the previous year's residue on the surface. In 2010, when Fillmore County no-till switched to true no-till, both no-till fields had residue in the 90% range contrastingly the tilled fields having about 40% cover. These percentages align with values given by the Natural Resources Conservation Service for tilled and no-till residue (USDA NRCS, 1992). Slot and ridge treatments at Clay County had about 40% residue cover while disk treatment residue was 14%.

Aggregate stability results showed no-till sites have significantly more stable aggregates (Figure 1.8). Forty-five percent and 33% of aggregates are stable in no-till fields at Fillmore County and Phelps County, respectively. Tilled field aggregate tests resulted in 28% and 13% stable aggregates from Fillmore County and Phelps County respectively.

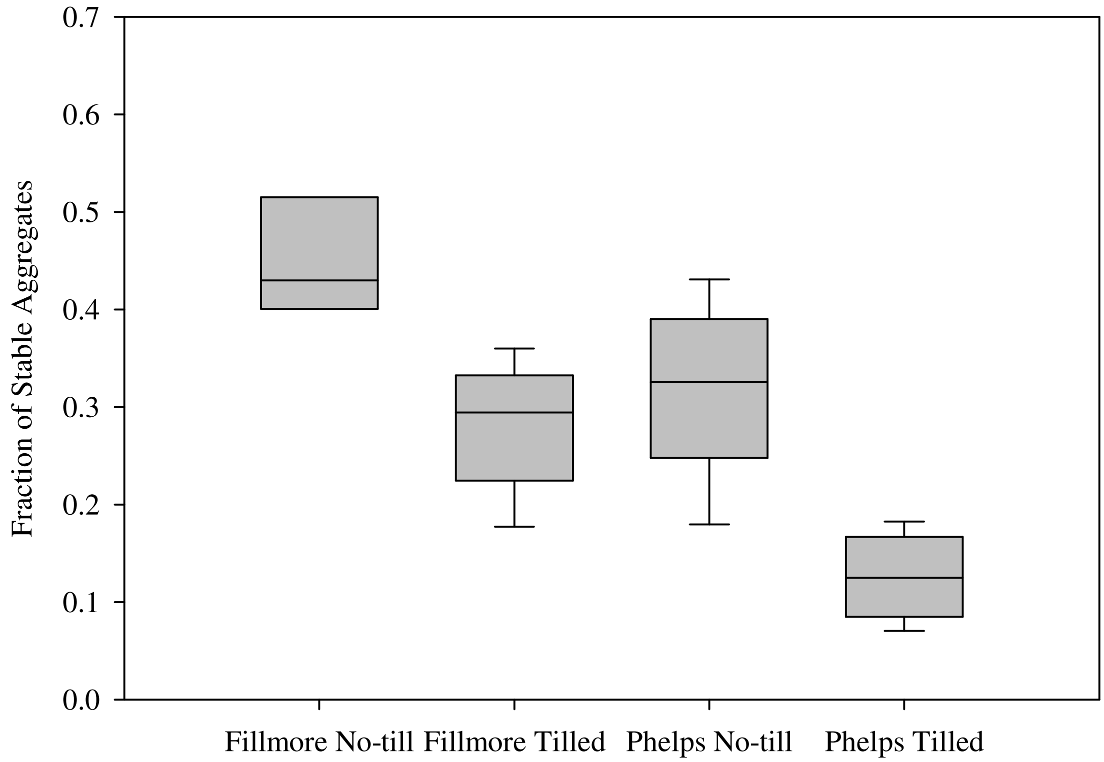

Figure 1.8. Fraction of stable aggregates at center pivot irrigated sites

Table 1.8. Results from percent residue, depressional storage (DS), and aggregate stability

County	Plot	May 2009 Residue, %	Late May 2010 Residue, % (std dev)	Early Aug 2009 DS, cm (std dev)	Stable Aggregates, % (stdev)
Fillmore	No-till	65	92.84 (6.70)	0.13 (0.06)	45 (0.08)
	Tilled	25	37.41 (15.30)	0.03 (0.02)	28 (0.06)
Phelps	No-till	82	91.42 (5.90)	0.13 (0.05)	33 (0.08)
	Tilled	21	46.74 (17.00)	0.02 (0.02)	13 (0.04)
Clay	Slot	NA	45.70 (8.50)	NA	31 (0.13)
	Ridge	NA	33.80 (10.50)	NA	36 (0.17)
	Disk	NA	14.70 (8.10)	NA	24 (0.12)

1.3.4 Macropores

On average about 0.01 - 0 .15% of the area of the field was found to have macropores (Table 1.9), which is at the lower end of the range cited by Logsdon et al. (1990) for pores greater in diameter than 0.04 cm (0.03-1.7% of total area). Since this study included pores larger than 0.1 cm, not 0.04 cm, it is expected that less area would be found. There was no difference in percentage of surface area from macropores between tilled and no-till at Fillmore County or at Phelps County, or between plots at Clay County. Rogers Farm had significantly higher macropore area in the no-till field. This may be from the long term applications of no-till. Rogers Farm has had consistent tillage practices for 28 years when experiment was conducted. The other sites have been consistent for about seven years. Another factor may be the depth at which measured (6.5 cm) did not correspond to the connectivity of the surface pores. Perret et al. (1999) used CAT scanning and found most macropore networks reach only the 4 cm length, falling short of the sampled region in this experiment. Future investigation to determine connectivity of the macropores to see how the network compares at different depths would help in understanding the effects of macropores on these fields.

Table 1.9.Percentage of area contributing to macropores

Site	Plot	Macropore area, %
Fillmore County	No-till	0.028
	Tilled	0.056
Phelps County	No-till	0.009
	Tilled	0.005
Rogers Farm	No-till	0.166
	Tilled	0.025
SCAL	Slot	0.101
	Ridge	0.100
	Disk	0.147

1.3.5 Discussion

Even though no difference was determined in macropore quantity at three of the four sites, percent residue, depressional storage, and aggregate stability were all significantly higher in no-till, which appeared to influence hydraulic conductivity and runoff. Hydraulic conductivity was significantly higher in the no-till field at Phelps County. The higher hydraulic conductivity measurements in the no-till field corresponded to significantly less runoff from the no-till field in Phelps County. Although this may be influenced by residue or aggregate stability, the slope of the no-till field is less than the tilled field in Phelps County, which could reduce runoff. However, depressional storage is not sensitive to the percent slope term. Changing the no-till field in Phelps County to have a slope matching the tilled field resulted in only a tenth of a millimeter drop in depressional storage.

In the no-till field at Fillmore County, the hydraulic conductivity values were significantly higher than tilled. The observed runoff, however, there was no significant difference found between tillage treatments. A few reasons could be increasing the runoff at the no-till field. Frequent rainfall and irrigation could result in no-till moisture content being higher, and therefore, increasing the observed runoff. Isensee et al. (1993) found on average, when events were less than six days apart, runoff was higher on the no-till field. As discussed previously, residue plays an important role in reducing runoff. Limited residue could lead to more surface sealing and reducing the hydraulic conductivity. Because Fillmore County no-till used strip tillage in 2009, 30% less residue covered the surface. However, no differences were visible among 2009 runoff and the other years.

Disk hydraulic conductivity measurements were significantly higher in SCAL rotational corn. This may be because of the bulk density being lower. Measurements taken in dryland corn showed tilled to have the highest hydraulic conductivity. Soil was dry and cracked which may have influence the abnormally high data from the tilled dryland corn.

Texture was found to be significantly different between the fields where the runoff plots were located. Infiltration rates are impacted by texture as shown by the Soil Water Characteristics tool, which takes percent sand, clay, and organic matter to predict hydraulic conductivity. This model predicted lower satiated conductivity in the no-till fields at Fillmore County and Phelps County, indicating the impact of no-till overshadowed the texture influence.

For future investigations, the time period between rainfall and irrigation events should be included in the analysis. No-till may remain at a higher moisture content, increasing the amount of runoff. Macropore connectivity should be quantified to better understand the impact large pores have on the field. Also, a longer time period between cultivation and hydraulic conductivity experiments should be practiced to account for surface sealing.

1.4 Conclusion

Effects of long-term no-till systems were found to be variable among sites. The surface hydraulic conductivity was significantly higher for no-till at the two center pivot irrigated sites, concluding at these sites, no-till did increase infiltration. Runoff was significantly higher in the tilled field in Phelps County, and in Fillmore County no significant difference between field runoff was found. However, the rotational corn furrow irrigated field and dryland rotational corn field had higher hydraulic conductivity in the tilled plot. The continuous corn furrow irrigated field and the dryland rotational soybean field showed little difference among tillage practices.

No-till fields showed greater residue, depressional storage, and higher aggregate stability indicative of no-till systems. At the center pivot irrigated sites, these qualities pointed to higher amount of water to infiltrate, and therefore, less runoff during rain and irrigation events. With these qualities, runoff is reduced and farmers may be able to lower pressure pivot packages to save energy.

1.6 References

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CHAPTER 2: DETERMINING SATIATED HYDRAULIC CONDUCTIVITY FOR THE GREEN AND AMPT EQUATION USING NATURAL RUNOFF DATA

2.1 Introduction

The state of Nebraska receives variable annual rainfall depths, ranging from about 30 cm to 73 cm rainfall moving west to east across the state (USGS, 2005). In many regions irrigation is necessary for growing crops, illustrated by the 8 million acres irrigated in Nebraska (USDA Census, 2007). Employing economical irrigation practices requires understanding the effect of management systems on the hydraulic properties of the soil (Gilley, 1984). With differences in rainfall, and a large percentage of agriculture land that is irrigated, focus must be put on the hydrology of the soil in order to understand how water can most effectively be used. This study was performed in eastern and south central Nebraska on rotational corn and soybean in order to understand the role tillage plays on water management. Conservation tillage systems may respond efficiently to low pressure irrigation by increasing infiltration and decreasing runoff. If expected infiltration rates can be quantified, this response would create an opportunity for energy savings and improve conservation of soil and water resources.

No-till planting is defined as minimal disturbance of the soil surface by placing the seed directly into the soil without disruption of the surface residue, and tillage is the breaking of the structure of soil surface by cultivation (ASABE, 2007). The effect of tillage practices on irrigation and rainfall is complex and requires knowledge of the influence different tillage systems have on the soil characteristics and how these qualities influence infiltration. Many variables play a part in adding to the complexity of the soil-water interaction. It is unknown how many of the variables must be taken into account in order to accurately predict how different tillage systems will impact runoff (Loague and Freeze, 1985).

Modeling infiltration into the soil simplifies the complexity and is a useful tool for quantifying runoff. The ability to accurately predict the multifaceted process of infiltration and runoff from easily measurable soil properties, simplifies soil hydrology, advances research, and aids in assimilating results. The useful instrument of modeling runoff sheds light on advantages to specific tillage systems.

The difference between infiltration rates and rainfall or irrigation intensity can be estimated using the Green and Ampt infiltration equation, which is based on continuity and Darcy's Law of water flow through soil (Green and Ampt, 1911). Many computer models use the Green and Ampt equation to model the infiltration of water into the soil. In order to run a Green and Ampt based model, properties that describe infiltration are required. The input parameters for the equation include the wetting front pressure head (h_f), satiated hydraulic conductivity (K_s), and fillable porosity ($\Delta\theta$). Satiated hydraulic conductivity describes the ability of a soil to transmit water under near saturated conditions (ASABE, 2007). This parameter is difficult to quantify because of its dependence on many other properties, and consequently, its high variability in space (Rehfeldt et al., 1992). Output values from the Green and Ampt equation are highly sensitive to this term, and the reliability of the Green and Ampt output depends on the accuracy of the satiated hydraulic conductivity (Brakensiek and Onstad 1977).

Methods for determining K_s range from pedotranfer functions to parameter optimization. Although calibrating a model by optimizing $K_{s,}$ such as minimizing the sum of squares of measured and observed runoff offers a reliable method for determining $K_{s,}$ calibration is difficult and time consuming. Frequently, observed runoff data are not available. To resolve this problem, many equations have been developed to predict K_s using easily measurable soil properties and the characteristics of the field as inputs.

Measuring all the required soil properties for a given area is often not a viable option. Pedotransfer functions offer equations to predict hard to measure parameters using easy-to-measure soil properties, such as texture. These properties can often be found from other resources, such as Web Soil Survey (USDA), therefore, requiring no field measurements. These functions allow for quick analysis and can be used to derive parameters for modeling.

The objective of this chapter is to investigate four pedotransfer functions models: Crust Factor, referring to an equation developed by Rawls et al (1990); ROSETTA (Schaap et al., 2001); an equation used in the Water Erosion Prediction Project (WEPP) (Nearing, 1996); and Soil Water Characteristics tool (SWC) (Saxton and Rawls, 2006) to determine which equation most accurately describes satiated hydraulic conductivity when both tilled and no-till fields are considered. These equations are also implemented to determine the most accurate method for describing center pivot irrigation runoff.

2.2 Methods

Runoff from rainfall and irrigation was observed during the 2010 crop season at two center pivot irrigated sites in Nebraska (see Chapter 1 for field descriptions). The sites, Fillmore County and Phelps County, each include paired no-till and tilled fields. To establish an accurate model for describing the impact of no-till planting on runoff, four equations were chosen to define satiated hydraulic conductivity in the Green and Ampt equation. The observed runoff was compared to the Green and Ampt predicted runoff values for each of the four pedotransfer functions.

2.2.1 The Green and Ampt equation

The Green and Ampt model (Green and Ampt, 1911) of a one-dimensional, piston flow wetting front and a constant initial moisture content was used in the infiltration rate calculations for the tilled and no-till fields. Using the iterative method for unsteady rainfall by Chow et al (1988), the pre-ponding equations are:

$$f(t) = R(t) \tag{2.1}$$

$$F(t+\Delta t) = \Delta t\, R(t) + F(t) \tag{2.2}$$

where f(t) = infiltration rate at time, t, R(t) = intensity of rainfall or irrigation, F(t+Δt) = cumulative infiltration at next time step. Time of ponding (t_p) is determined once f(t+Δt)

$< R(t)$. Assuming no accumulation of ponded water depth on surface, the equations are then:

$$f(t_p) = R(t_p) \tag{2.3}$$

$$F(t_p) = K_s\, h_f\, \Delta\theta / (R(t_p)-K_s) \tag{2.4}$$

$$\Delta t' = (F(t_p) - F)/R(t_p) \tag{2.5}$$

$$t_p = t + \Delta t' \tag{2.6}$$

$$\Delta\theta = 0.9\, \eta - \theta_i \tag{2.7}$$

where $\Delta t'$ = increase in time from the beginning of the time interval to when ponding occurs, η = porosity, θ_i = initial moisture content. After surface satiation, the infiltration equations are adjusted to:

$$f = K_s\, [(h_f\, \Delta\theta / F) + 1] \tag{2.8}$$

$$t = \{F - F(t_p) - h_f\, \Delta\theta\, [\ln(F + h_f\, \Delta\theta) / F(t_p) + h_f \cdot \Delta\theta)]\} / K_s + t_p. \tag{2.9}$$

Equation 2.9 is implicit in respect to F, and an iterative solver must be used to obtain cumulative infiltration for each step. In replacement of Equation 2.10, an explicit equation was used for calculating F after ponding occurs, which was developed by D. E. Eisenhauer (personal communication, 2010). Values compared favorably with equations developed by Hachum and Alfaro (1980), which confirmed the correctness of the model.

Porosity was calculated from field measured bulk density. Assuming 90% of porosity described field saturation, or satiation, when air is trapped in soil pores resulting in incomplete soil saturation (SSSA, 1996), θs = 0.9 η. The average initial matric potential was determined using 15 cm Watermarks in two locations at each field to describe the first 30 cm of soil. The Soil Water Characteristics tool developed by Saxton and Rawls (2006) was used to create a soil water retention curve (Figures 2.1, 2.2) from percent sand, percent clay, bulk density, and percent organic matter to find initial moisture content before each rainfall or irrigation event.

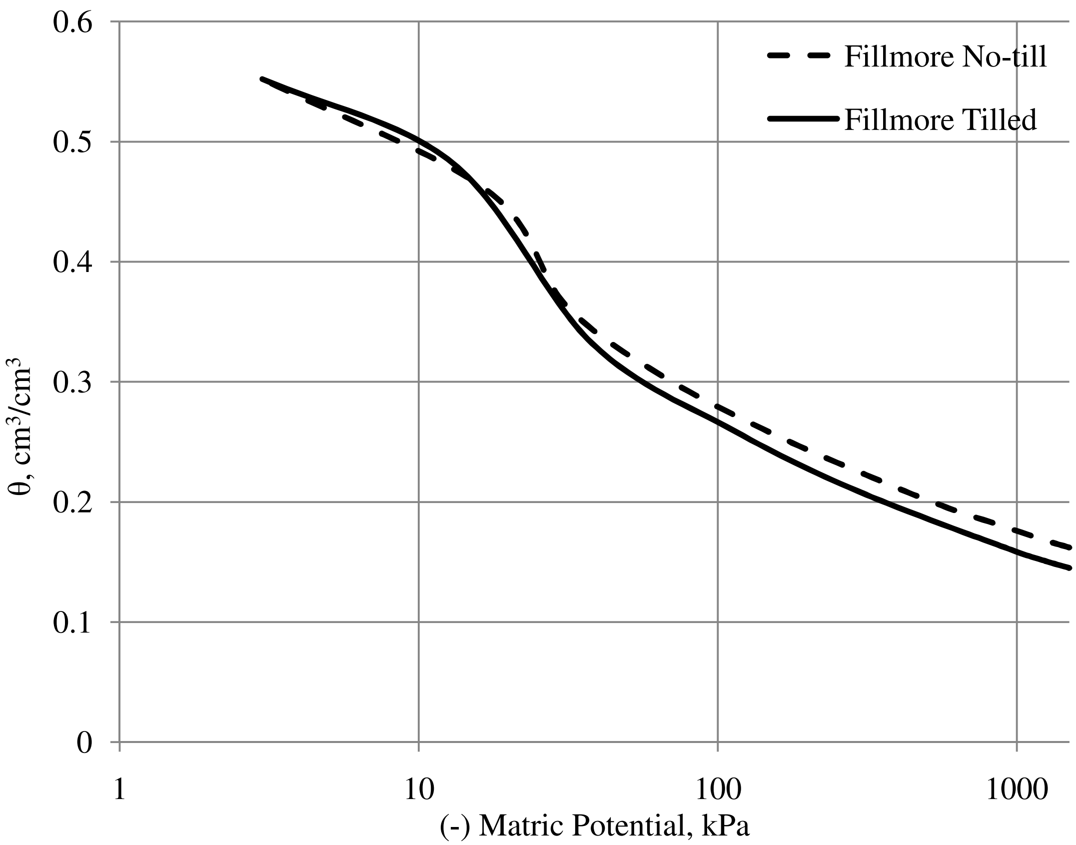

Figure 2.1. Soil water retention curve for Fillmore County developed using the Soil Water Characteristics tool

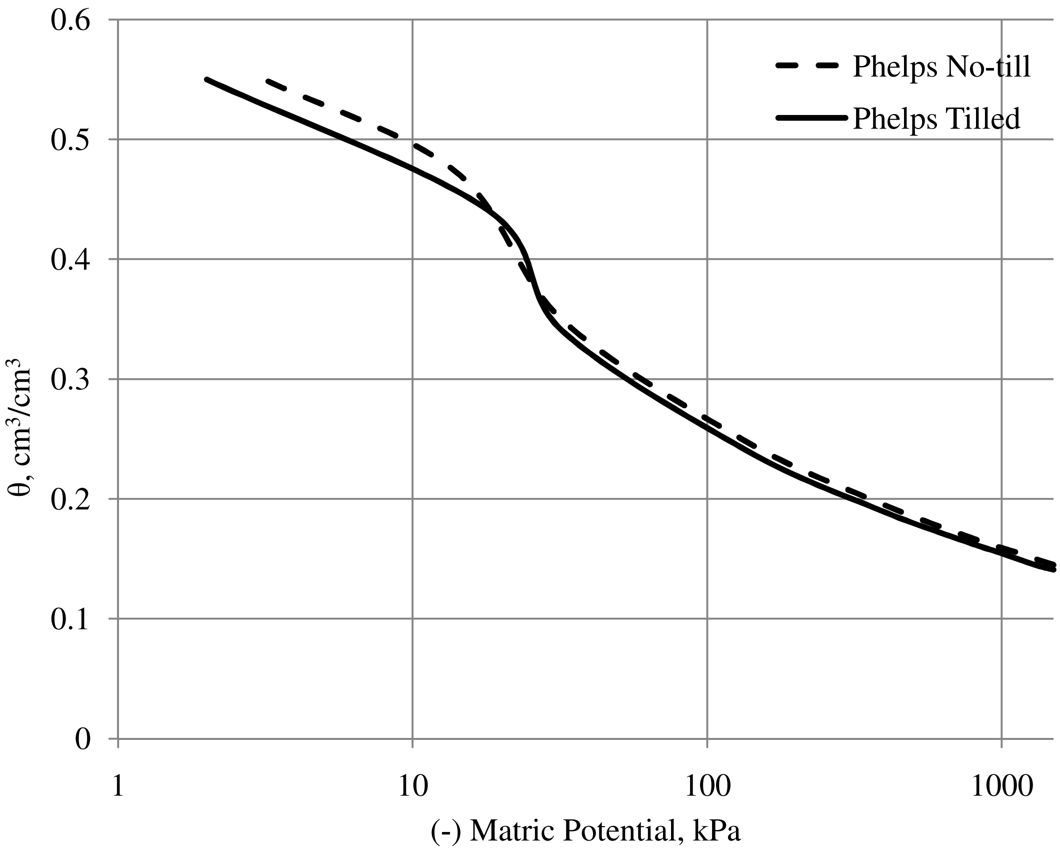

Figure 2.2. Soil water retention curve for Phelps County developed using the Soil Water Characteristics tool

Wetting front pressure head was calculated using the Rawls and Brakensiek (1983) pedotransfer function:

$$h_f = \exp [6.53 - 7.326 (0.9 \eta) + 0.00158 (Clay)^2 + 3.809 (0.9 \eta)^2 + 0.000344 (Sand)(Clay) - 0.04989 (Sand)(0.9 \eta) + 0.0016 (Sand)^2 (0.9 \eta)^2 + 0.0016 (Clay)^2 (0.9 \eta)^2 - 0.0000136 (Sand)^2 (Clay) - 0.00348 (Clay)^2 (0.9 \eta) - 0.000799 (Sand)^2 (0.9 \eta)] \quad (2.10)$$

where Sand and Clay equal the percent sand and clay contents respectively. The calculated parameters for wetting front pressure head and satiated moisture content, used in the Green and Ampt model are shown in Table 2.1.

Table 2.1. Green and Ampt input parameters. ρ_b = bulk density, h_f = wetting front pressure head, and θ_s = field saturated moisture content

Site	Field	θ_s, cm^3/cm^3 (std dev)	h_f, cm (std dev)	ρ_b, g cm^{-3} (std dev)
Fillmore County	No-till	0.50	35.9	1.19
		(0.02)	(4.2)	(0.05)
	Tilled	0.61	28.1	1.09
		(0.14)	(1.2)	(0.40)
Phelps County	No-till	0.51	29.5	1.15
		(0.01)	(3.7)	(0.02)
	Tilled	0.52	23.9	1.10
		(0.00)	(0.6)	(0.0)

To solve for cumulative infiltration during a rainfall or irrigation event, an accurate value for K_s must be developed. This parameter can range in orders of magnitude when measured (Rawls et al., 1993). Many models offer estimates of this parameter and are discussed below.

2.2.2 *Satiated hydraulic conductivity*

The first method applied to define the satiated hydraulic conductivity was the field measured procedure. The inverse Green and Ampt infiltration equation was applied to calculate field satiated surface hydraulic conductivity as discussed in Chapter 1. The data measured in the field are given in Table 1.3.

Early season, ponded infiltration tests did not include the effect of aggregate breakdown; therefore, the second method to determine satiated conductivity was Rawls's crust adjustment equation (Rawls et al., 1990). The equation adjusts the field measured surface hydraulic conductivity to account for the effects of the surface seal. An adjusted satiated hydraulic conductivity, K_c, was used based on the crust conductivity developed by Rawls et al. (1990).

$$K_c = K_s \cdot SC \cdot Z / (\Psi_i + Z) \tag{2.11}$$

$$SC = 0.736 + 0.0019 \cdot (\text{Sand}) \tag{2.12}$$

$$\Psi_i = 45.19 - 46.68 \cdot (SC) \tag{2.13}$$

SC and Ψ_i, the correction factor for partial saturation and matric potential drop at the subcrust level, respectively, which are developed from pedotransfer functions. Crust thickness, Z, was assumed to be 0.5 cm for both tillage treatments as was in the Rawls et al. study (1990).

The second model to define K_s was ROSETTA (Schaap et al., 2001). ROSETTA uses five pedotransfer functions developed from the input of bulk density and percent sand, silt, and clay. This computational model is an artificial neural network (Schaap et al., 2001).

The equations in the Water Erosion Prediction Project (WEPP) (Nearing et al., 1996) were used to calculate K_s. WEPP uses an optimized conductivity for the fallow condition based evaluation of 43 soils. The fallow hydraulic conductivity (K_{ef}) is calculated using Hydrologic Soil Group and percent sand. For Hydrologic Soil Group B, the following describes fallow hydraulic conductivity for all four fields (Nearing et al., 1996):

$$K_{ef} = 1.17 + 0.072 \text{ Sand}. \quad (2.14)$$

Based on the curve number, which is an indication of how much runoff is expected from a surface for specified management practices and cropping, ratios were developed by Nearing et al. (1996) to describe the crop condition hydraulic conductivity (K_s) from the fallow condition. According to the Nearing et al. (1996) research, the ratio of K_s/K_{ef} was consistent within a soil group for a given land use and tillage practice. The ratios provided by Nearing et al. (1996) are shown in Table 2.2. In addition to the ratios, a regression analysis related K_s to the fallow hydraulic conductivity and curve number by Equation 2.15.

Table 2.2. Ratio of cropped to fallow hydraulic conductivity given by Nearing et al., 1996

Crop Type	N	K_s/K_{ef}
Conventional corn	81	1.58
Conservation corn	80	1.79
Conventional soybean	81	1.70
Conservation soybean	80	1.91

Equation 2.15 was developed by Nearing et al. (1996) to provide a means of using management practices not provided in the above ratio table (Table 2.2). According to

Nearing et al. (1996), the equation more accurately describes cropped satiated hydraulic conductivity when compared to the ratios.

$$K_s = 56.82\ K_{ef}^{\ 0.286} / [1 + 0.051 \exp (0.06\ N)] - 2 \qquad (2.15)$$

where N = the runoff curve number. The WEPP equation developed for cropped hydraulic conductivity requires knowledge of the curve number for a given field. The SCS Handbook (1985) gives curves numbers for different land uses and treatments. The curve number for conventional tillage in soybean adequately described the tilled fields where runoff was observed; however the closest description in the handbook for no-till land was conservation tillage. This curve number was originally developed on cultivated land with varying amounts of residue (Rawls and Onstad, 1980) and may not be descriptive of the no-till fields in this study. Since minimal literature describes curve numbers for no-till fields, the data collected from runoff events at the two center pivot irrigated sites were used to develop a curve number to compare with the handbook tabular value. This was accomplished by rearranging the SCS curve number equation to solve for maximum surface storage, S (Hawkins et al., 1985):

$$S = 5[P + 2Q - (4Q^2 + 5\ PQ)^{1/2}] \qquad (2.16)$$

where P = rainfall and Q = runoff. Then, the curve number was calculated by averaging the maximum surface storage, S, for all events per treatment application (USDA-SCS, 1985):

$$N = 25400/(254 + S). \tag{2.17}$$

In the above equation, S has units of mm. Calculated curve numbers for tilled and no-till fields were used in Equation 2.15.

Lastly, Soil Water Characteristics tool (SWC) (Saxton and Rawls 2006) was used to predict satiated hydraulic conductivity. A compilation of regression equations from other studies is used in the model. SWC requires inputs of percent sand and clay or textural class, organic matter, and bulk density.

2.2.3 Depressional storage

The amount of water stored on the soil surface before runoff occurs is depressional storage, DS and needs to be considered in the model. Two methods were used to find this value. NRCS (2005) provides a table of values based on percent residue and percent slope on a field. The second method was measuring DS in the field. Random roughness is a measure of the variation in height of the surface depressions due to soil relief and surface residue and relates to the depth of water that can be stored on the surface. Random roughness was determined using the Saleh chain method (Saleh, 1993). A 1.0 m roller chain (ANSI 35 riv.type) was carefully positioned on the ground, parallel to the row, hugging residue and surface contours. The reduced length was measured. The roughness of the field was determined using Saleh's chain method equation for random roughness.

$$RR = (1 - L_2 / L_1)100 \tag{2.18}$$

where RR = random roughness, L_1 = the length of the chain, L_2 = the adjusted length of the chain when draped over divots and residue on the ground.

Once ponding occurs, the water begins to pool in depressions on the surface and is referred to as the depressional storage. From the random roughness, depressional storage was calculated by Equation 1.3 developed by Onstad (1987).

$$DS = 0.112 \cdot RR + 0.031 \cdot RR^2 - 0.012 \cdot RR \cdot S \tag{2.19}$$

where DS = depressional storage in cm and S = percent slope. The depth of depressional storage was subtracted from the total runoff modeled using the Green and Ampt equation in order to account for variations in roughness.

2.2.4 Model validation

The models used were assessed based on efficiency and linear regression statistics. The cumulative runoff for each observed event was plotted against predicted cumulative runoff from the Green and Ampt model based on the different hydraulic conductivities. Similar values of observed and modeled landed close to the unit slope regression line.

Nash-Sutcliff efficiency (NSE) was used to evaluate the hydraulic conductivity values (Nash and Sutcliff, 1970):

$$NSE = 1 - [\sum (Y_{obs} - Y_{model})^2 / \sum (Y_{obs} - Y_{mean})^2] \qquad (2.20)$$

where NSE is the coefficient of efficiency, Y_{obs} is the observed runoff from rainfall and irrigation, Y_{model} is the predicted runoff for each event during 2010 crop season, and Y_{mean} is the mean observed event runoff. NSE can range from $-\infty$ to 1. A perfect fit is 1, indicating the sum of squares cancelled out due to the observed and predicted values being equal. A negative number indicates the model is no better than using the mean of the data as the predictor.

The root mean squared error (RMSE) was also calculated by:

$$RMSE = [\sum (Y_{obs} - Y_{model})^2 / n]^{1/2}. \qquad (2.21)$$

In the above equation, n = number of runoff events captured. The RMSE indicates precision, and the smaller the number, the closer the model matches the observed values. RMSE has the same units as the values being compared and the magnitude of the RMSE is based on the data.

Lastly, the percent bias (PBIAS) was found (Moriasi et al, 2007).

$$PBIAS = [\sum (Y_{model} - Y_{obs})100/\sum (Y_{obs})] \quad (2.22)$$

where PBIAS indicates the positive or negative percentage of deviation of the modeled data from the observed. A positive value indicates the model over predicted the runoff and a negative value indicates the tendency of the model to under predicted the runoff.

2.2.5 Observed runoff

Each of the four fields contained three micro runoff plots, which included a rain gage, runoff frame, gutter, sump, and pressure transducer, as described in Chapter 1. The Soil Hydrologic Group of each field is B. In 2010, a tipping rain gauge was installed in soybean to determine intensity of rainfall and irrigation. Because of the completeness and detail of the rain data, along with the high amount of collected observed runoff events in 2010, these data were chosen for comparison with the Green and Ampt model. Utilizing the rain intensity and runoff data, hydrographs were developed for both observed data and the modeled data from the iterative Green and Ampt equation.

Irrigation application rates formed by the rain gauge located in the middle runoff plot in each field (span 5 in Fillmore and span 7 in Phelps) were plotted for each irrigation runoff event. Using the center pivot design for the fields, design application rate curves were formed corresponding to the sprinklers in each span where runoff plots were located for a 2.54 cm application. The characteristics of the center pivots used for the design curves are shown in Table 2.3.

Table 2.3. Center pivot characteristics. R = distance to sprinkler; R_s = system length; W_r = wetted radius, D_a = depth applied.

Site	Plot	Span	R, m	Q, L/s	D_a, cm	R_s, m	W_r, m	Field size, ha
Fillmore County	No-till	3	123	37.9	2.5	392	9.8	48
		5	219					
		7	343					
	Tilled	3	145	48.9	2.5	395	8.5	49
		5	251					
		7	341					
Phelps County	No-till	7	359	50.5	2.5	395	6.2	49
	Tilled	7	355	50.5	2.5	397	8.5	49

2.3 Results and Discussion

2.3.1 Observed runoff

Twenty-six runoff events were measured during the growing season of 2010. Six of the runoff events were due to irrigation events. The runoff data were used to create the event hydrographs to compare with the Green and Ampt modeled hydrographs. Sample hydrographs are shown in Figures 2.3 and 2.4, and the observed and modeled hydrographs for all the events in 2010 are provided in Appendix A.

2.3.2 Satiated hydraulic conductivity

Hydraulic conductivity was estimated using four models. Table 2.4 provides the hydraulic conductivity values predicted by each model. These K_s values were used in the Green and Ampt iterative equation for each monitored runoff event in 2010. The WEPP hydraulic conductivity results for both the ratio developed by Nearing et al. (1996) that is derived from the tabular curve number found in the SCS handbook (WEPP Tbl 2.2) and the curve number calculated from the maximum surface storage measured on the fields (WEPP Eqn 2.15) are shown in Table 2.4. The hydraulic conductivity derived from the ratio provided by Nearing et al. (1996), WEPP Tbl 2.2, was used in runoff analysis.

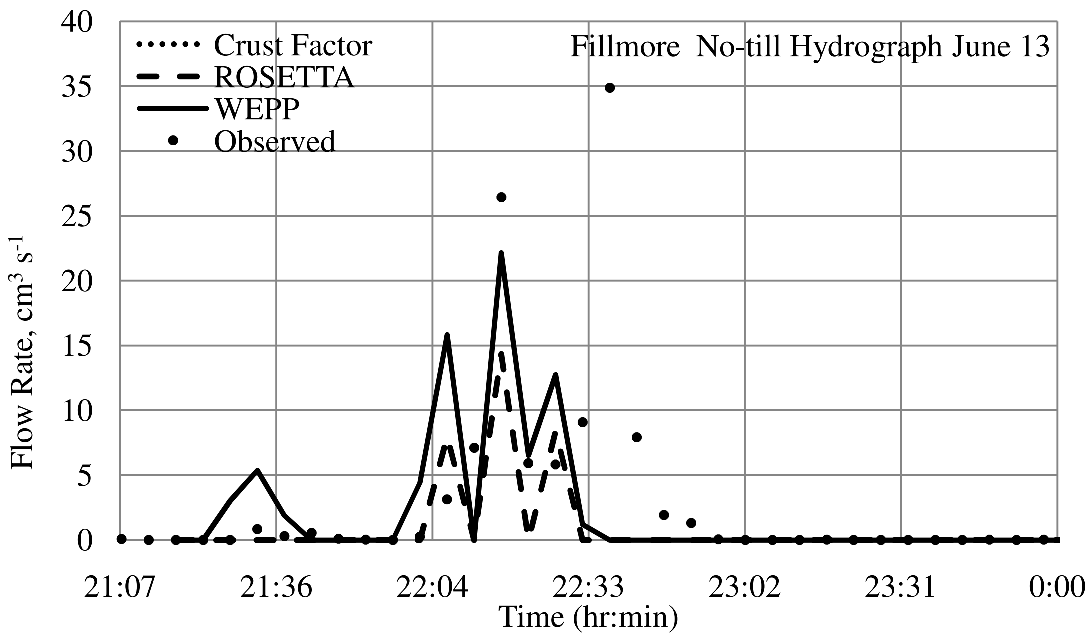

Figure 2.3. Observed and predicted runoff hydrographs.

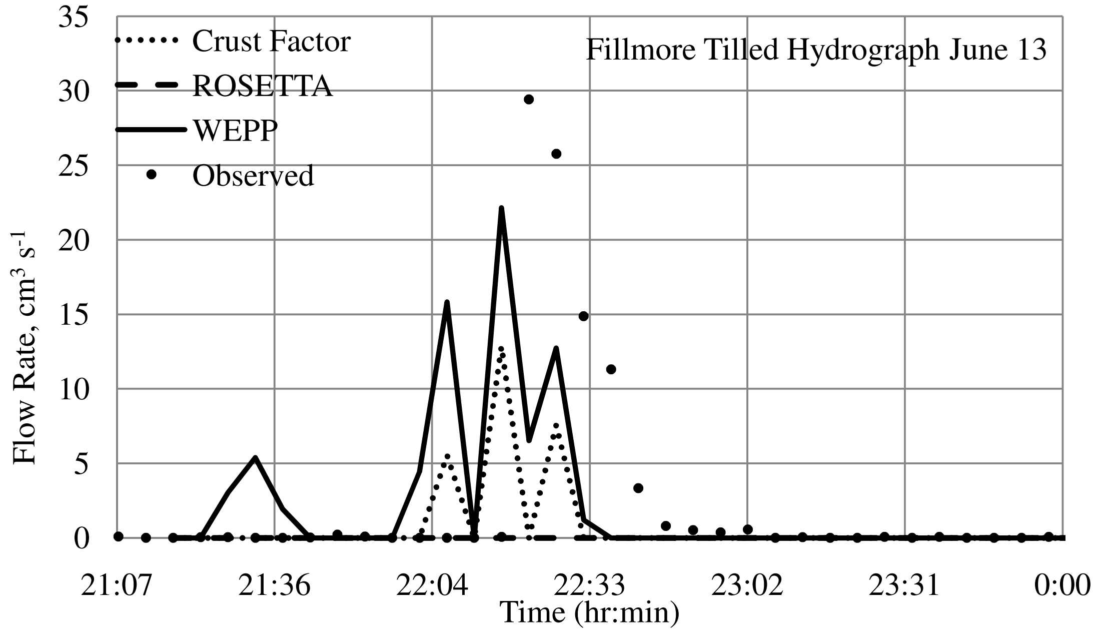

Figure 2.4. Observed and predicted hydrographs.

Table 2.4. Satiated hydraulic conductivities of the surface layer used in the Green and Ampt model

Site	Plot	Experimentally Measured	Crust Factor	ROSETTA	WEPP Tbl 2.2	WEPP Eqn 2.15	SWC
		Hydraulic conductivity, cm h^{-1}					
Fillmore County	No-till	6.18 (2.10-18.22)*	3.22	1.55	0.52	0.53	2.14
	Tilled	3.89 (1.44-10.49)	1.28	7.24	0.44	0.42	2.56
Phelps County	No-till	8.21 (3.47-19.44)	5.85	1.76	0.52	0.53	2.49
	Tilled	2.82 (1.26-6.30)	0.26	2.99	0.51	0.44	2.94

$*mean \pm standard\ deviation = 10^{[log_{10}(\bar{y}) + log_{10}(s_y)]}$

2.3.3 Depressional storage

Depressional Storage was determined using the table from NRCS (2005) and measured values (Table 2.5). Comparing the modeled runoff outputs using both depressional storage numbers to the measured runoff, the measured DS resulted in higher efficiency and less percent bias. Therefore, in the analysis for model comparison, the measured DS values were used.

Table 2.5. Depressional Storage from NRCS and from measured

Site	% Residue	% Slope	NRCS Depressional Storage, cm	Measured Depressional Storage, cm
Fillmore No-till	93	1.0	2.00	0.13
Fillmore Tilled	37	0.9	1.42	0.02
Phelps No-till	91	0.2	2.16	0.13
Phelps Tilled	47	0.5	1.73	0.03

2.3.4 Rainfall runoff

Efficiency and error values, along with the cumulative modeled and measured runoff for the season are given in Table 2.5. PBIAS and NSE values corresponded in all but two categories (Phelps County No-till and Phelps County Composite) for picking the optimal model for each grouping. RMSE values did not always align with the chosen PBIAS and NSE best model. NSE values were often negative, indicating poor efficiency for the model. PBIAS is therefore used in discussion to compare models.

Field measured surface hydraulic conductivity resulted in the high K_s values. Although high values were also observed in the lab, using the field measured hydraulic conductivity as the parameter for the Green and Ampt equation resulted in no runoff throughout the crop season and, therefore, was not consistent with the observed runoff. Discrepancies between modeled runoff using the measured saturated hydraulic conductivities and measured runoff may be due to the hydraulic conductivity testing methods or characteristics of the field at the time of hydraulic conductivity measurement. Testing may have destroyed the surface seal that results from water drop impact, or created cracks in the soil. Early season measurement did not account for compaction of the seasonal soil surface after tillage or surface crusting from multiple rainfall and irrigation events (Mapa et al., 1986).

Table 2.4. Root mean squared error (RMSE), Nash-Sutcliff efficiency (NSE), percent bias (PBIAS), and cumulative runoff from rainfall based on the hydraulic conductivity derived from four models. Values are given for each field individually and the combined data (composite) and separated by tillage type and site.

	Measured	Crust Factor					ROSETTA					WEPP Tbl 2.2					SWC			
Grouping	Runoff, cm	RMSE, cm	NSE	Bias, %	Runoff, cm		RMSE, cm	NSE	Bias, %	Runoff, cm		RMSE, cm	NSE	Bias, %	Runoff, cm		RMSE, cm	NSE	Bias, %	Runoff, cm
Fillmore County No-till	4.80	1.15	-2.41	-100.00	0.00		0.84	-0.82	-75.48	1.19		0.15	0.95	-12.62	4.23	*	0.99	-1.53	-87.44	0.61
Fillmore County Tilled	5.70	0.73	-1.34	-59.08	2.33		1.04	-3.05	-86.63	0.76		0.56	-0.39	10.73	6.29	*	0.48	-5.88	16.19	1.21
Phelps County No-till	5.00	0.31	0.44	-74.99	1.04		0.34	0.39	20.49	5.01	*	0.65	-1.40	155.30	10.62		0.27	-0.07	58.79	3.42
Phelps County Tilled	9.60	0.79	-0.87	20.63	10.25		0.77	-0.69	-87.68	1.31		0.66	-0.30	6.40	12.02	*	0.59	-1.62	-38.03	1.37
No-till Composite	9.80	0.58	-0.17	-88.44	1.04		0.49	0.24	-31.13	6.20	*	0.57	-0.10	64.98	14.85		0.50	0.13	-55.30	4.02
Tilled Composite	15.30	0.80	-0.71	-7.10	12.58		0.86	-0.89	-87.31	2.07		0.66	-0.15	7.91	18.31	*	0.83	-0.84	-84.20	2.58
Fillmore County Composite	10.50	0.93	-1.87	-77.90	2.33		0.95	-1.77	-81.50	1.95		0.44	0.36	-0.01	10.52	*	0.57	-3.35	-37.25	1.82
Phelps County Composite	14.60	0.61	-0.28	-6.22	11.29	*	0.60	-0.18	-57.31	6.32		0.66	-0.51	48.20	22.64		0.53	-0.28	-55.42	4.79
Composite	25.80	0.71	-0.38	-35.99	13.62		0.70	-0.30	-67.36	8.27		0.62	-0.06	28.18	33.16	*	0.69	-0.32	-73.94	6.60

* indicates best NSE for given grouping

The Crust Factor equation, developed by Rawls et al. (1990), takes into account surface crusting. In the Crust Factor equation, experimental data were used and adjusted lower to account for the surface crust. This was the only model that predicted the Phelps County no-till field to have higher hydraulic conductivity than the tilled field. This is significant since Phelps no-till experienced significantly less runoff than the Phelps County tilled field throughout the season. Although this method did predict more runoff events than the unadjusted experiment values, this model still predicted low runoff depths. Phelps County tilled field was the only field where total runoff was over predicted by the Crust Factor model. The pooled percent bias for all fields was -36%. The composite Phelps County runoff was most accurately described by this model (PBIAS = -6%).

ROSETTA predicts hydraulic conductivity using the soil properties of percent sand, silt, and clay and bulk density. The PBIAS was -67% when all four fields were considered collectively. Modeled runoff data for most fields were lower than observed data. The exception to this was Phelps County no-till field, predicting one hundredth of a centimeter more than observed. Because ROSETTA does not include adjustments for management practices, such as residue left on the ground or the effect of rain impaction, the model did not account for the influence of tillage systems on infiltration and runoff. ROSETTA best predicted runoff from the composite no-till fields and the no-till field in Phelps County.

The WEPP model predicts satiated hydraulic conductivity for fallow conditions and adjusts the value by considering crop type and management practices through the curve number. Curve numbers were calculated using the measured runoff data from the micro runoff plots. The no-till curve number was 83, and the curve number for the tilled fields was 87. These values were higher than SCS (1985) tabular values for curve number (Table 2.5). One reason for this may be the number of small rainfall depths used to predict the curve number was at the low end of the curve number versus precipitation curve so the values did not represent the curve number asymptote (Hawkins et al., 1985). Another reason is the assumed initial abstraction ratio may be too high (initial abstraction/S = 0.2) (Woodward et al., 2003).

Table 2.5. Curve numbers, N, from the SCS Handbook (WEPP Tbl 2.2), 1985 and inversely measured from observed runoff events (WEPP Eqn 2.15)

	N for Hydrological Soil Group B	
Crop Type	WEPP Tbl 2.2	WEPP Eqn 2.15
Conventional beans	81	87
Conservation beans	80	83

Ratio values describing the cropped to fallow hydraulic conductivities are shown in Table 2.6. Using the curve number from the micro runoff plot data in the WEPP equation (Equation 2.15) indicated a ratio close to what was described by Nearing et al., 1996. Ratios 1.70 and 1.91 were used to calculate K_s from K_{ef}, which were given in the paper by Nearing et al. (1996). K_s values were similar for the two different methods used, resulting in similar results for each model. The ratios provided by Nearing et al. (1996) based on the SCS curve numbers (WEPP Tbl 2.2) were therefore used in the analysis instead of the derived curve numbers with Equation 2.15 (WEPP Eqn 2.15).

Table 2.6. Cropped to fallow hydraulic conductivity ratio

	K_s/K_{ef}	
Crop Type	WEPP Tbl 2.2*	WEPP Eqn 2.15**
Conventional beans	1.70	1.49
Conservation beans	1.91	2.11

* WEPP Tbl 2.2 is the optimized ratio to describe the given soil group in Nearing et al., 1996.
** WEPP Eqn 2.15 is the ratio determined using Equation 2.15 from Nearing et al. 1996.

Using the WEPP Tbl 2.2 hydraulic conductivity, runoff was over predicted at the no-till field in Phelps County with a PBIAS of 155%. Other than Phelps County no-till field, WEPP most accurately predicted all sites. The composite PBIAS was equal to 28%, and when Phelps no-till was not considered, the PBIAS was 3.22%. The Fillmore County composite PBIAS was -0.01%.

SWC predicted hydraulic conductivity based on bulk density and percent sand, clay, and organic matter. The composite PBIAS was -74%. SWC model had low RMSE values, however it did not have the smallest PBIAS for any grouping.

Scatter plots for each model are shown in Figures 2.5-2.8. The graphs show the model predicted value for each runoff event against the observed runoff event. Each event had a different depth of rainfall. The closer the two values, the closer to the 1:1 line the points fall. Crust Factor is accurate with some scatter. ROSETTA and SWC graphs display the underestimation of the modeled runoff depths. The WEPP graph exhibits the accuracy of the model, especially at Fillmore County, which follows the regression line; however most of the Phelps County no-till field events were overestimated.

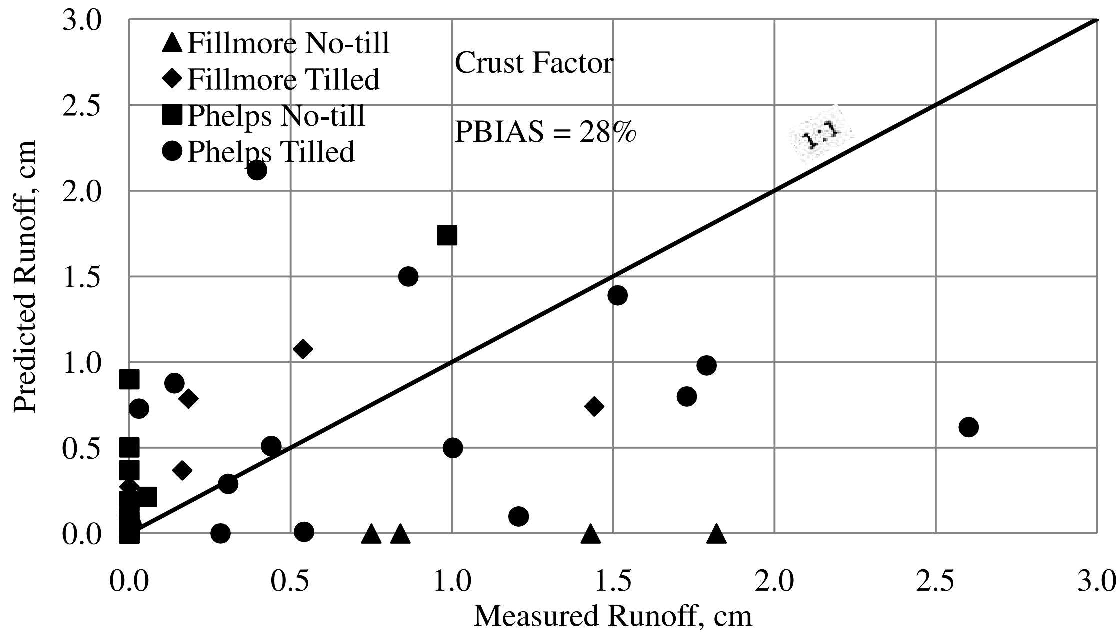

Figure 2.5. Observed runoff vs. Crust Factor predicted runoff in 2010

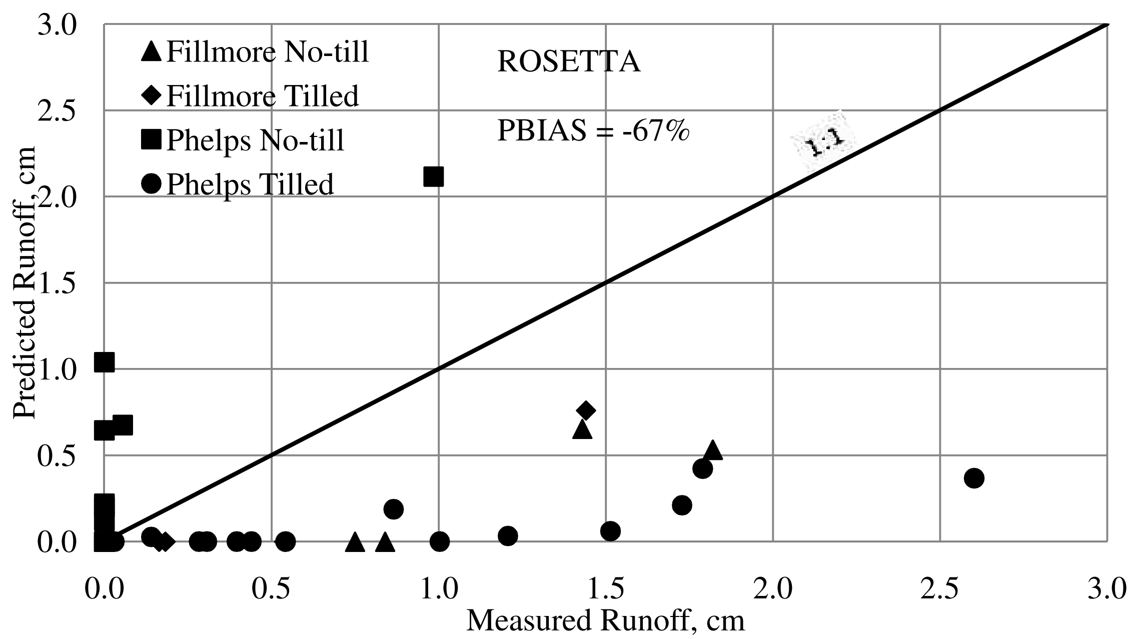

Figure 2.6. Observed runoff vs. ROSETTA predicted runoff in 2010

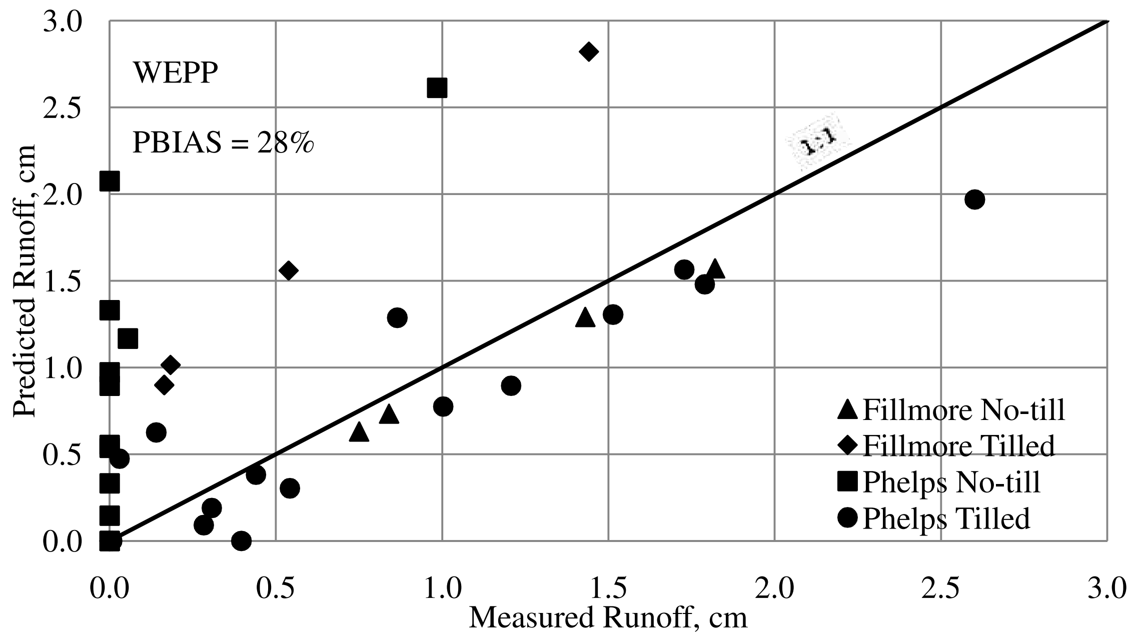

Figure 2.7. Observed runoff vs. WEPP predicted runoff in 2010

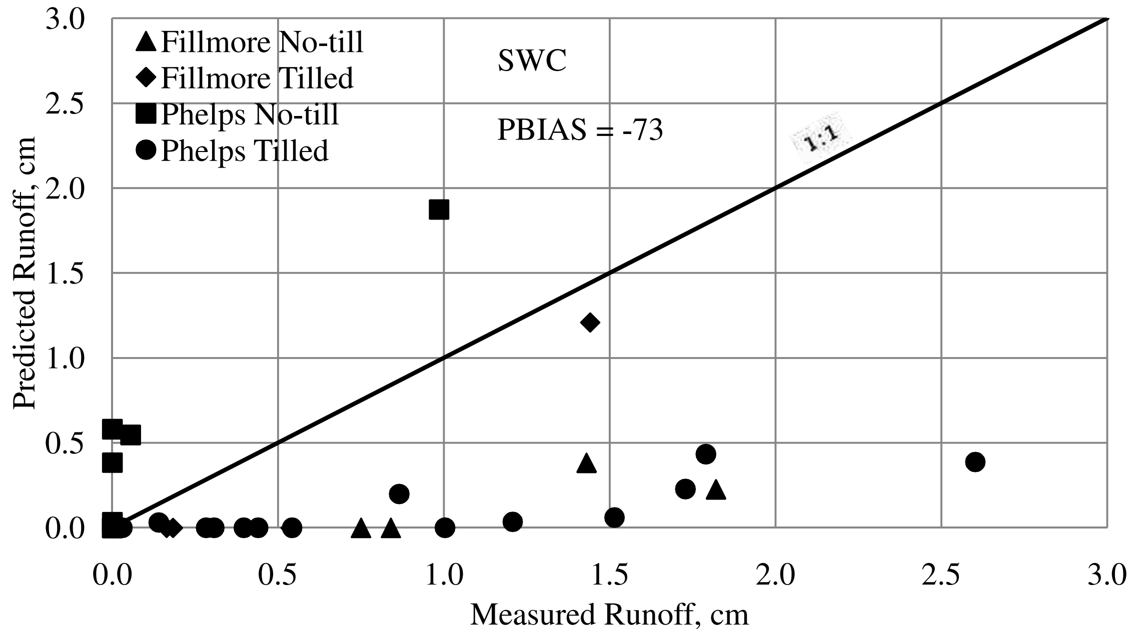

Figure 2.8. Observed runoff vs. SWC predicted runoff in 2010

2.3.5 Irrigation

From the runoff events investigated, irrigation runoff events were isolated for analysis. Irrigation rate curves for specific events were formed to illustrate the effectiveness of the tipping rain gauge and application rate relationship. Figures 2.9-2.11 show the rain gauge captured the smoothness of the application rate. All models performed poorly with the irrigation runoff prediction. ROSETTA, WEPP, and SWC underestimated runoff. SWC had the best PBIAS of -9%. WEPP had a PBIAS of 129%. Table 2.9 shows the values for the observed irrigation runoff from 2010.

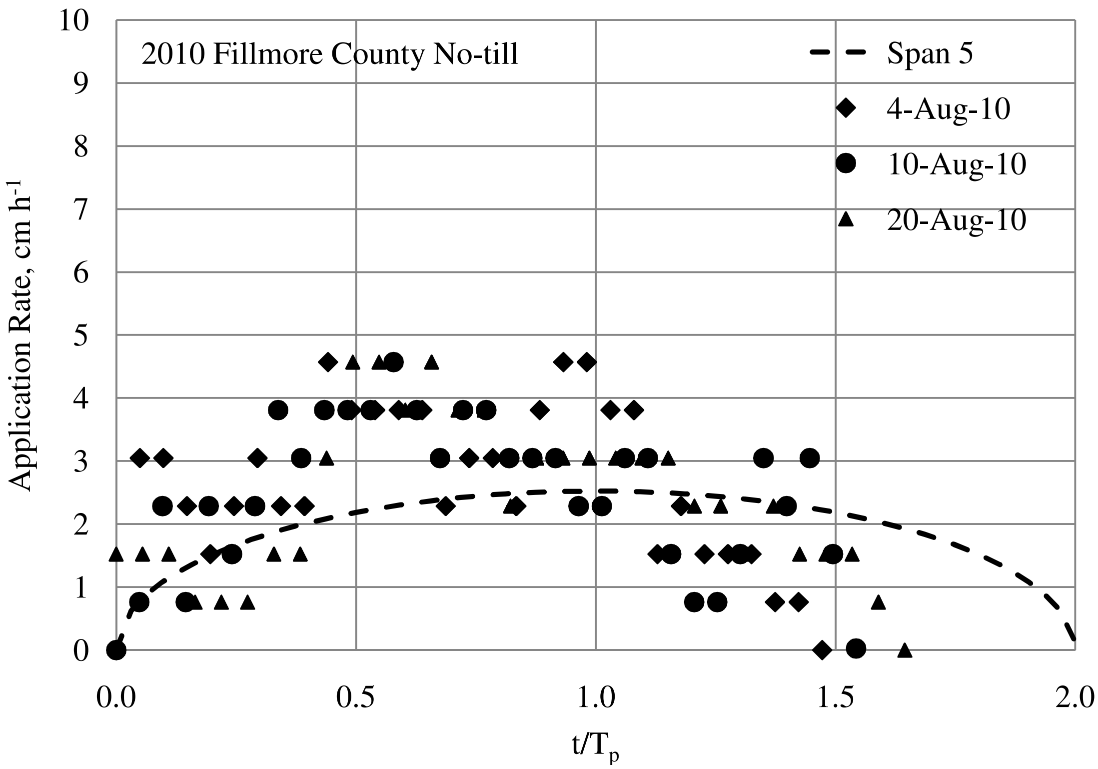

Figure 2.9. Fillmore County no-till modeled irrigation application rate and the observed tipping rain gauge curve from Span 5

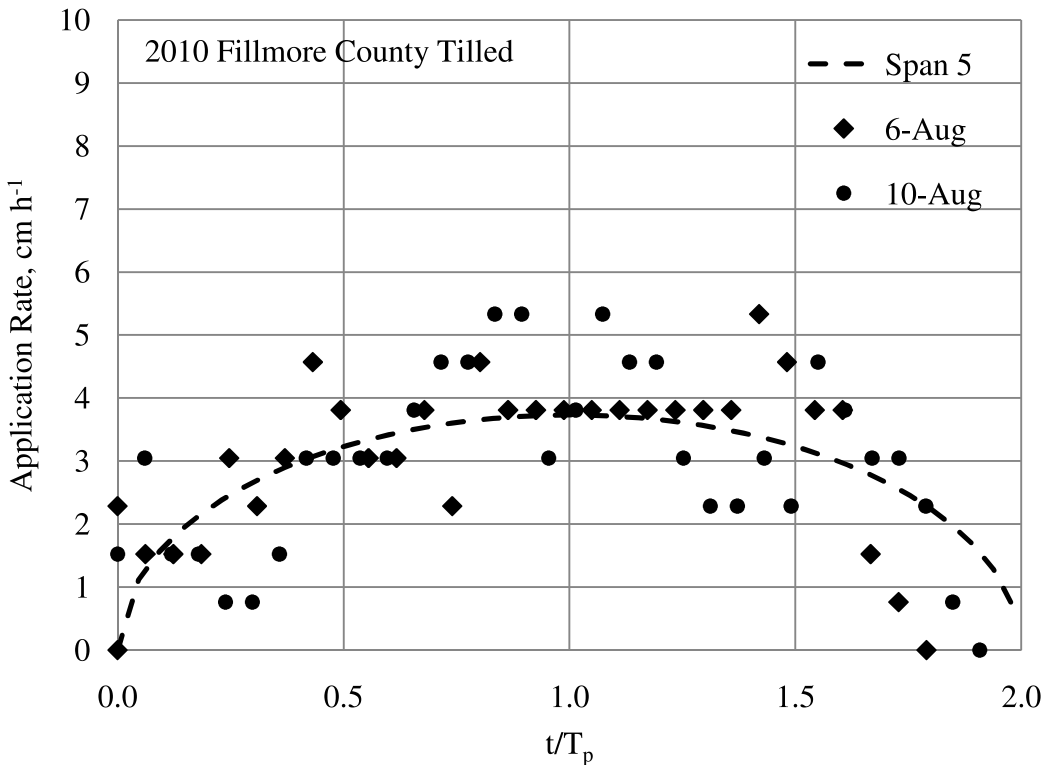

Figure 2.10. Fillmore County tilled modeled irrigation application rate and the observed tipping rain gauge curve from Span 5

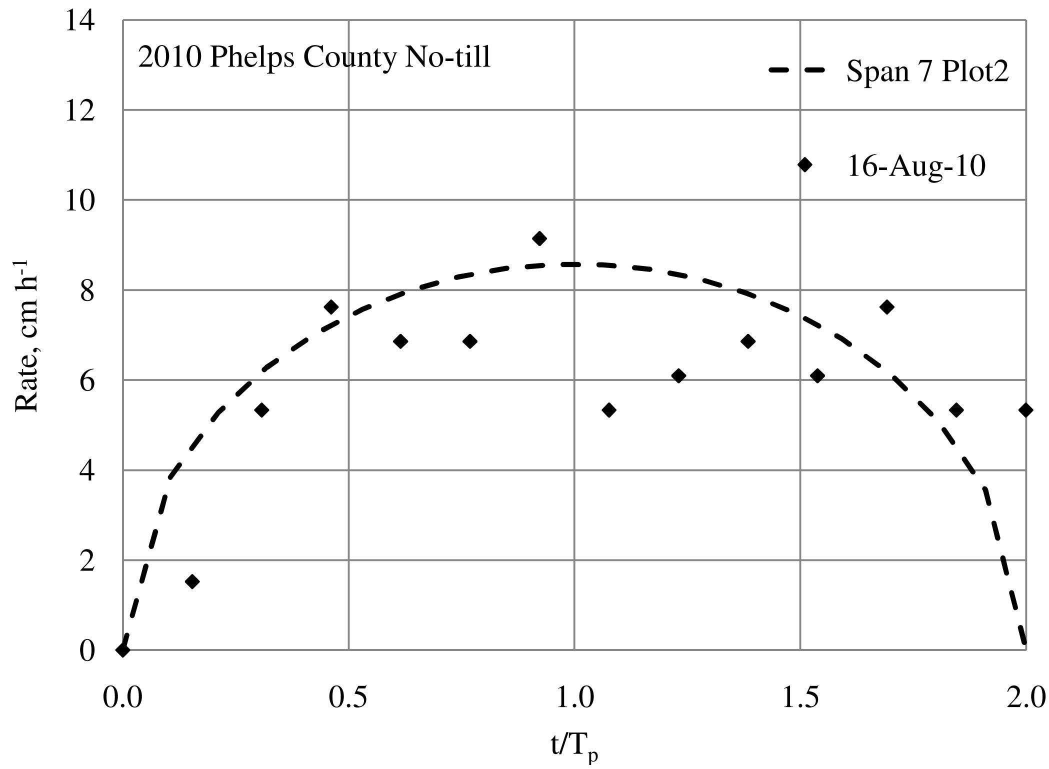

Figure 2.11. Phelps County no-till modeled irrigation application rate and the observed tipping rain gauge curve from Span 7

Table 2.7. Modeled runoff for 2010 irrigation runoff events

Site	Date	Irrigation, cm	Measured	Crust Factor	ROSETTA	WEPP	SWC
			Runoff, cm				
Fillmore County No-till	4-Aug	2.69	0.02	0.00	0.00	0.29	0.00
	10-Aug	2.74	0.03	0.00	0.00	0.26	0.00
	20-Aug	2.14	0.04	0.00	0.00	0.03	0.00
Fillmore County Tilled	6-Aug	3.33	0.47	0.00	0.00	0.74	0.00
Phelps County No-till	13-Jun	2.18	0.83	0.10	1.08	1.86	0.80

Discussion

Runoff is sensitive to the hydraulic conductivity parameter in the Green and Ampt equation. Brakensiek and Onstad (1977) found that a 10% lower K_s value over predicts the volume of runoff by 44%. This makes it difficult for one model to accurately describe any field. For example, no model could predict the low observed runoff at Phelps County no-till field. Some condition affecting the runoff in this field was not taken into account in these models. Factors such as stem flow can effect infiltration. Also the assumptions in the Green and Ampt model can influence results. The wetting front is assumed to be a piston, when in reality, the wetting front does not have a sharp boundary of saturation. The model did not account for redistribution of water during drying periods of the storm when the intensity decreased after ponding. Lastly, no head of water was assumed to be at the surface once ponding occurred. These assumptions can affect the results.

Investigating four models for predicting an accurate hydraulic conductivity for different soil types and tillage at the four fields in this study resulted in no overall optimal model. The most accurate model for determining hydraulic conductivity of the given fields was WEPP, which had a negative efficiency (NSE = -0.06) and a PBIAS of 28%. WEPP poorly predicted the no-till field at Phelps County, and when the no-till field at Phelps County was excluded from analysis, the NSE was a satisfactory 0.58 with a PBIAS of 3%. WEPP is the only model out of the four to be derived from field measured data. The other three models were derived using laboratory experiments. A drawback to WEPP was the regression equation for K_{ef} was developed using only one no-till field.

SWC and ROSETTA had the highest PBIAS values. These models did not take into account surface crusting as in the Crust Factor model or the management practices as in the curve number used in WEPP. These are important processes when considering infiltration (Blevins et al., 1983). When only irrigation runoff was considered, SWC had the highest efficiency.

Pairing tilled and no-till fields, the WEPP model, which accounts for tillage applications, had the lowest PBIAS for the composite tilled fields. ROSETTA was the best model for no-till fields. The curve number used in WEPP for no-till was the value for conservation soybean given in the SCS handbook. This number was derived from experiments on tilled fields with more than 30% residue cover (Rawls and Brakensiek, 1986). This does not describe the no-till soybean fields. A lower curve number would be expected, which would reduce runoff predicted from the no-till sites. With proper descriptive curve numbers, WEPP may be able to better describe the no-till field in Phelps County.

2.4 Conclusion

Realizing the amount of runoff expected on a field with a given soil type or certain management practices is important in order to quantify water savings as well as understanding the benefits of irrigation and tillage management. The Green and Ampt equation has been proven to be an accurate and useful model for calculating infiltration into the soil. The equation is highly sensitive to the hydraulic conductivity term, a term that is difficult to accurately measure in the field or calculate due to high amount of influences, such as texture, surface cover, rainfall energy, soil structure, ect. Also, hydraulic conductivity is highly variable in a field and throughout the crop season.

Four pedotransfer functions were evaluated to find a good predictor of hydraulic conductivity that can be used when comparing tilled and no-till fields: Crust Factor, ROSETTA, WEPP and SWC. WEPP had the highest efficiency for the four fields compared in this research. WEPP used field measured data, which displays the effect of soil management practices. Although WEPP poorly described the no-till field at Phelps County, it had the lowest composite PBIAS and the lowest PBIAS for the other three fields. Consistency in a model is most important in order to use the model for any application.

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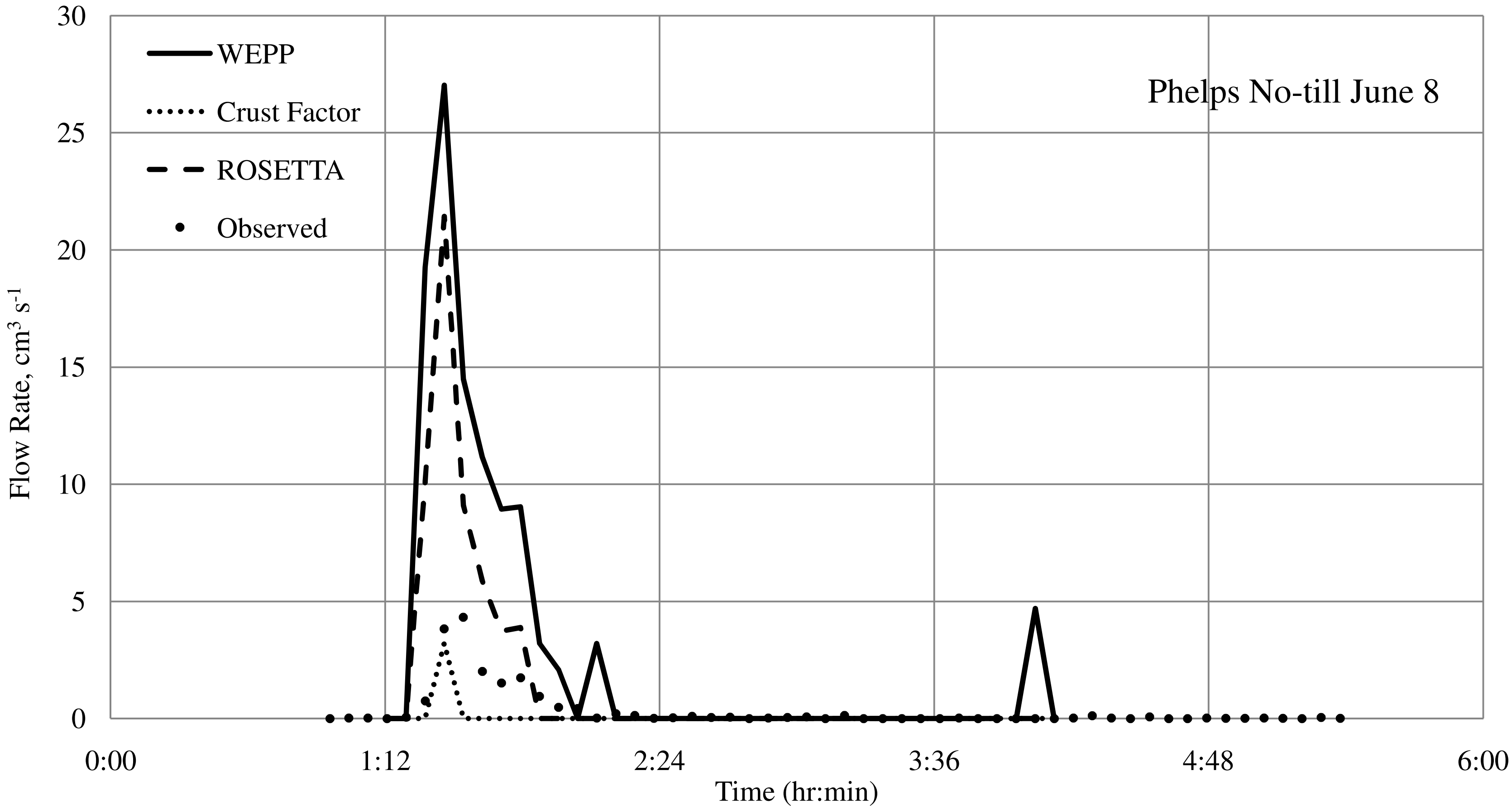
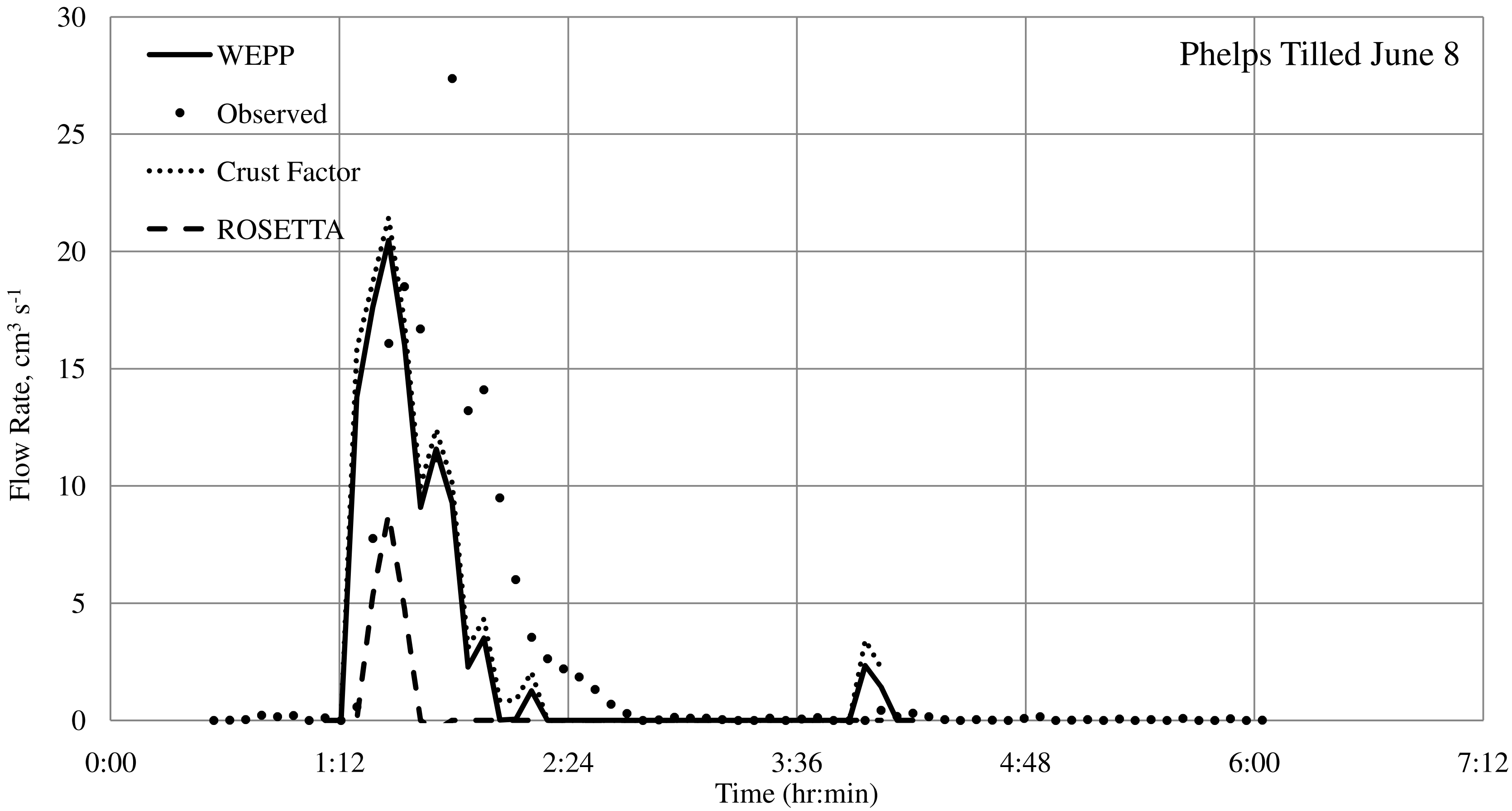
CHAPTER 3 APPENDIX A: OBSERVED AND GREEN AND AMPT PREDICTED RUNOFF HYDROGRAPHS

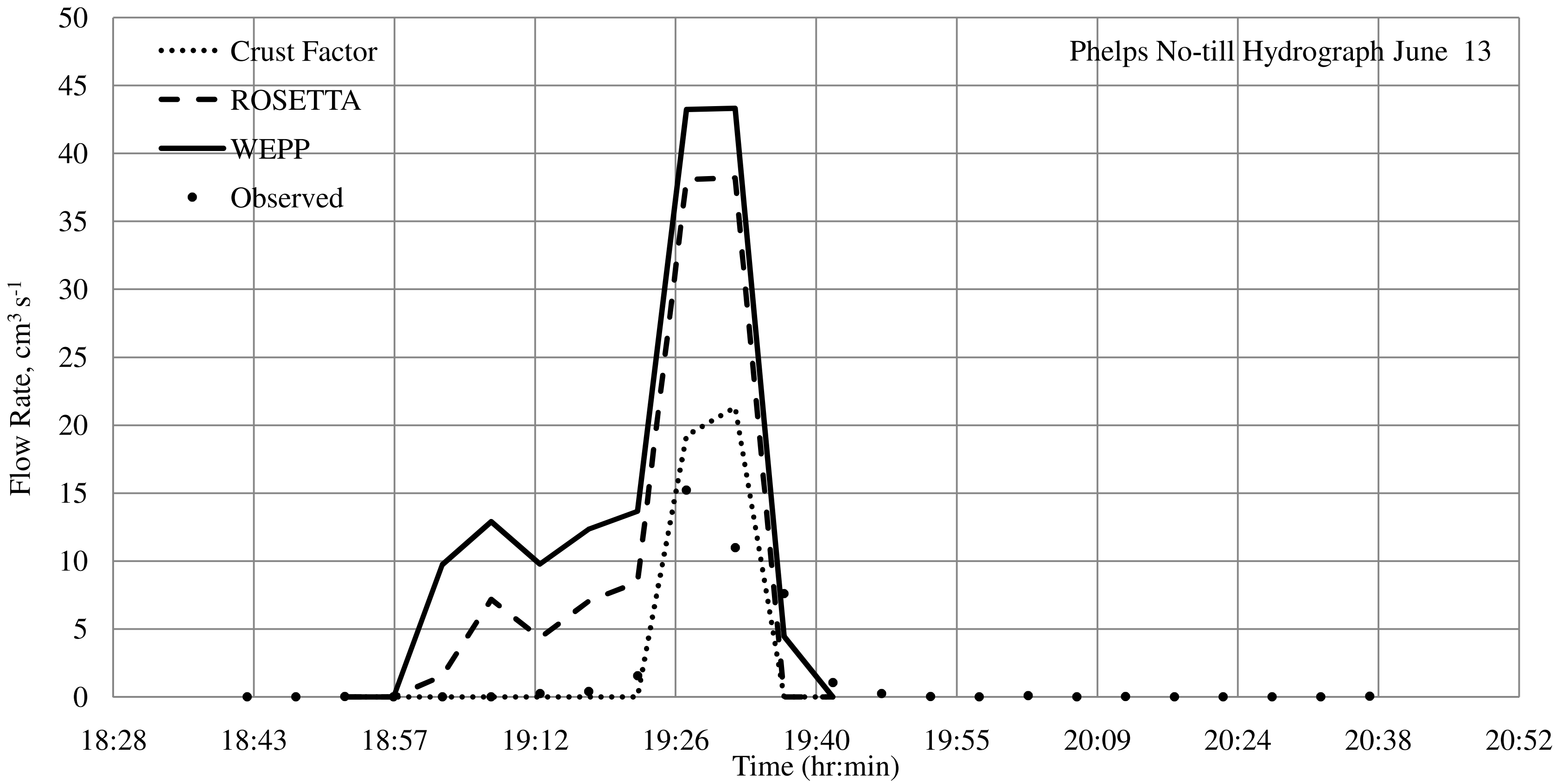
Using the models described in Chapter 2 to determine satiated hydraulic conductivity, runoff was predicted from the iterative Green and Ampt equation. Runoff hydrographs from rainfall and irrigation for each model were plotted with the observed runoff. Graphs were made for each field for every observed runoff event in 2010.

3.1 Phelps Hydrographs

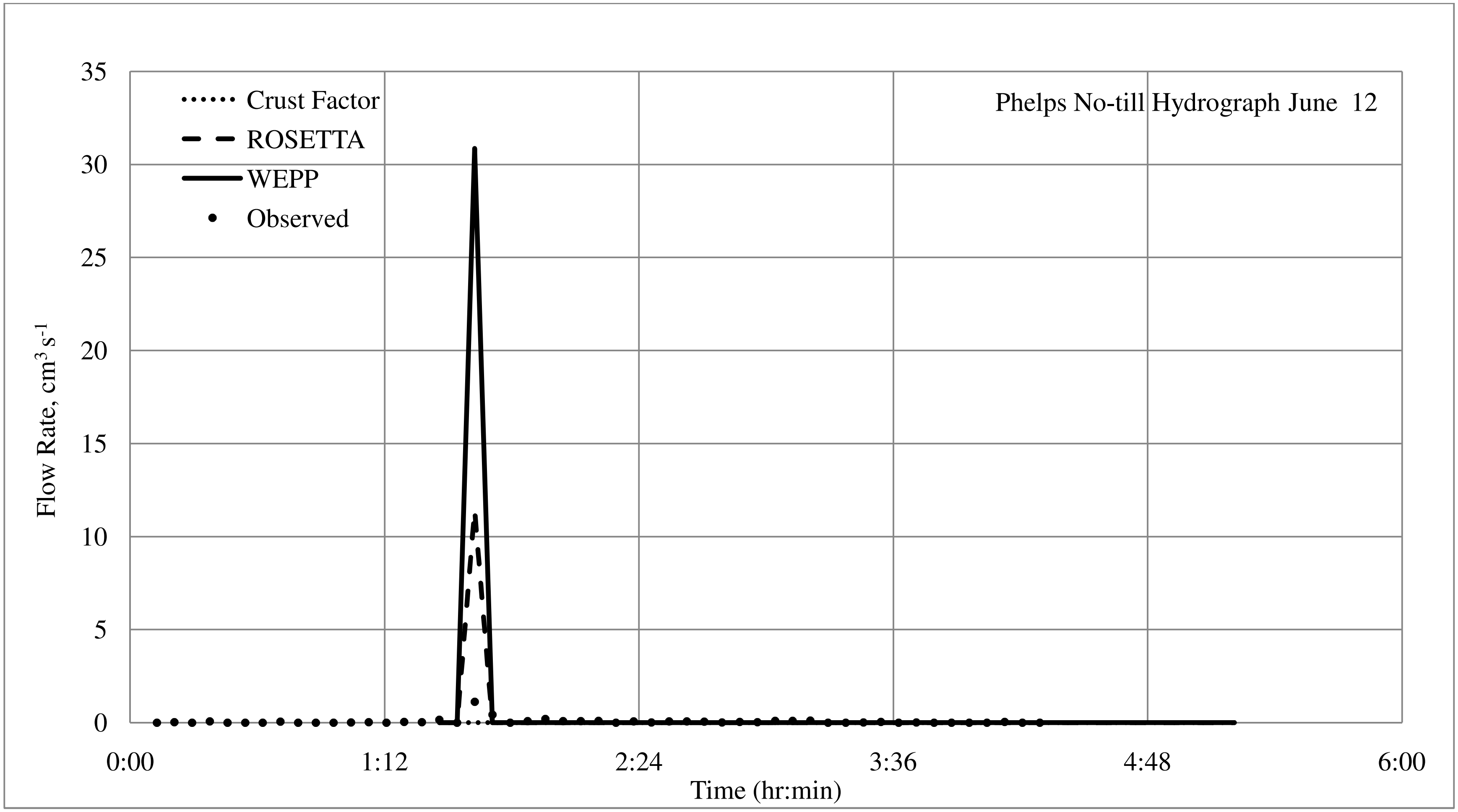




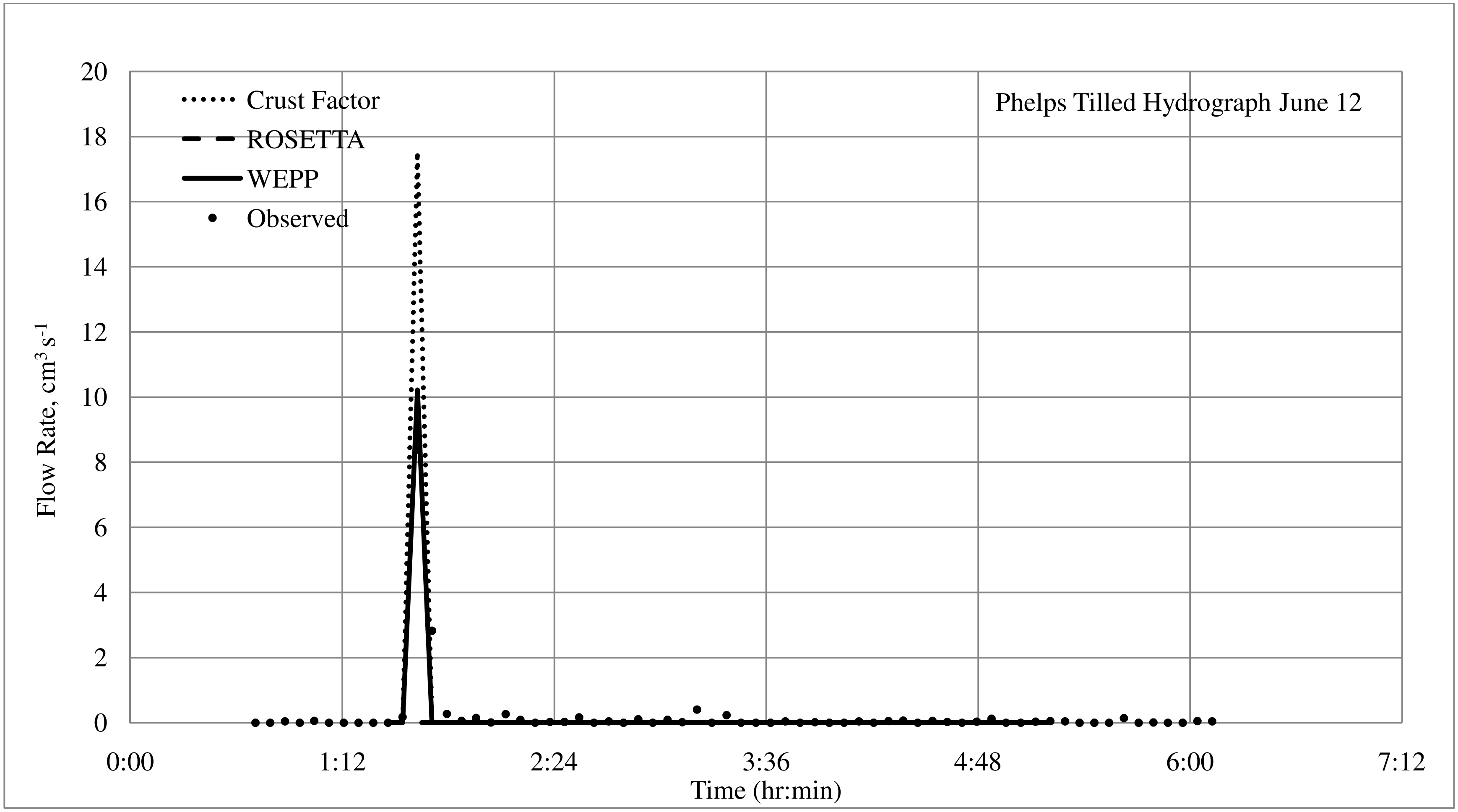
Phelps Tilled June 8
WEPP
Observed
Crust Factor
ROSETTA
Flow Rate, cm3 s-1
Time (hr:min)
0
5
10
15
20
25
30
0:00
1:12
2:24
3:36
4:48
6:00
7:12



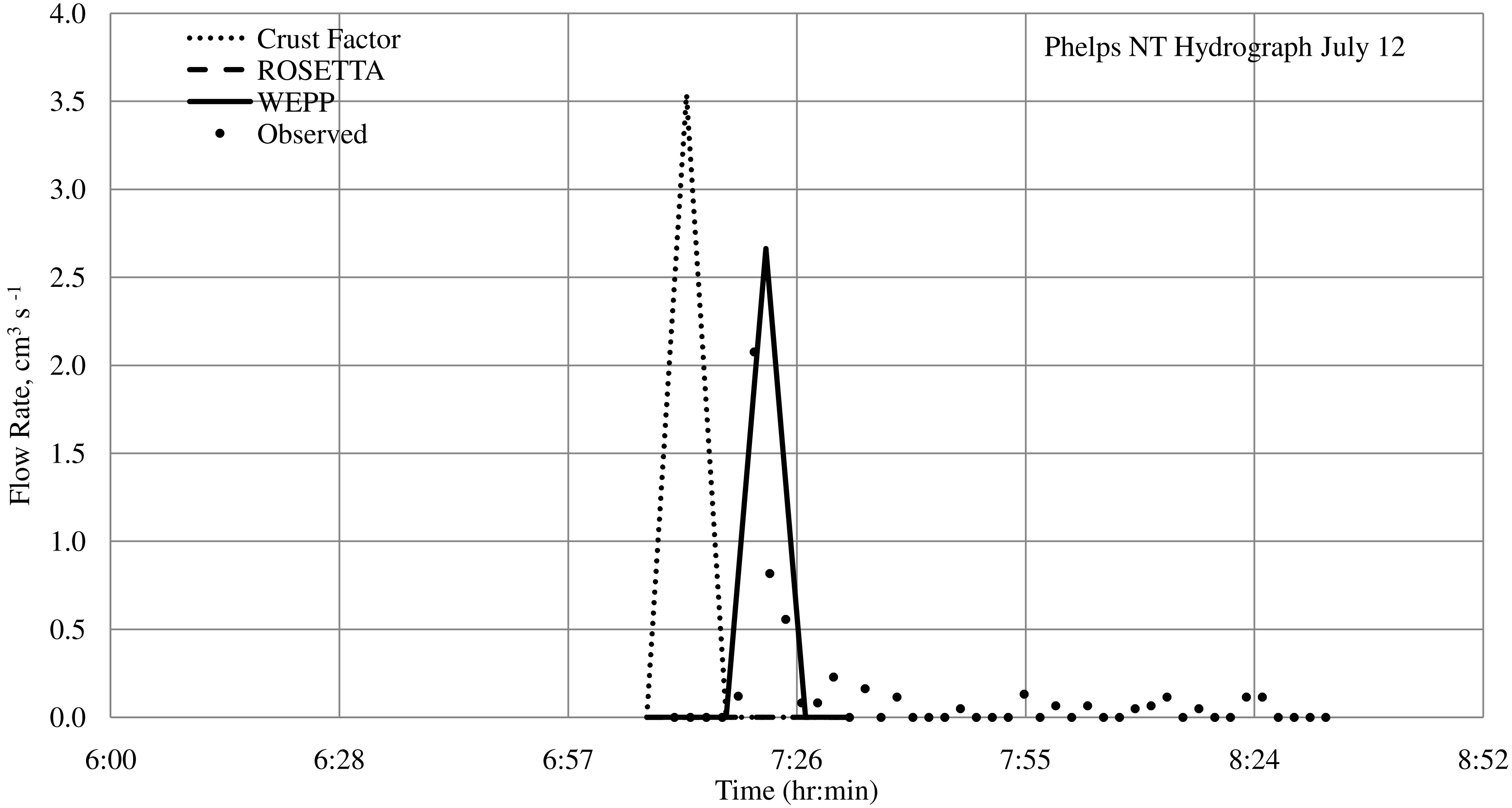
Phelps No-till Hydrograph June 13
Crust Factor
ROSETTA
WEPP
Observed
Flow Rate, cm^3 s^{-1}
0
5
10
15
20
25
30
35
40
45
50
18:28
18:43
18:57
19:12
19:26
19:40
19:55
20:09
20:24
20:38
20:52
Time (hr:min)

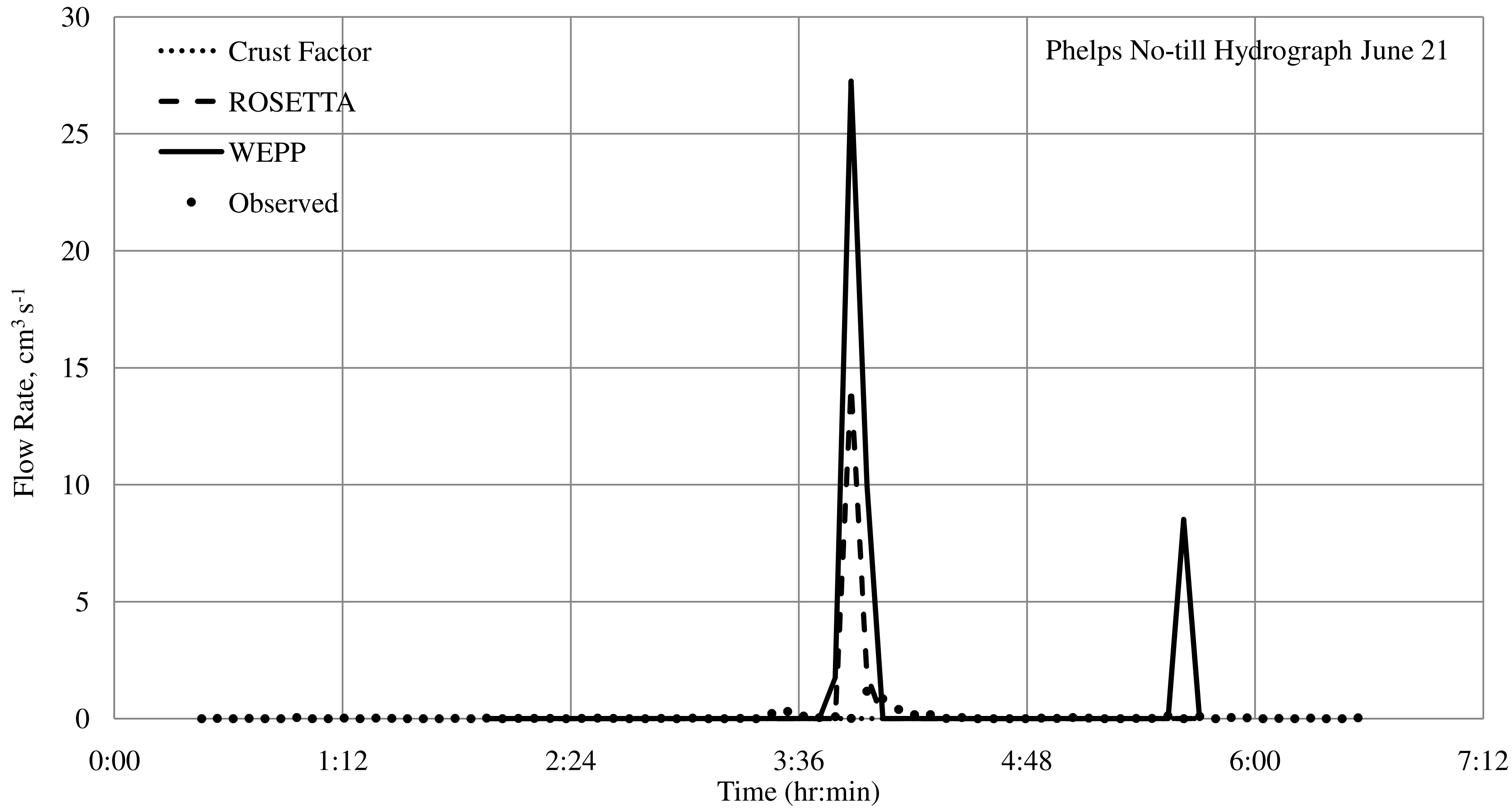


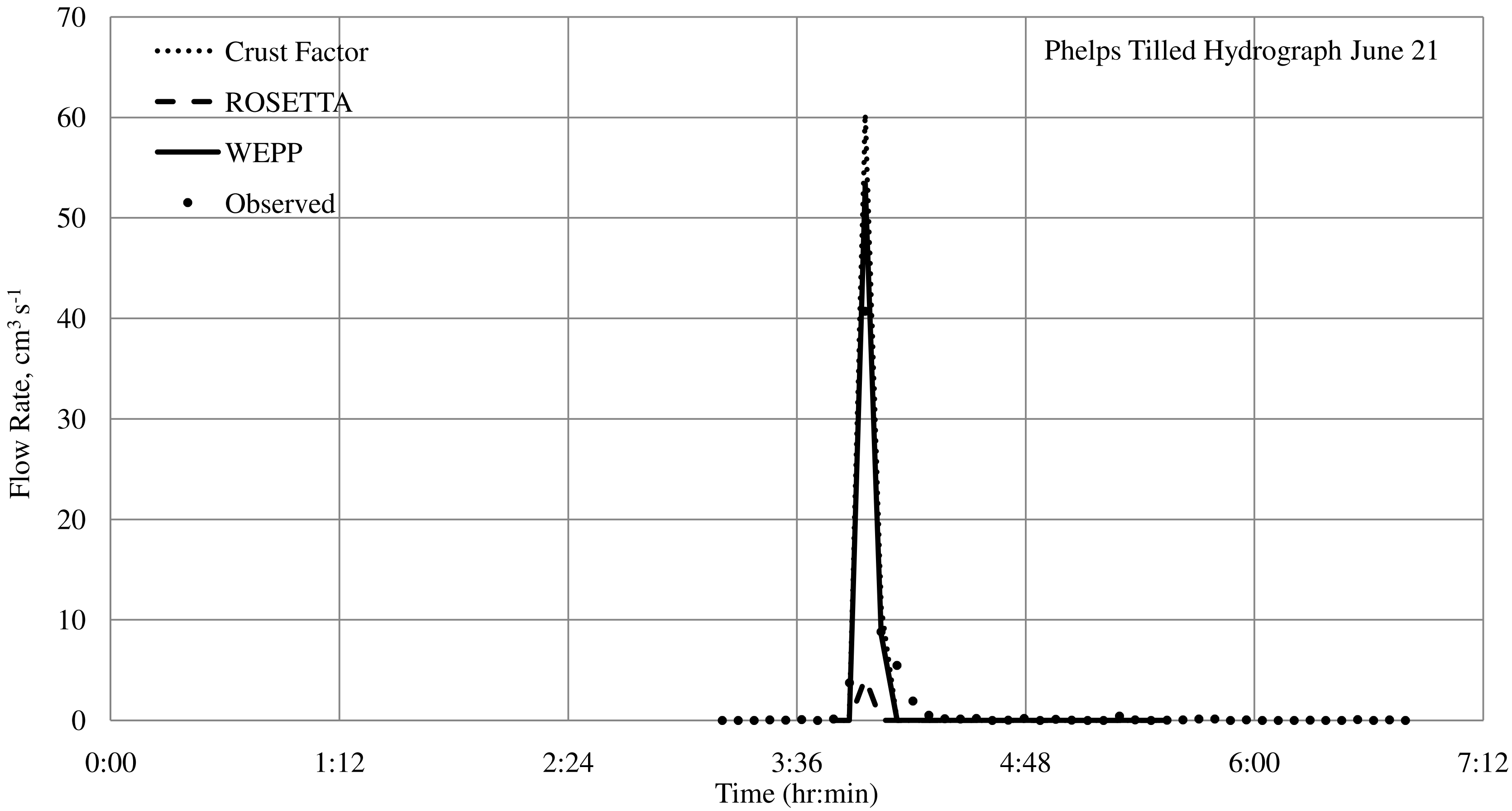
Crust Factor
ROSETTA
WEPP
Observed
Phelps No-till Hydrograph June 12
Flow Rate, cm³ s⁻¹
35
30
25
20
15
10
5
0
0:00
1:12
2:24
3:36
4:48
6:00
Time (hr:min)

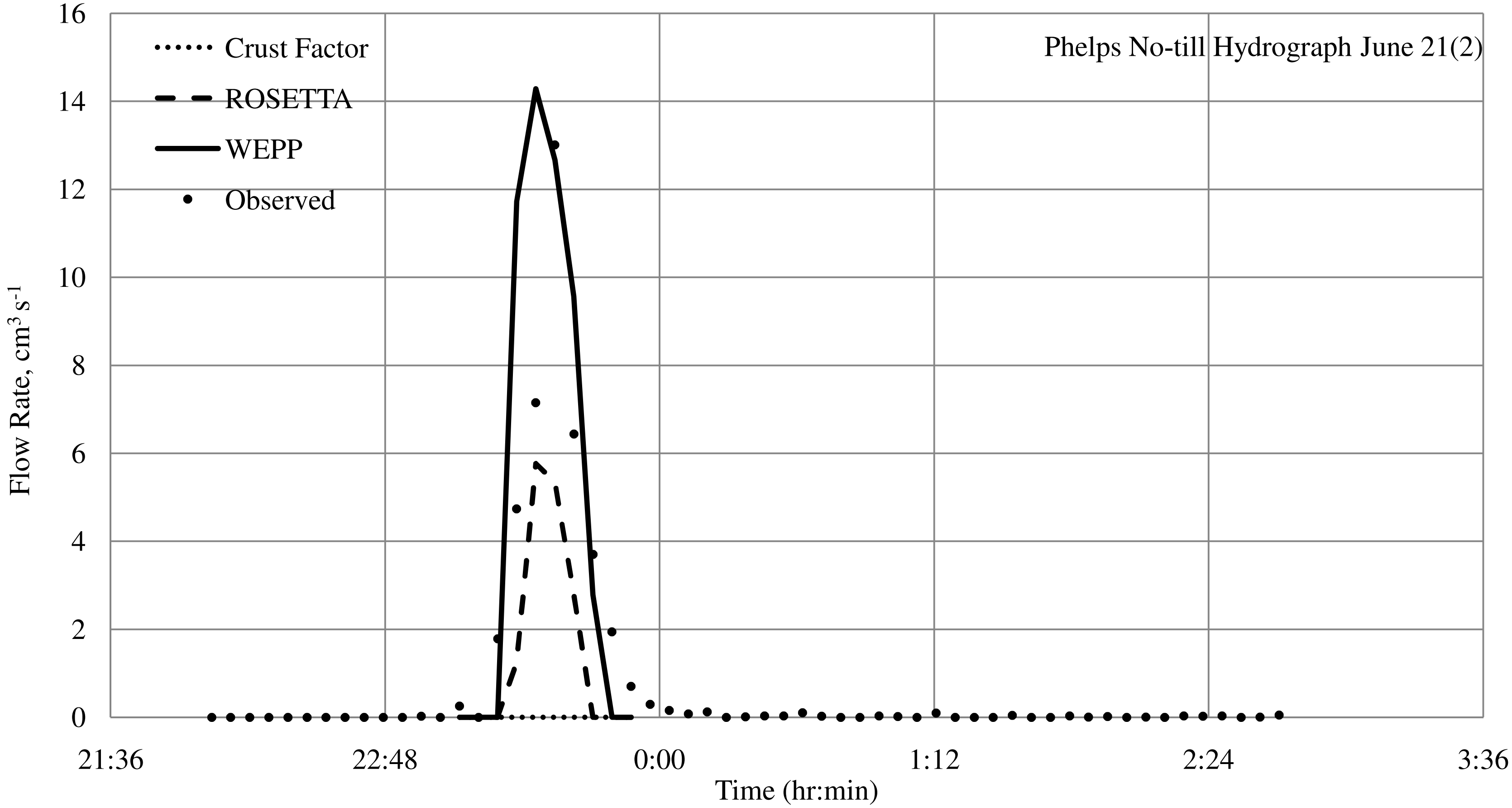


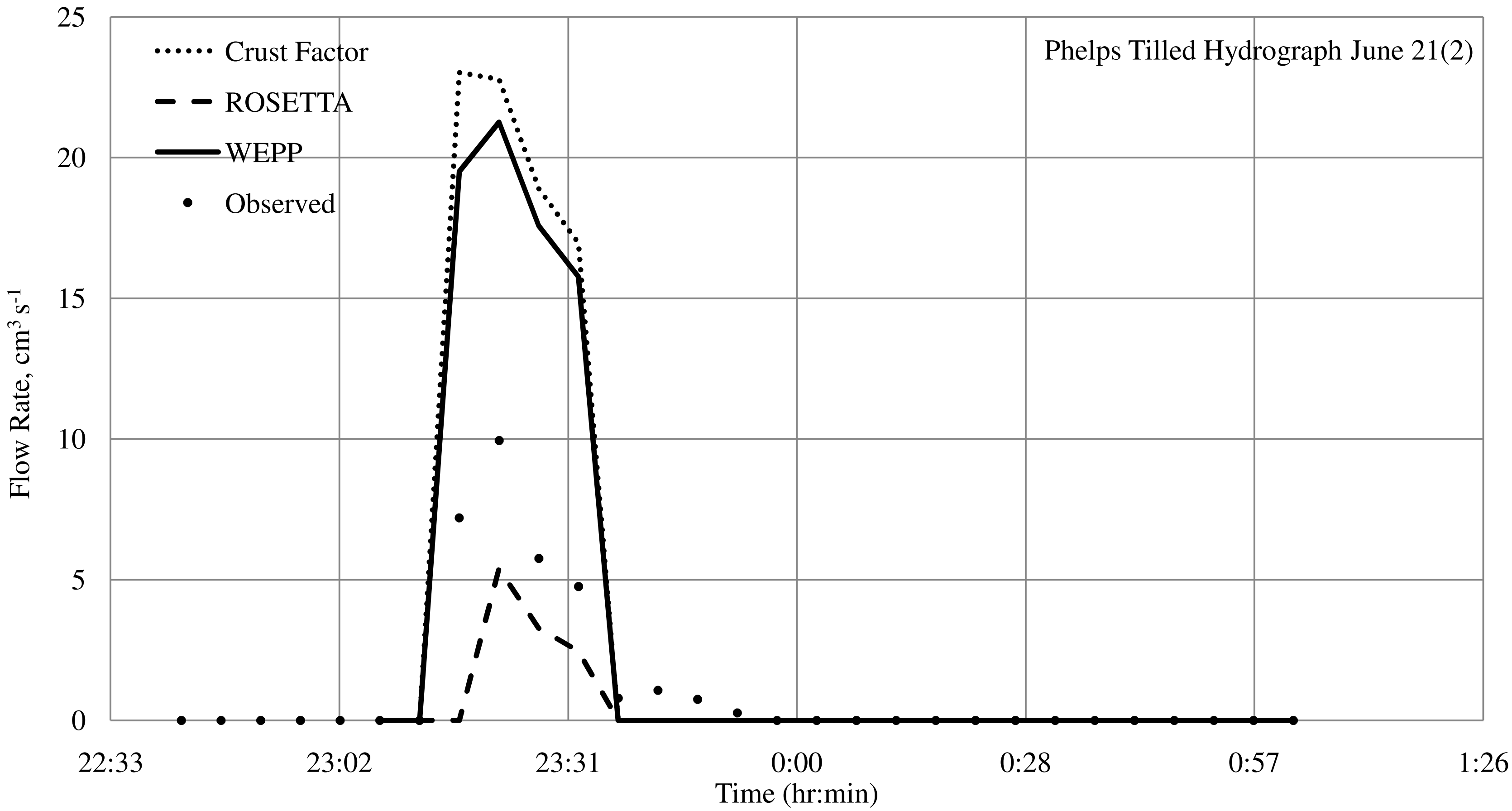
Phelps Tilled Hydrograph June 12
Crust Factor
ROSETTA
WEPP
Observed
Flow Rate, cm3 s-1
20
18
16
14
12
10
8
6
4
2
0
0:00
1:12
2:24
3:36
4:48
6:00
7:12
Time (hr:min)

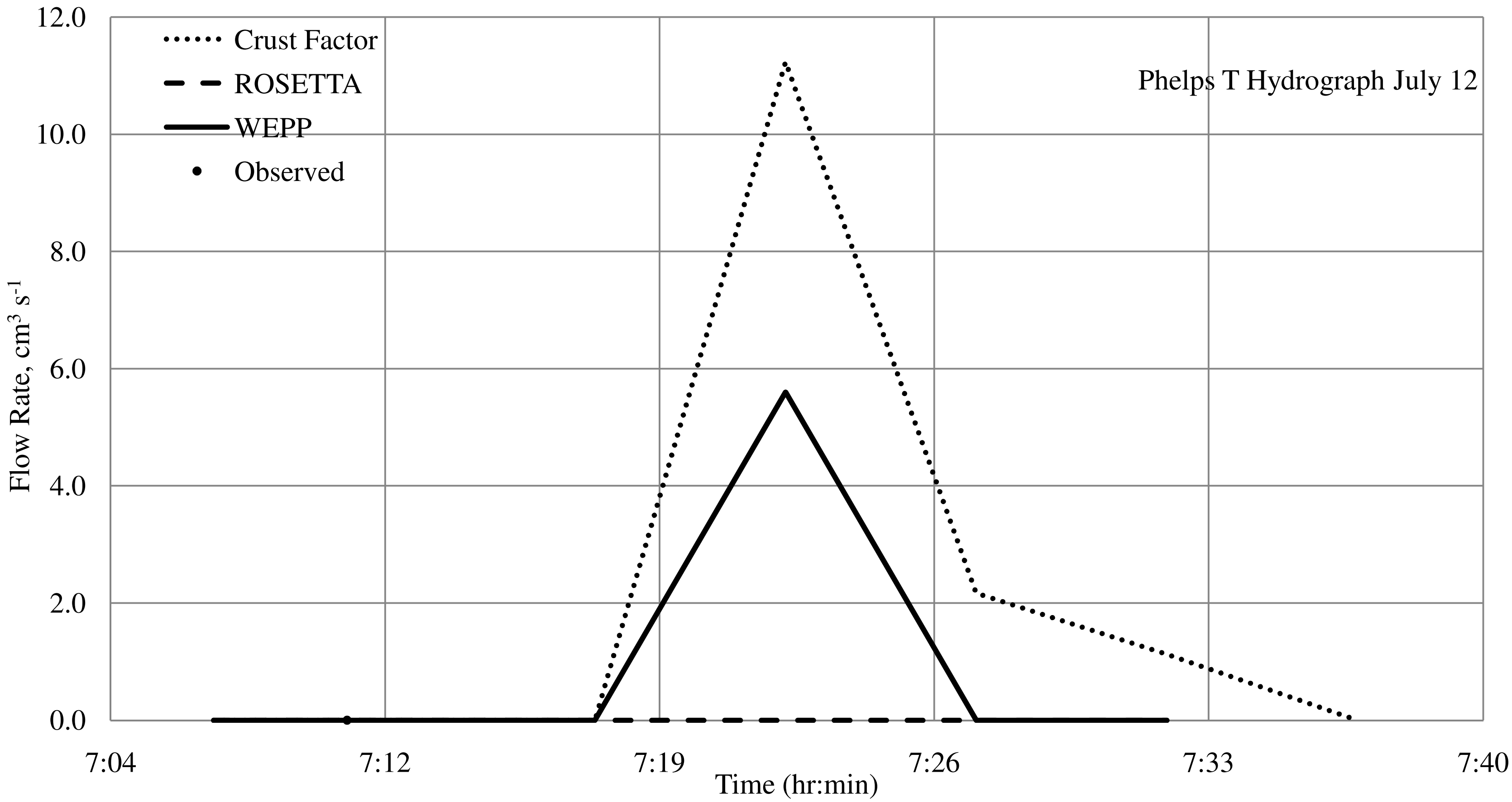

Crust Factor
ROSETTA
WEPP
Observed
Phelps NT Hydrograph July 12
Flow Rate, cm3 s -1
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
6:00
6:28
6:57
7:26
7:55
8:24
8:52
Time (hr:min)


Phelps No-till Hydrograph June 21
Crust Factor
ROSETTA
WEPP
Observed
Flow Rate, cm3 s-1
Time (hr:min)
0
5
10
15
20
25
30
0:00
1:12
2:24
3:36
4:48
6:00
7:12

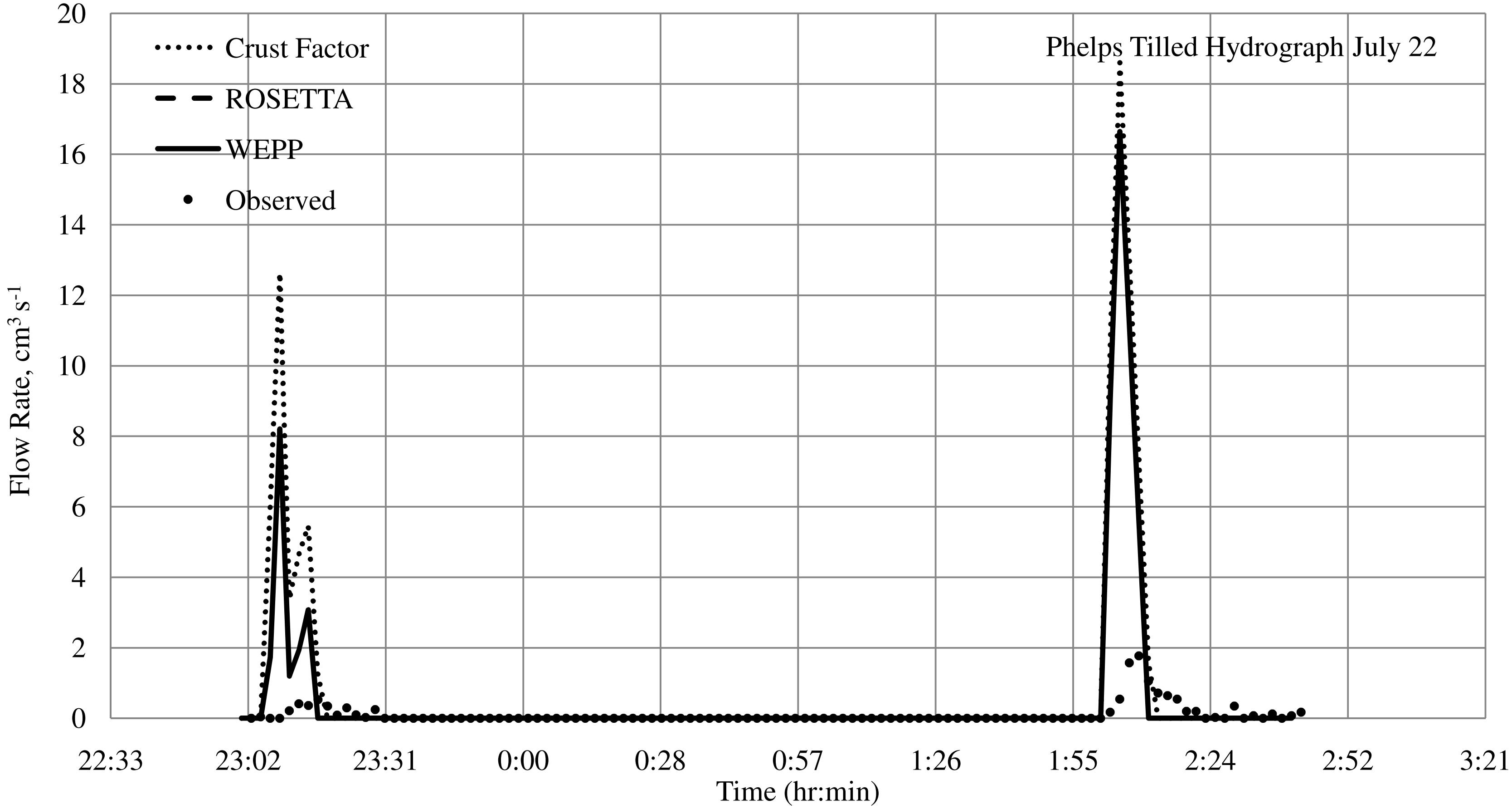

Crust Factor
ROSETTA
WEPP
Observed
Phelps Tilled Hydrograph June 21
Flow Rate, cm3 s-1
Time (hr:min)
0
10
20
30
40
50
60
70
0:00
1:12
2:24
3:36
4:48
6:00
7:12

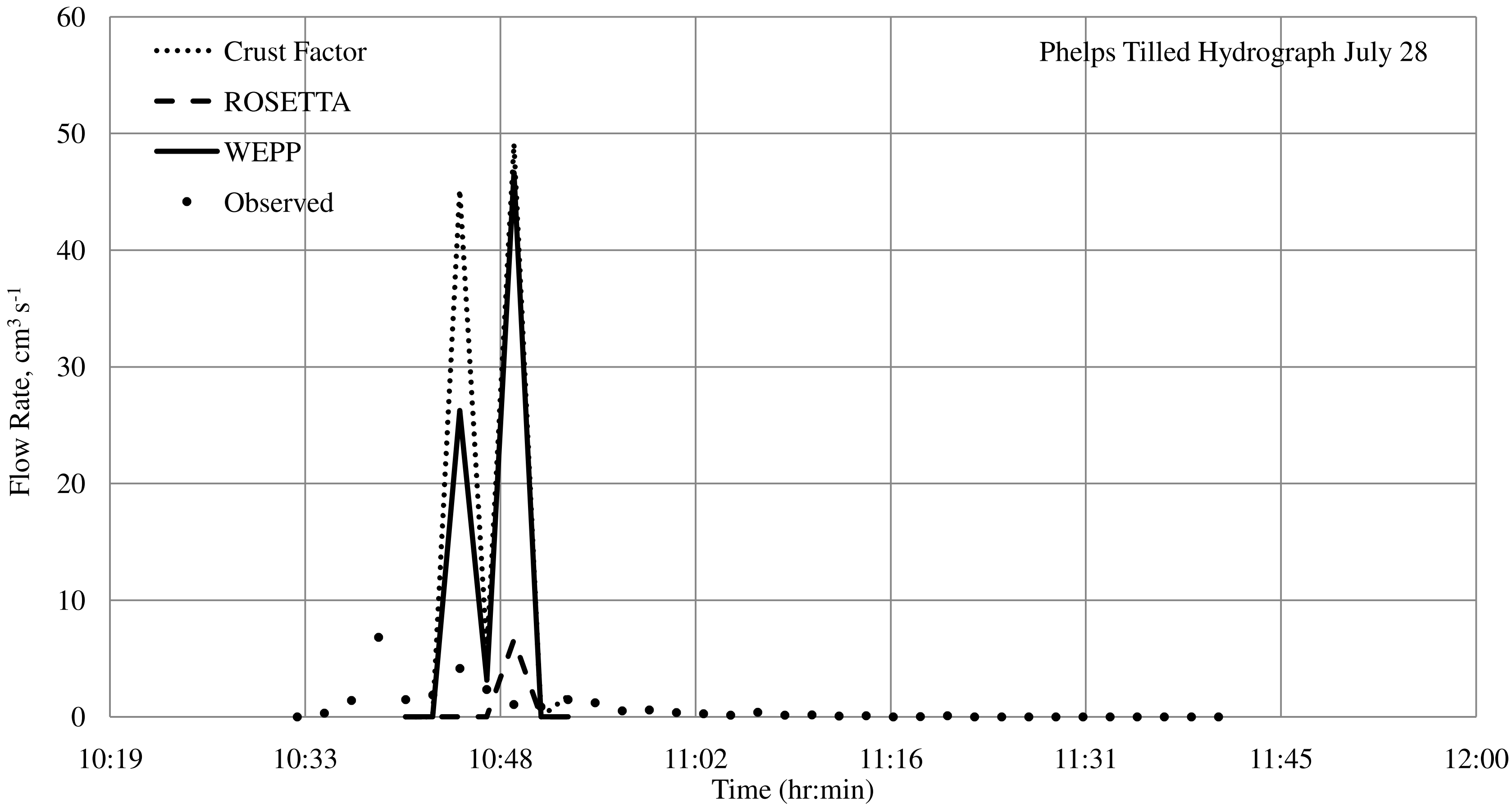

Phelps No-till Hydrograph June 21(2)
Crust Factor
ROSETTA
WEPP
Observed
Flow Rate, cm3 s-1
Time (hr:min)
16
14
12
10
8
6
4
2
0
21:36
22:48
0:00
1:12
2:24
3:36

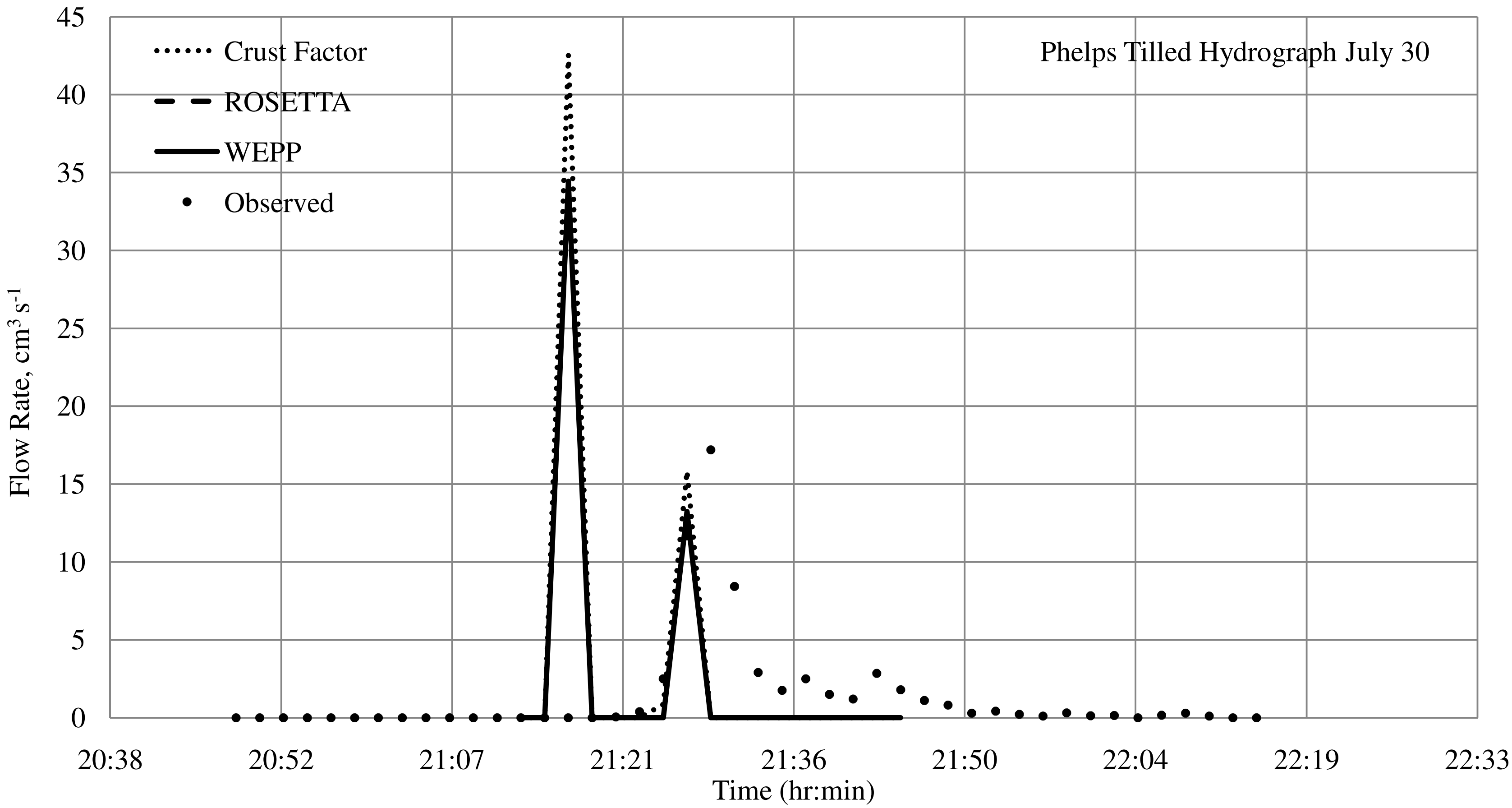

Phelps Tilled Hydrograph June 21(2)
Crust Factor
ROSETTA
WEPP
Observed
Flow Rate, cm3 s-1
Time (hr:min)
25
20
15
10
5
0
22:33
23:02
23:31
0:00
0:28
0:57
1:26

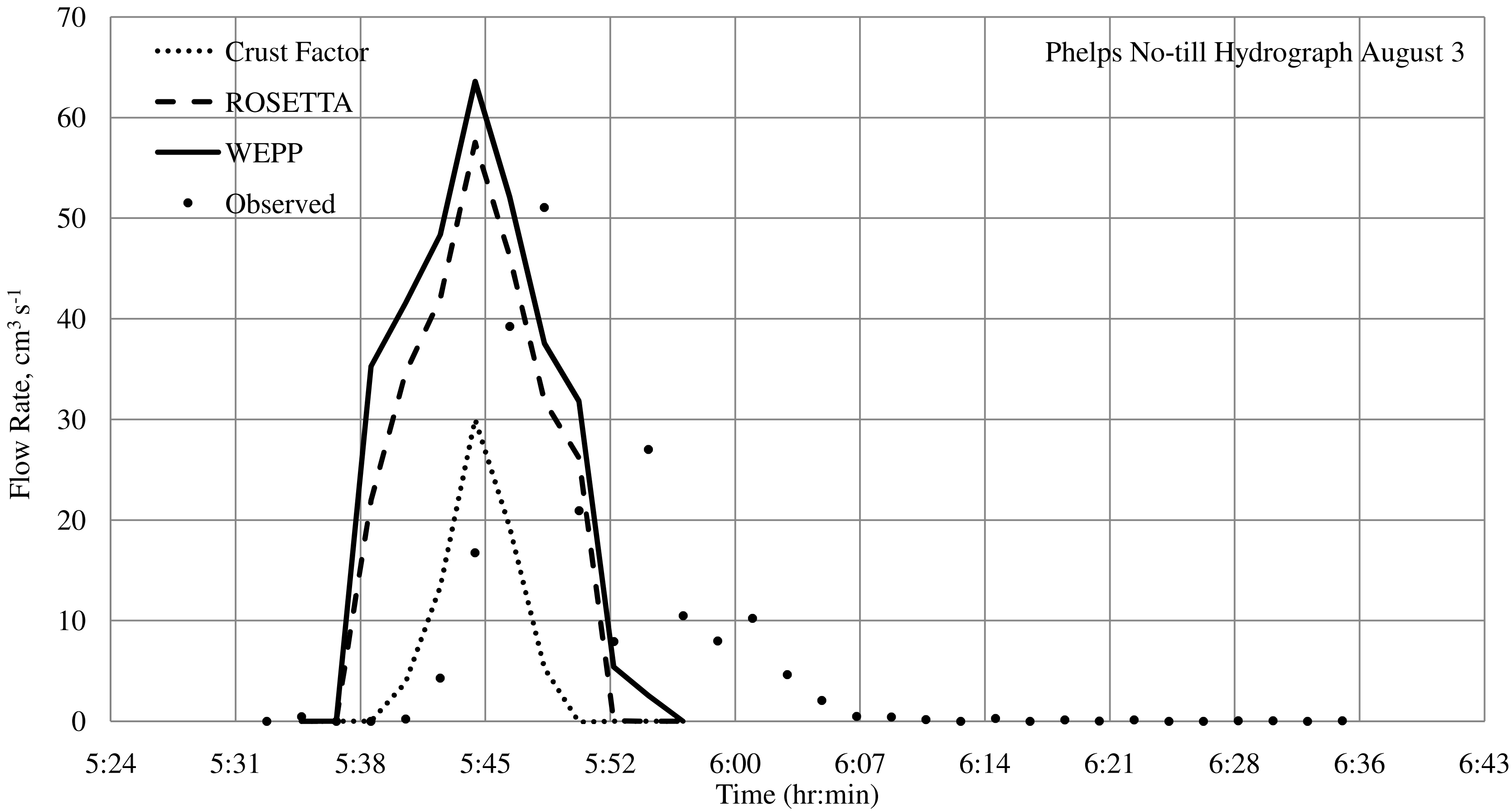


Crust Factor
ROSETTA
WEPP
Observed
Phelps T Hydrograph July 12
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Flow Rate, cm3 s-1
7:04
7:12
7:19
7:26
7:33
7:40
Time (hr:min)

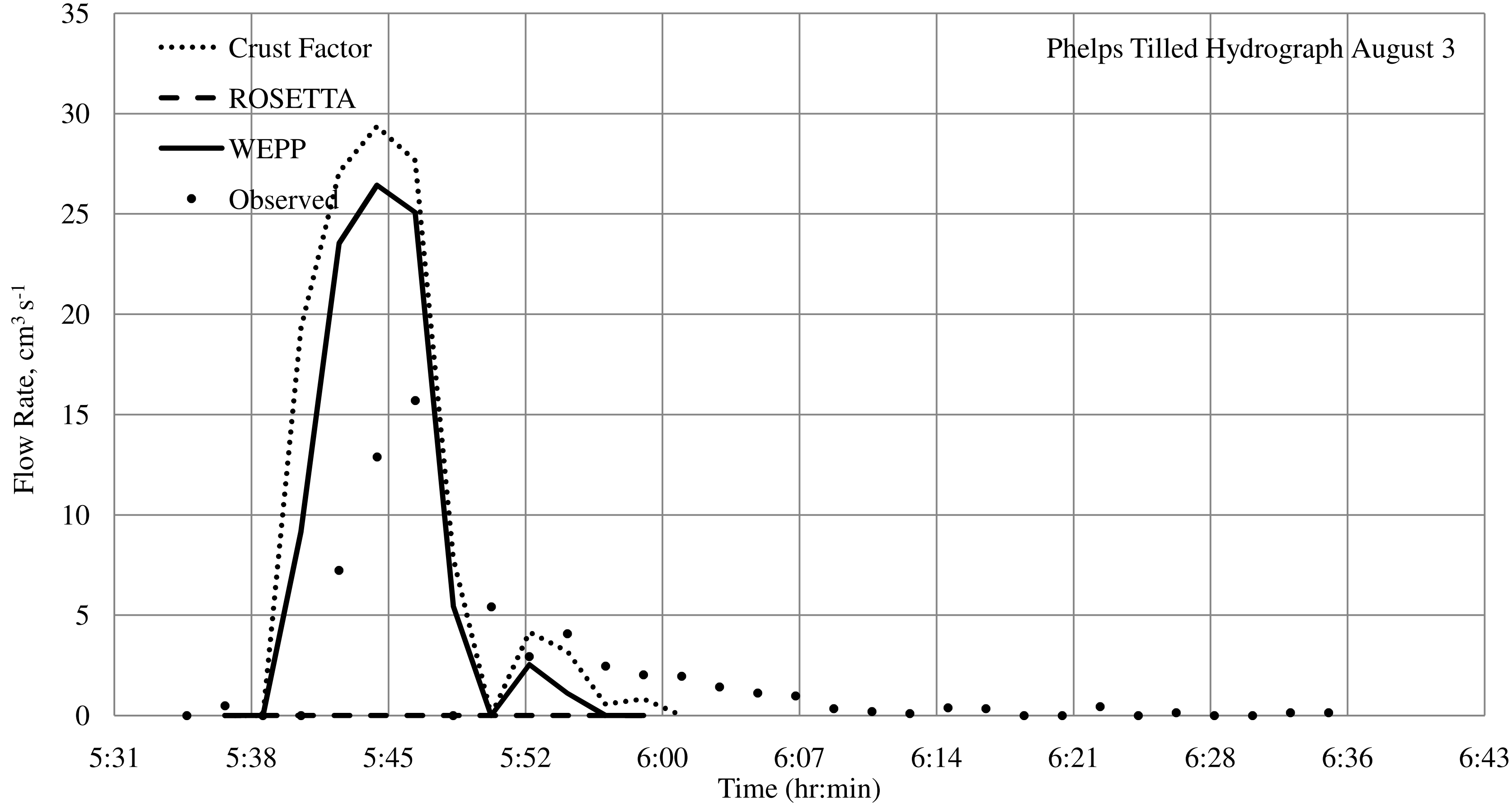

Phelps Tilled Hydrograph July 22
Crust Factor
ROSETTA
WEPP
Observed
Flow Rate, cm3 s-1
Time (hr:min)
0
2
4
6
8
10
12
14
16
18
20
22:33
23:02
23:31
0:00
0:28
0:57
1:26
1:55
2:24
2:52
3:21


Phelps Tilled Hydrograph July 28
Crust Factor
ROSETTA
WEPP
Observed
Flow Rate, cm3 s-1
60
50
40
30
20
10
0
10:19
10:33
10:48
11:02
11:16
11:31
11:45
12:00
Time (hr:min)

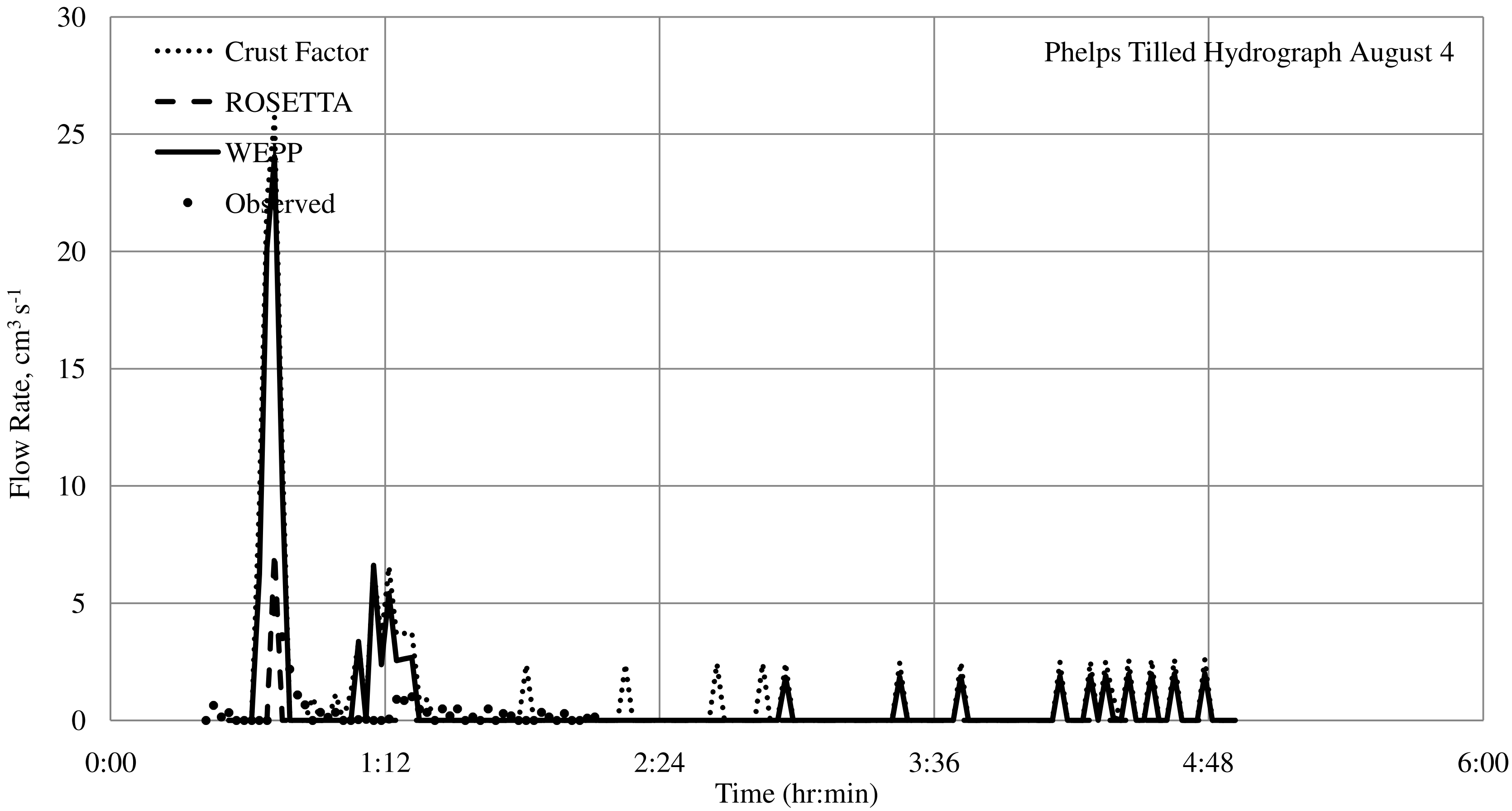

Phelps Tilled Hydrograph July 30
Crust Factor
ROSETTA
WEPP
Observed
Flow Rate, cm3 s-1
Time (hr:min)
45
40
35
30
25
20
15
10
5
0
20:38
20:52
21:07
21:21
21:36
21:50
22:04
22:19
22:33



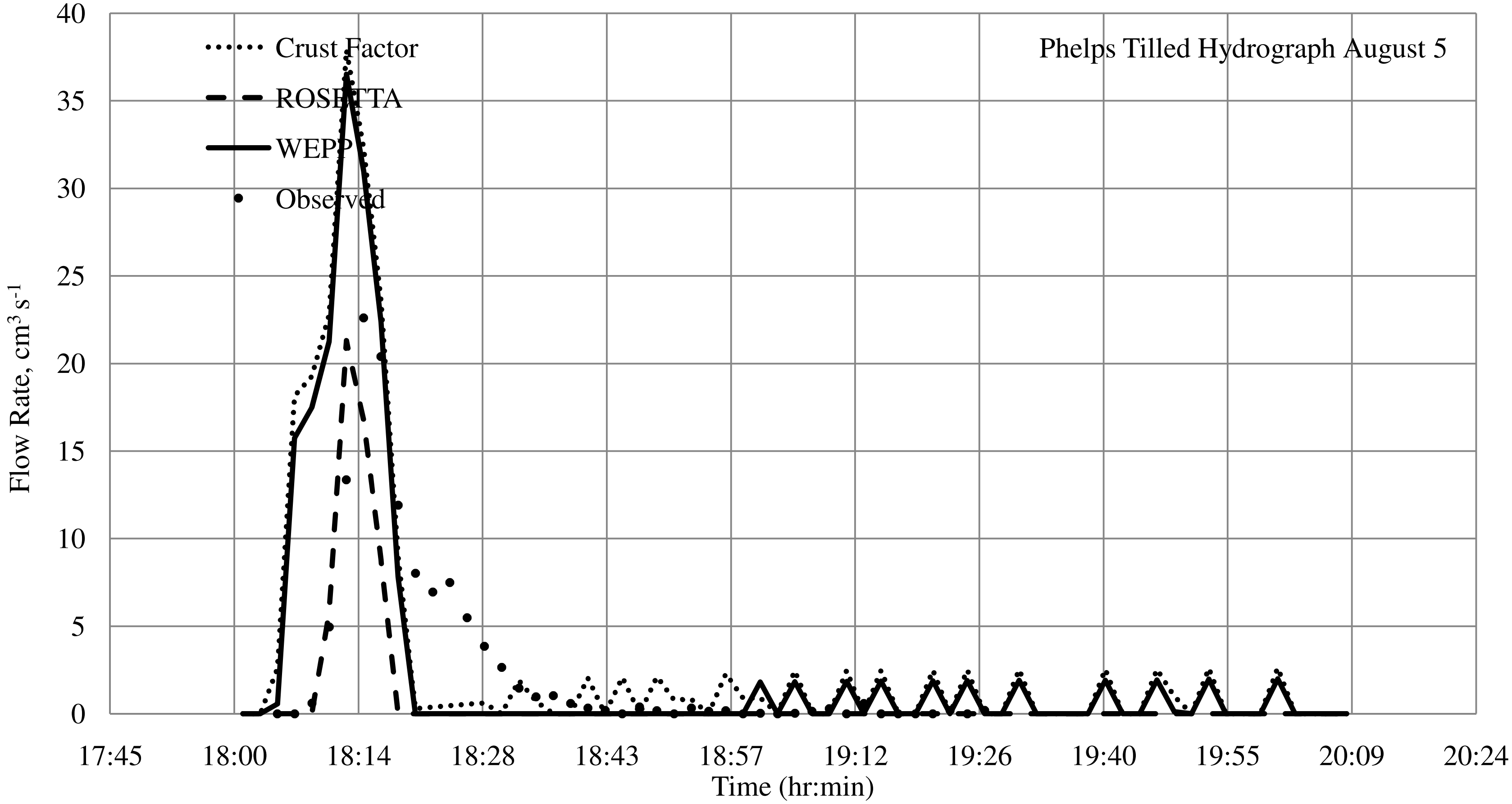
Phelps No-till Hydrograph August 3
Crust Factor
ROSETTA
WEPP
Observed
Flow Rate, cm3 s-1
Time (hr:min)
0
10
20
30
40
50
60
70
5:24
5:31
5:38
5:45
5:52
6:00
6:07
6:14
6:21
6:28
6:36
6:43

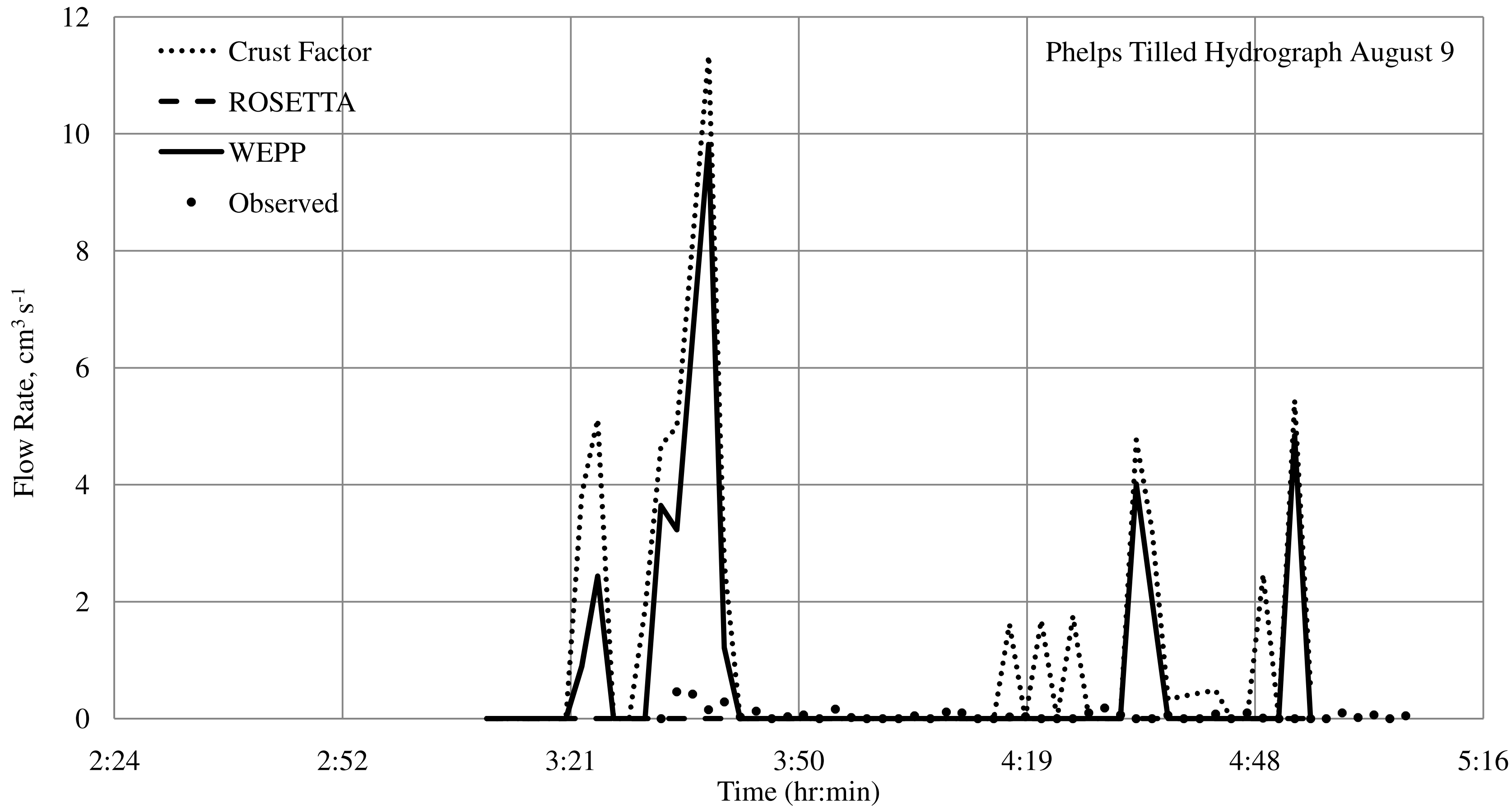


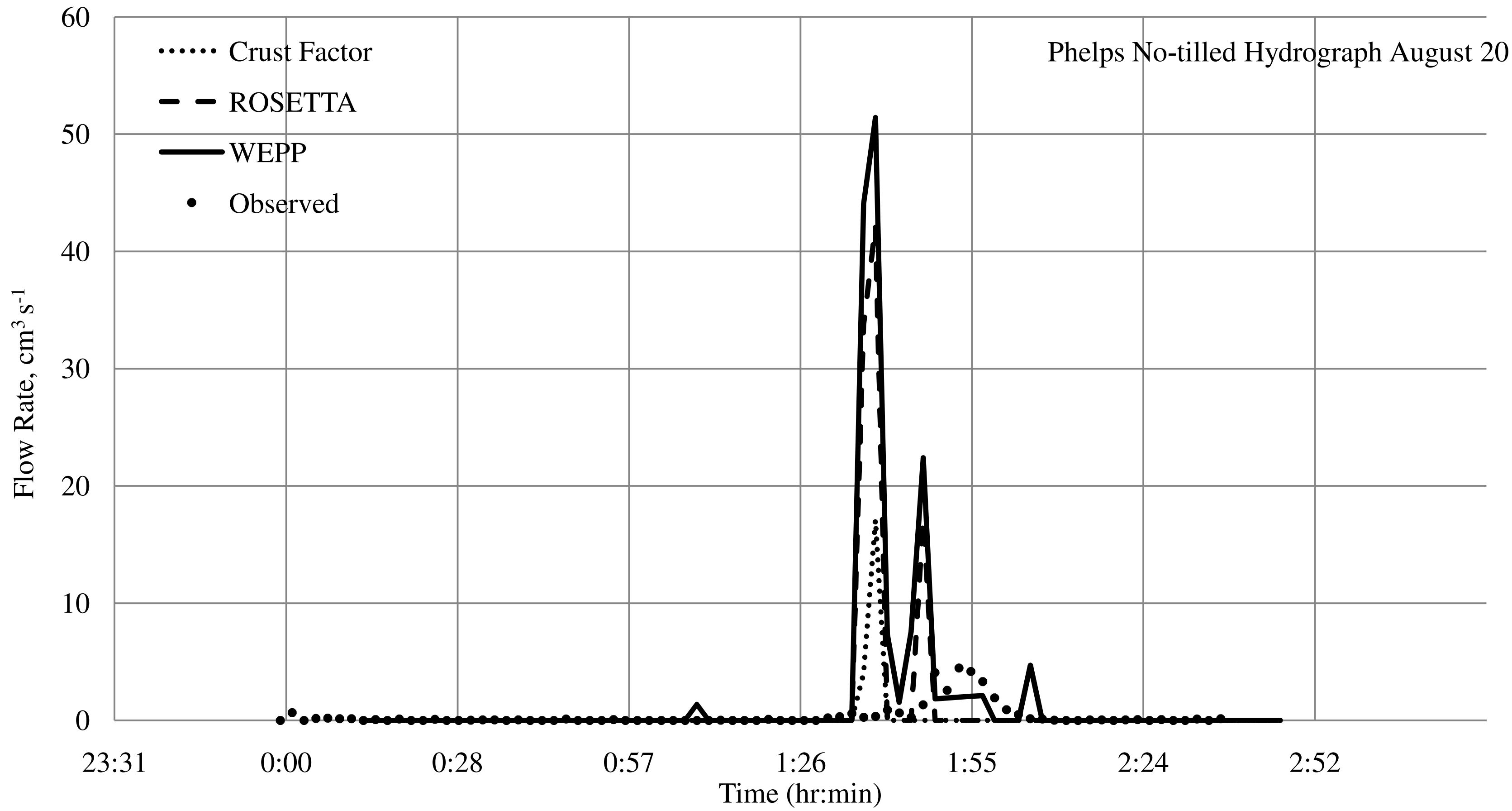
Phelps Tilled Hydrograph August 3
Crust Factor
ROSETTA
WEPP
Observed
Flow Rate, cm3 s-1
Time (hr:min)
35
30
25
20
15
10
5
0
5:31
5:38
5:45
5:52
6:00
6:07
6:14
6:21
6:28
6:36
6:43

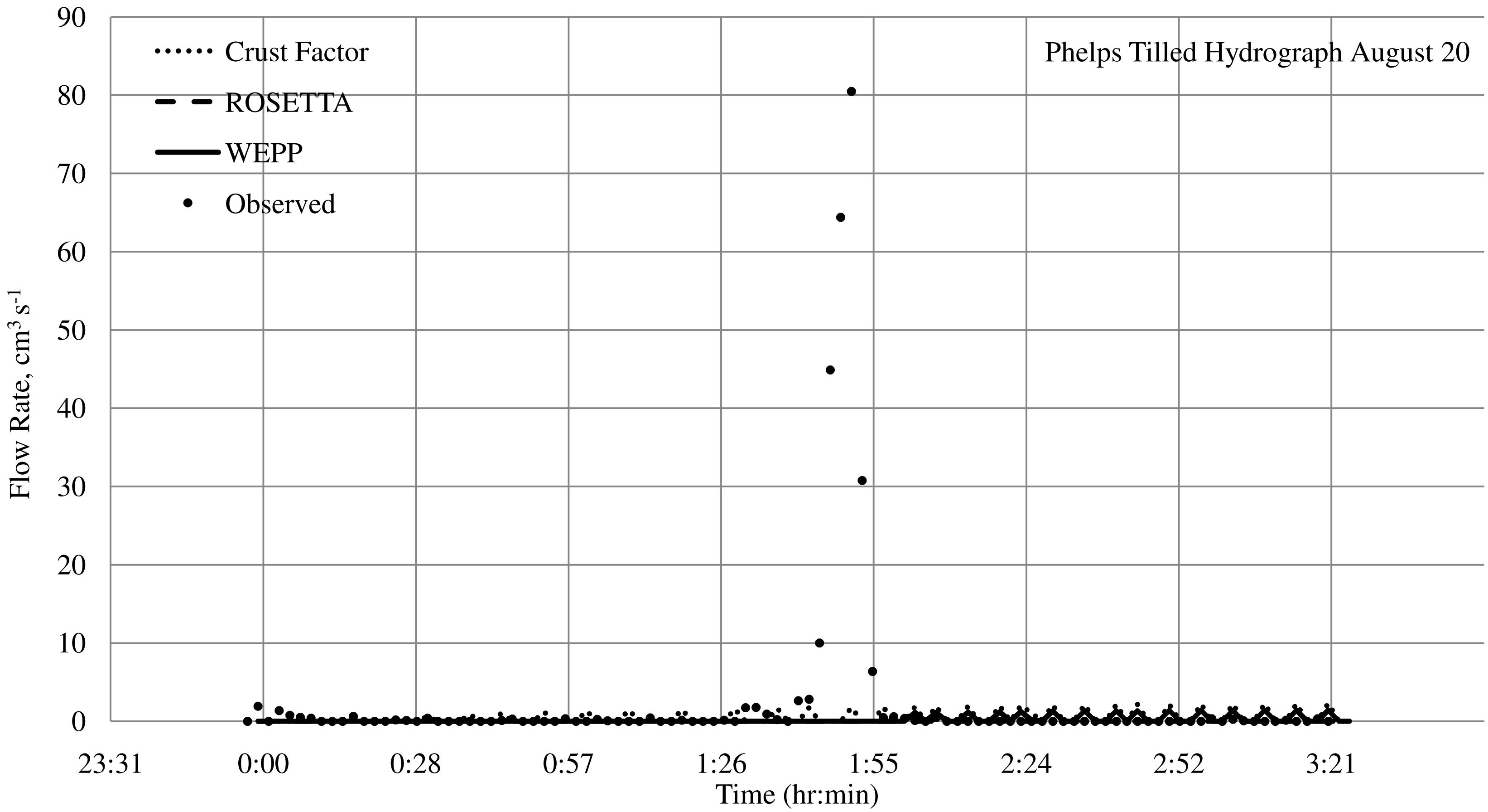


Crust Factor
ROSETTA
WEPP
Observed
Phelps Tilled Hydrograph August 4
Flow Rate, cm3 s-1
Time (hr:min)
30
25
20
15
10
5
0
0:00
1:12
2:24
3:36
4:48
6:00

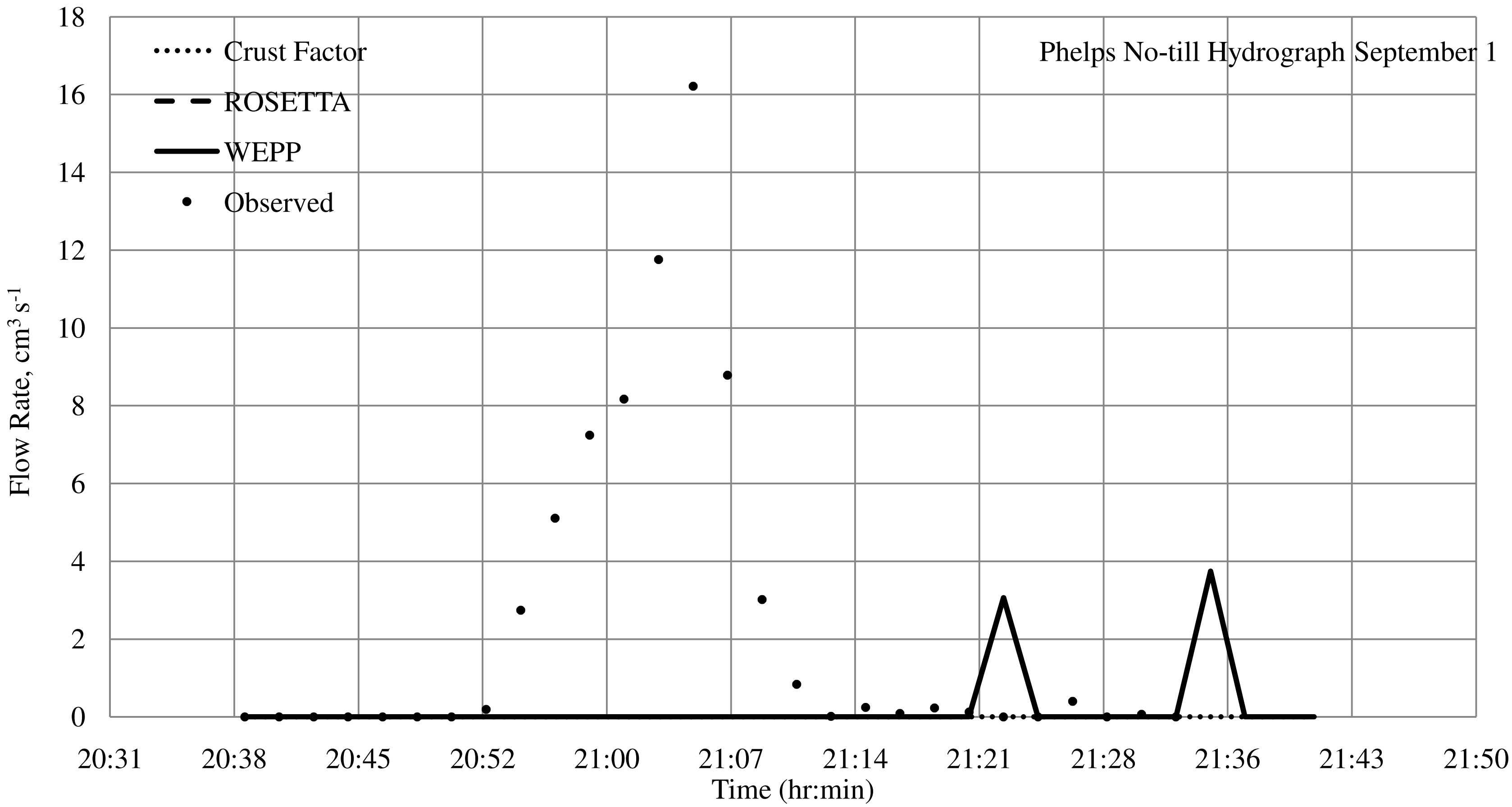

Phelps Tilled Hydrograph August 5
Crust Factor
ROSETTA
WEPP
Observed
Flow Rate, cm3 s-1
Time (hr:min)
0
5
10
15
20
25
30
35
40
17:45
18:00
18:14
18:28
18:43
18:57
19:12
19:26
19:40
19:55
20:09
20:24


Crust Factor
ROSETTA
WEPP
Observed
Phelps Tilled Hydrograph August 9
Flow Rate, cm³ s⁻¹
12
10
8
6
4
2
0
2:24
2:52
3:21
3:50
4:19
4:48
5:16
Time (hr:min)

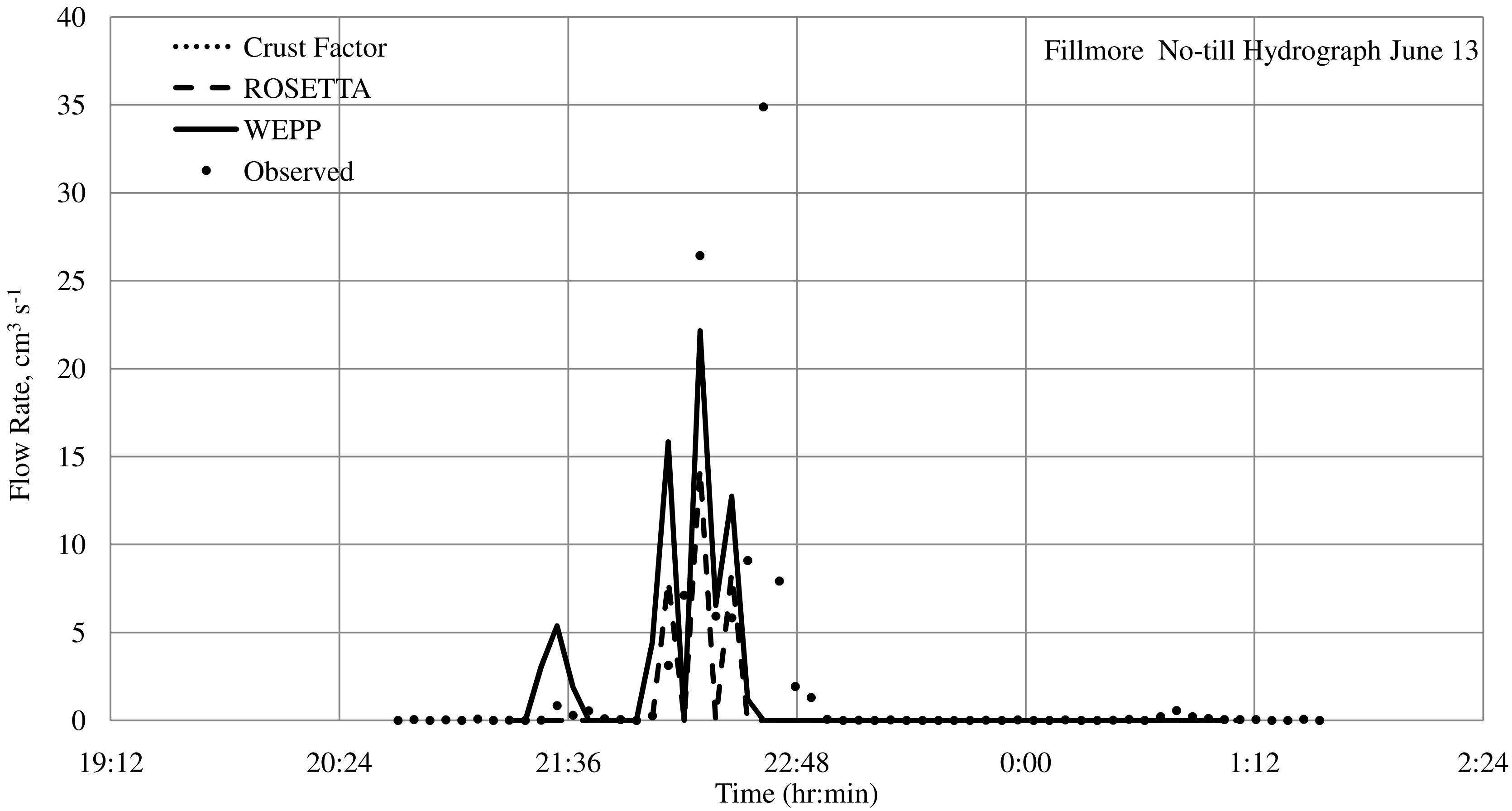

Crust Factor
ROSETTA
WEPP
Observed
Phelps No-tilled Hydrograph August 20
60
50
40
30
20
10
0
Flow Rate, cm3 s-1
23:31
0:00
0:28
0:57
1:26
1:55
2:24
2:52
Time (hr:min)

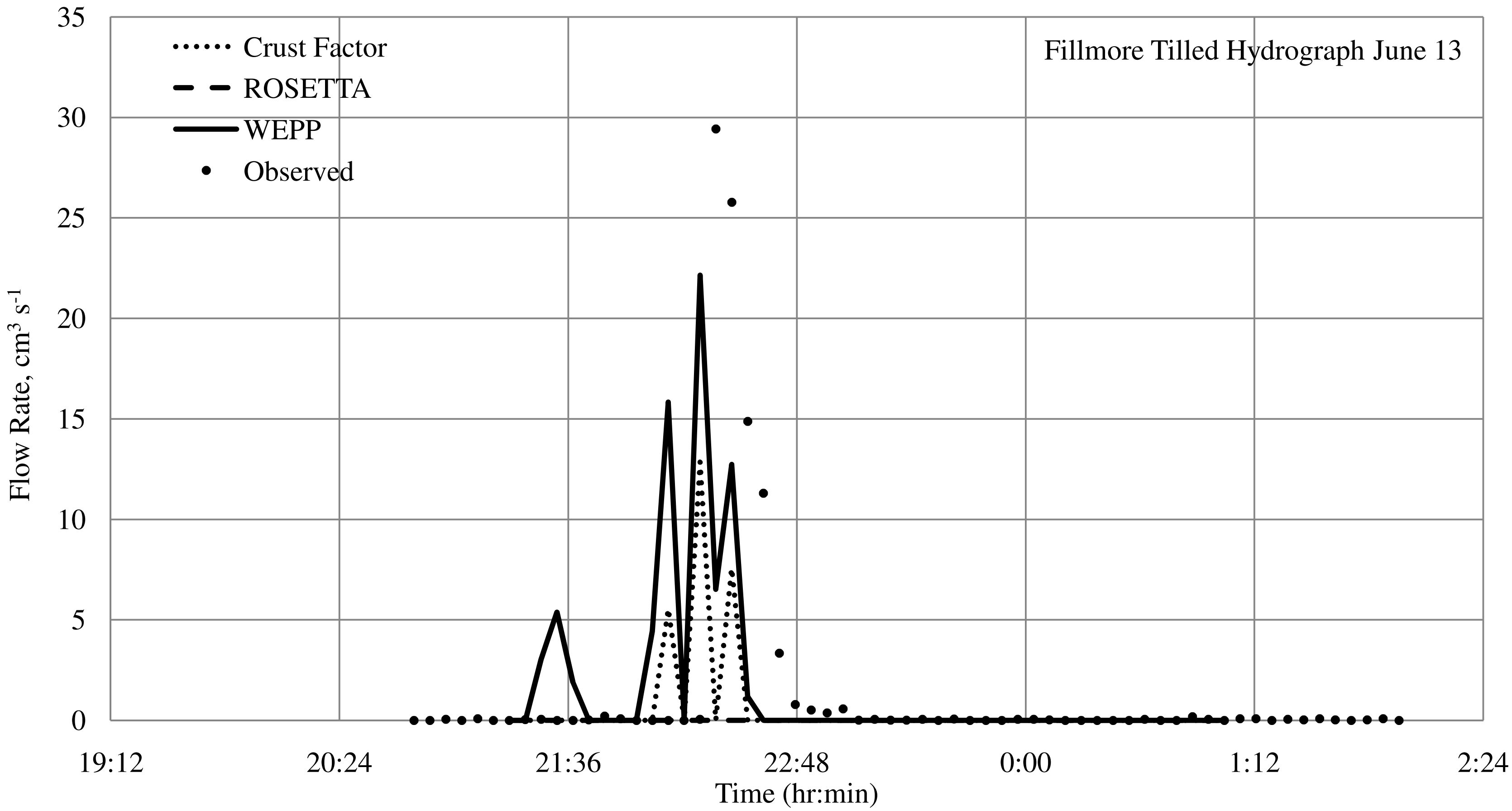


Phelps Tilled Hydrograph August 20
Crust Factor
ROSETTA
WEPP
Observed
Flow Rate, cm3 s-1
Time (hr:min)
0
10
20
30
40
50
60
70
80
90
23:31
0:00
0:28
0:57
1:26
1:55
2:24
2:52
3:21

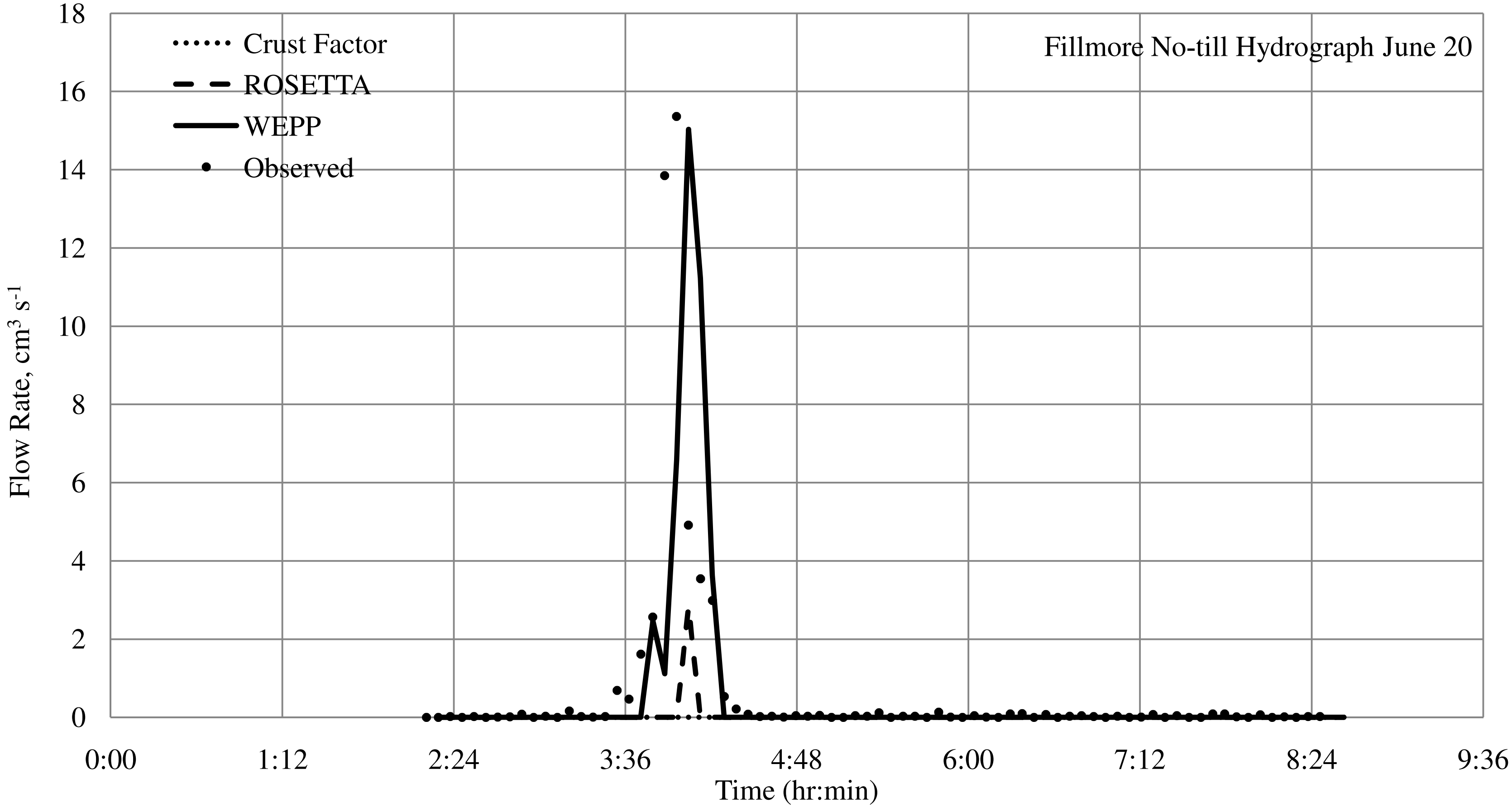


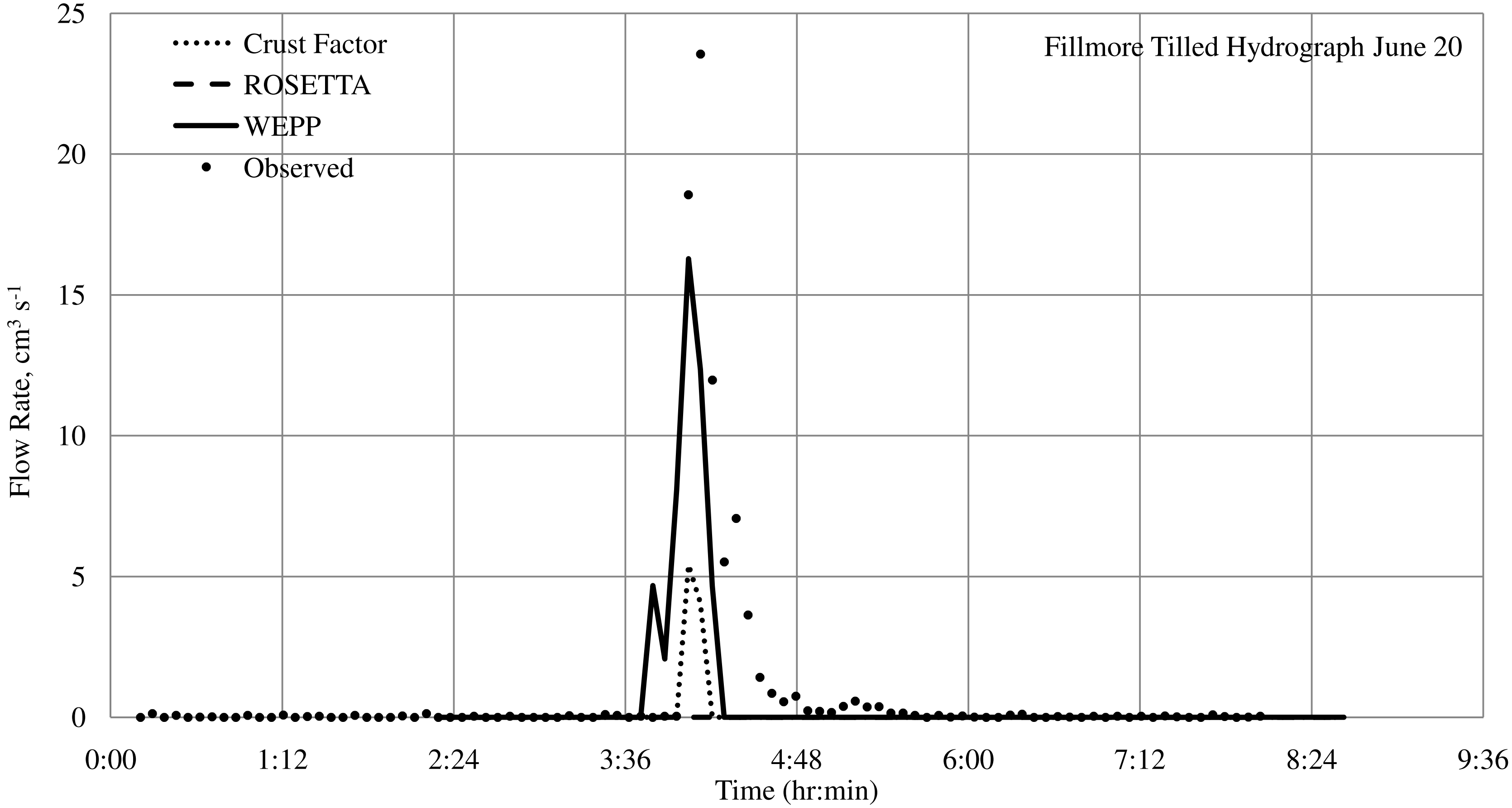
Fillmore hydrographs

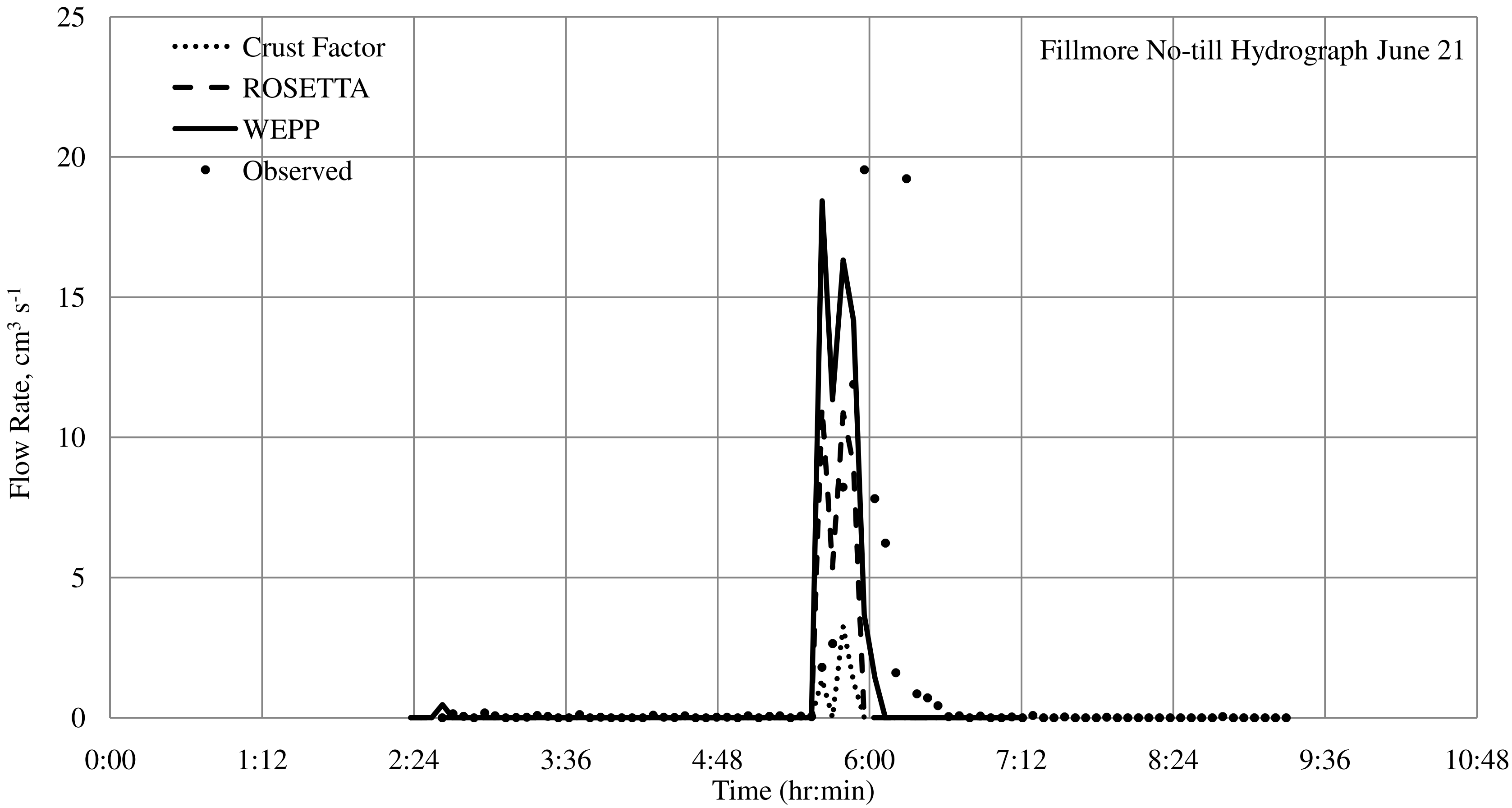

Fillmore No-till Hydrograph June 13
Crust Factor
ROSETTA
WEPP
Observed
Flow Rate, cm^3 s^{-1}
0
5
10
15
20
25
30
35
40
19:12
20:24
21:36
22:48
0:00
1:12
2:24
Time (hr:min)

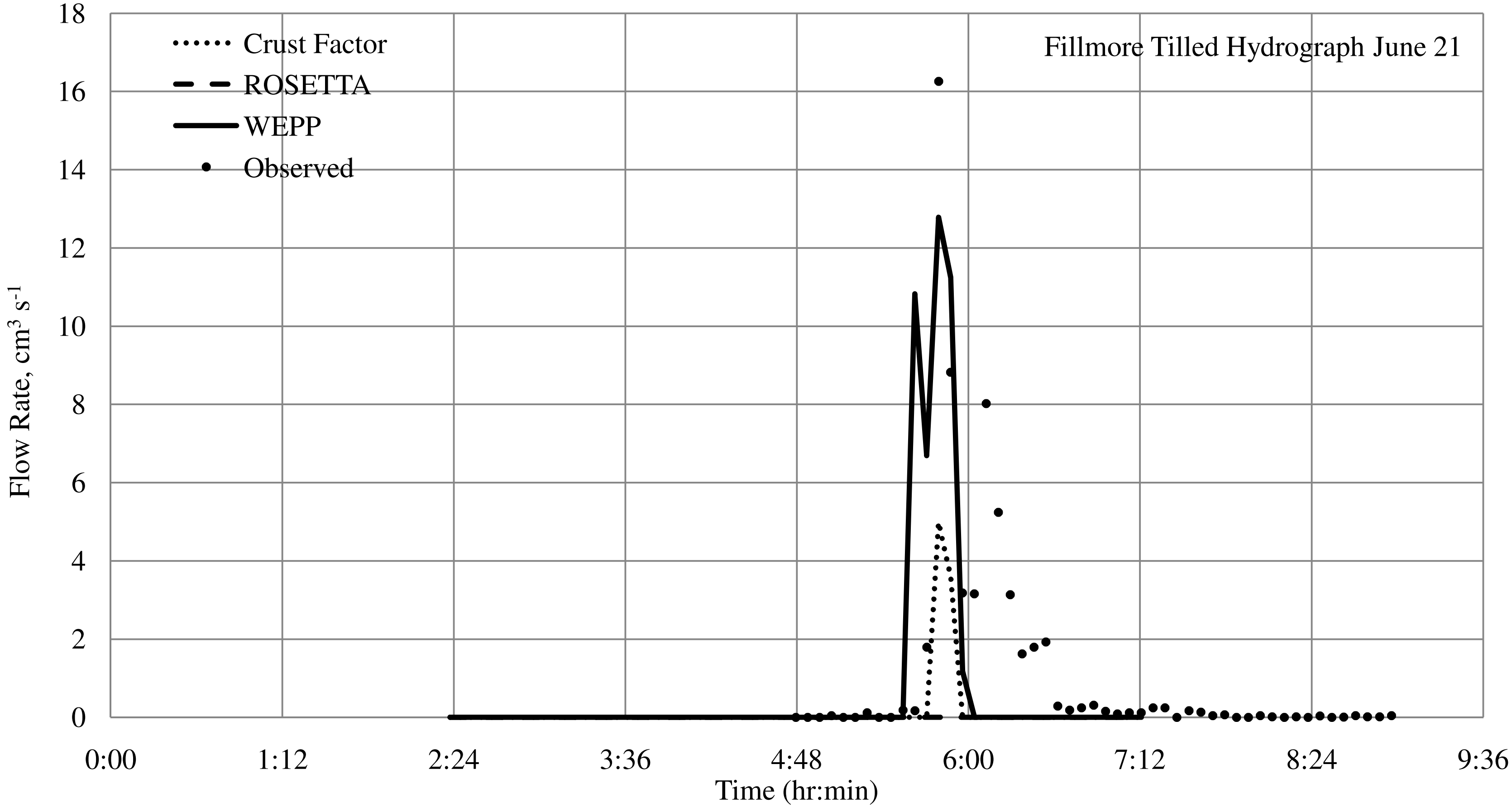


Crust Factor
ROSETTA
WEPP
Observed
Fillmore Tilled Hydrograph June 13
Flow Rate, cm3 s-1
35
30
25
20
15
10
5
0
19:12
20:24
21:36
22:48
0:00
1:12
2:24
Time (hr:min)

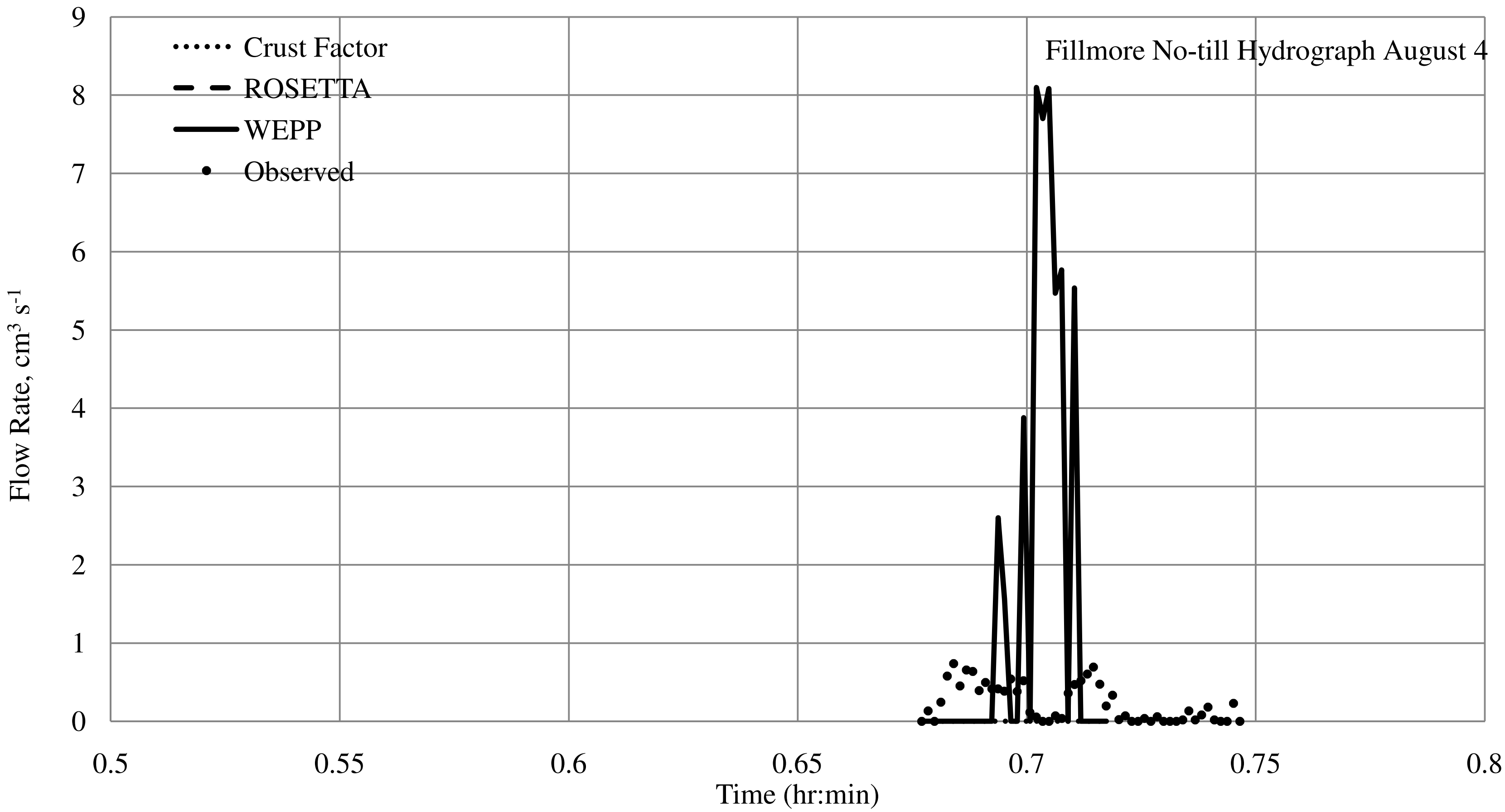

Fillmore No-till Hydrograph June 20
Crust Factor
ROSETTA
WEPP
Observed
Flow Rate, cm^3 s^{-1}
0
2
4
6
8
10
12
14
16
18
0:00
1:12
2:24
3:36
4:48
6:00
7:12
8:24
9:36
Time (hr:min)

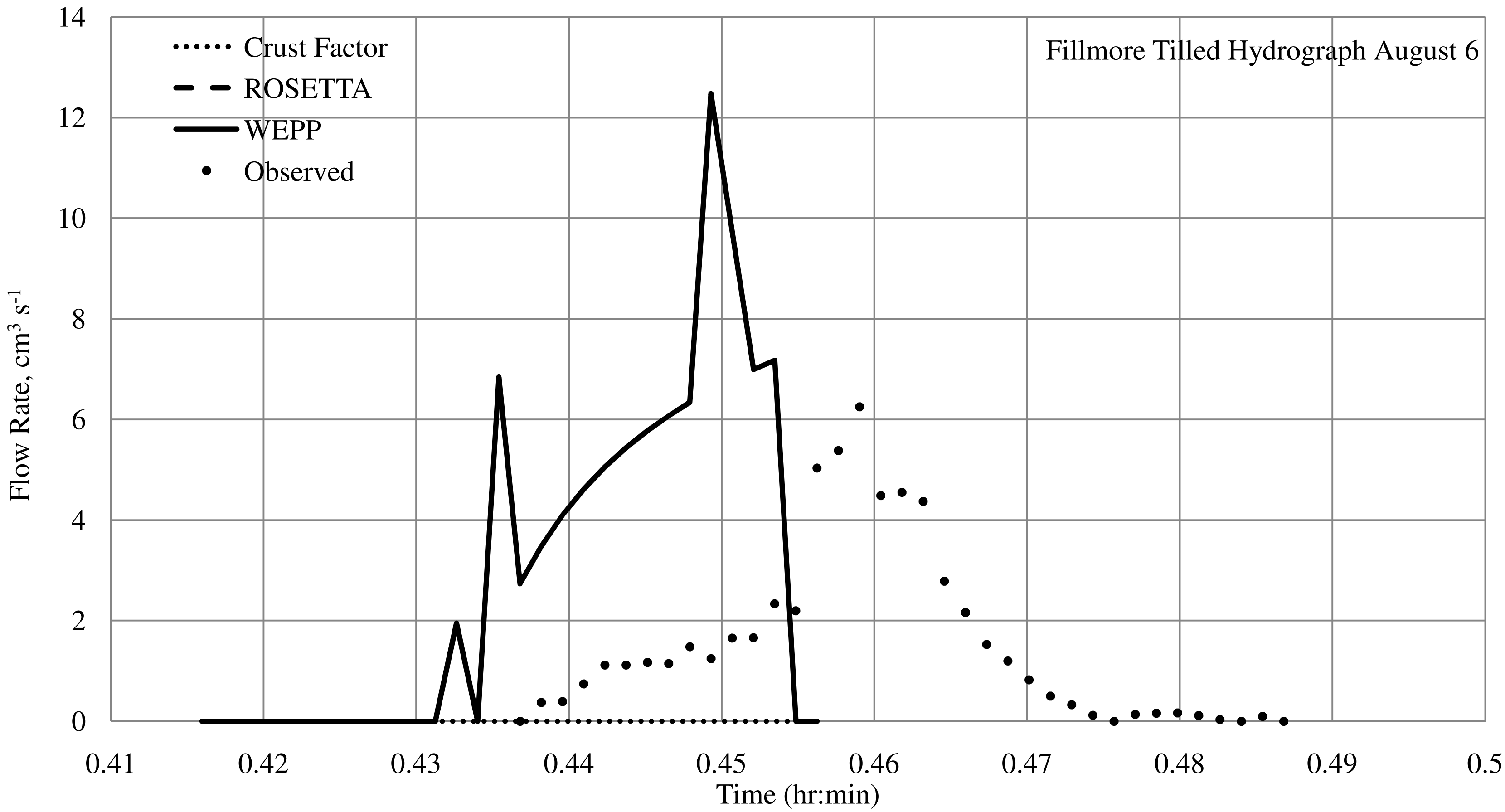

Crust Factor
ROSETTA
WEPP
Observed
Fillmore Tilled Hydrograph June 20
Flow Rate, cm3 s-1
0
5
10
15
20
25
0:00
1:12
2:24
3:36
4:48
6:00
7:12
8:24
9:36
Time (hr:min)

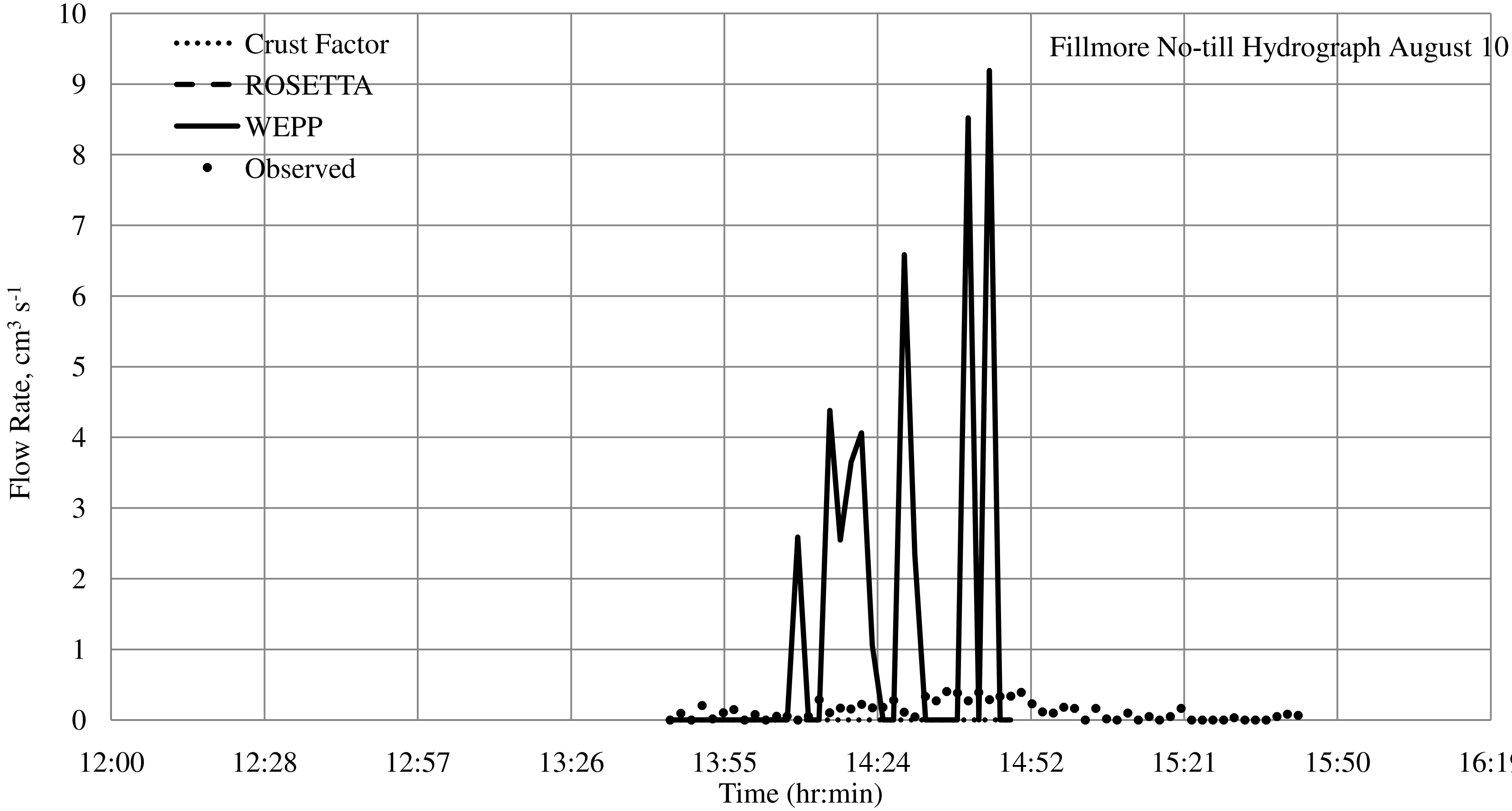

Crust Factor
ROSETTA
WEPP
Observed
Fillmore No-till Hydrograph June 21
Flow Rate, cm3 s-1
Time (hr:min)
0
5
10
15
20
25
0:00
1:12
2:24
3:36
4:48
6:00
7:12
8:24
9:36
10:48



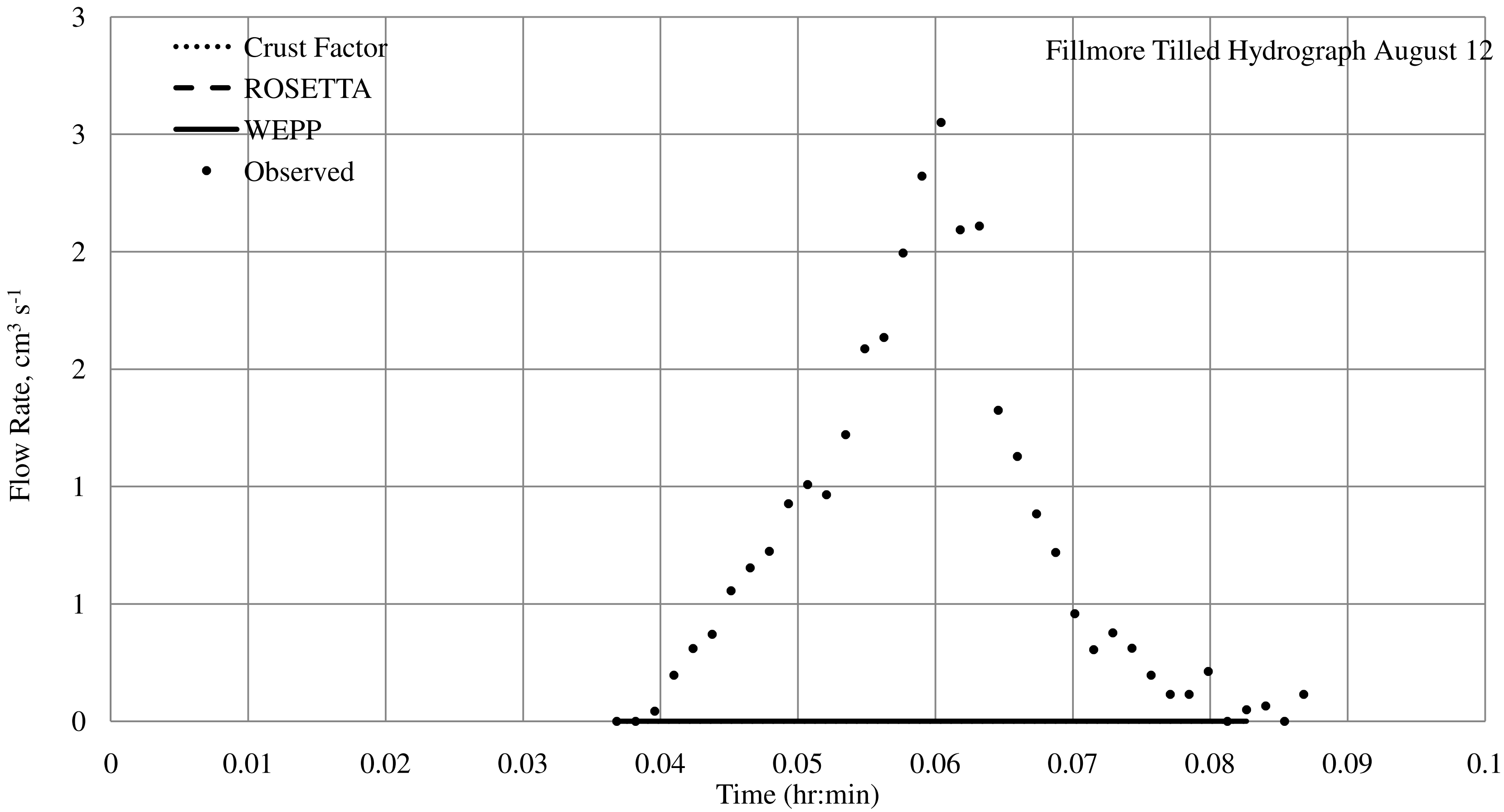
Fillmore Tilled Hydrograph June 21
Crust Factor
ROSETTA
WEPP
Observed
Flow Rate, cm³ s⁻¹
Time (hr:min)
0
2
4
6
8
10
12
14
16
18
0:00
1:12
2:24
3:36
4:48
6:00
7:12
8:24
9:36

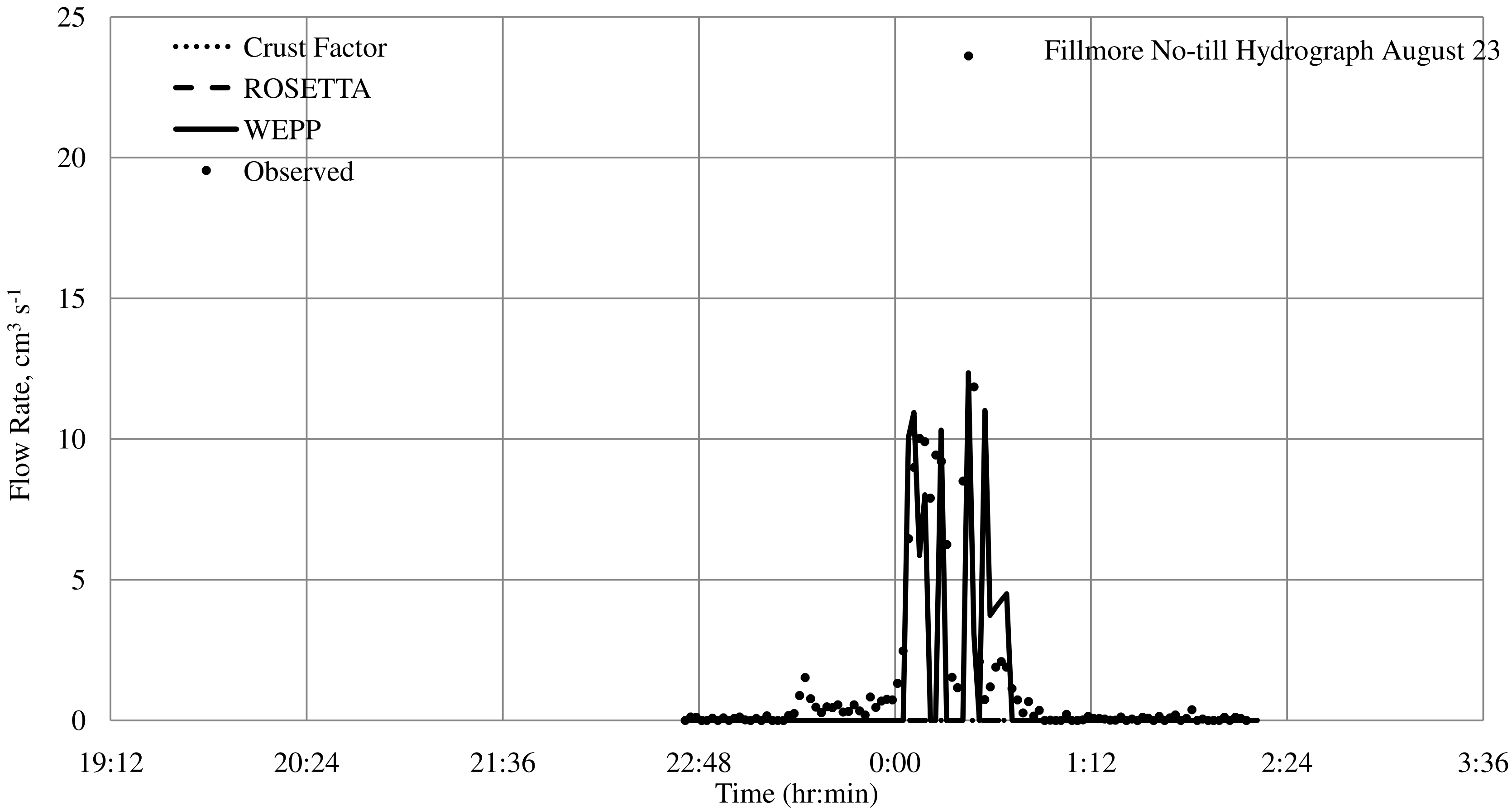

Fillmore No-till Hydrograph August 4
Crust Factor
ROSETTA
WEPP
Observed
Flow Rate, cm3 s-1
Time (hr:min)
0
1
2
3
4
5
6
7
8
9
0.5
0.55
0.6
0.65
0.7
0.75
0.8


Fillmore Tilled Hydrograph August 6
Crust Factor
ROSETTA
WEPP
Observed
Flow Rate, cm³ s⁻¹
Time (hr:min)
0
2
4
6
8
10
12
14
0.41
0.42
0.43
0.44
0.45
0.46
0.47
0.48
0.49
0.5

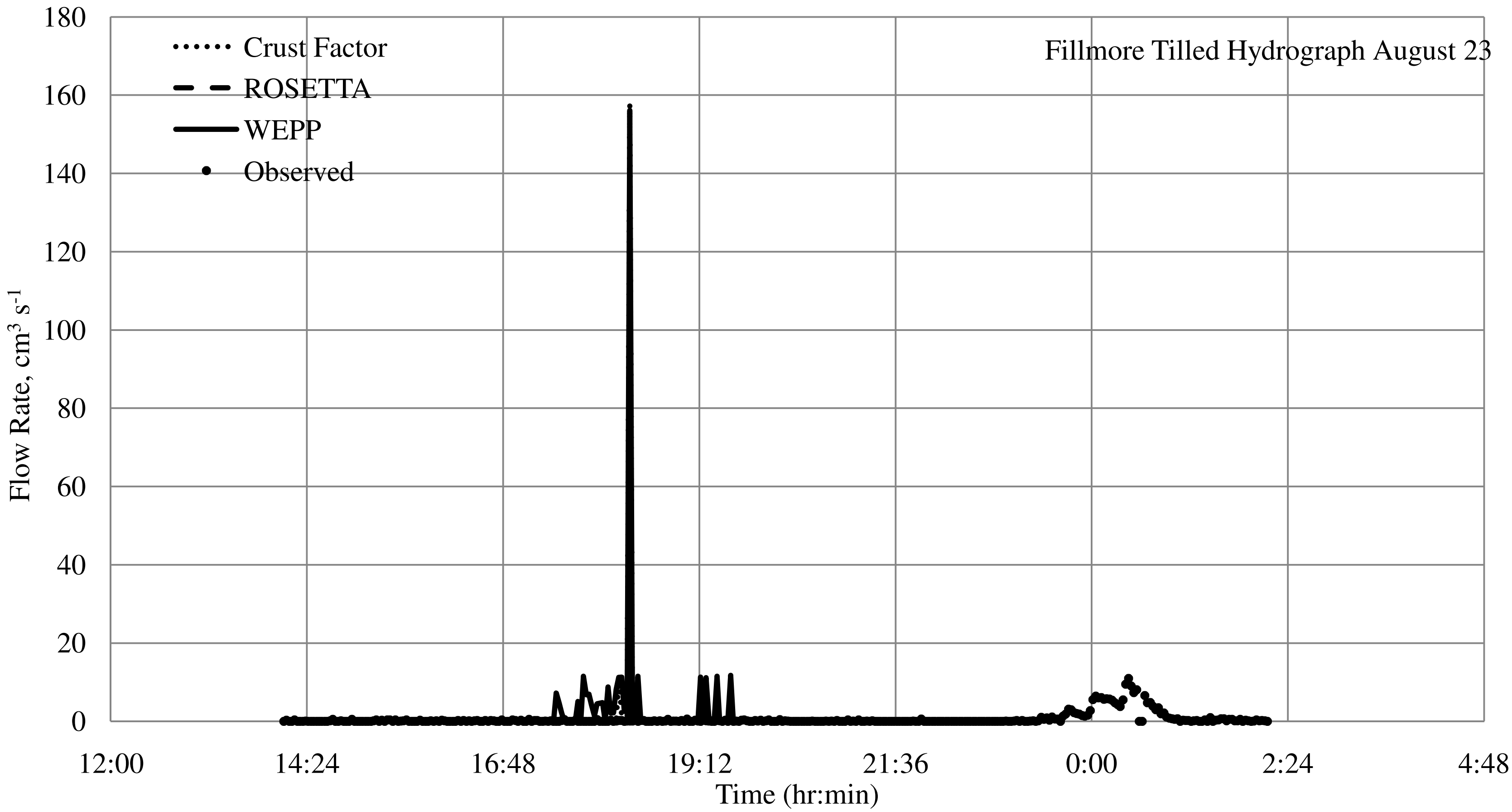


Fillmore No-till Hydrograph August 10
Crust Factor
ROSETTA
WEPP
Observed
Flow Rate, cm3 s-1
Time (hr:min)
0
1
2
3
4
5
6
7
8
9
10
12:00
12:28
12:57
13:26
13:55
14:24
14:52
15:21
15:50
16:19


Fillmore Tilled Hydrograph August 12
Crust Factor
ROSETTA
WEPP
Observed
Flow Rate, cm^3 s^{-1}
3
3
2
2
1
1
0
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Time (hr:min)



Fillmore No-till Hydrograph August 23
Crust Factor
ROSETTA
WEPP
Observed
Flow Rate, cm3 s-1
25
20
15
10
5
0
19:12
20:24
21:36
22:48
0:00
1:12
2:24
3:36
Time (hr:min)


Fillmore Tilled Hydrograph August 23
Crust Factor
ROSETTA
WEPP
Observed
Flow Rate, cm3 s-1
Time (hr:min)
180
160
140
120
100
80
60
40
20
0
12:00
14:24
16:48
19:12
21:36
0:00
2:24
4:48

CHAPTER 4 APPENDIX B: VADOSE ZONE PROPERTIES

4.1 Field Plots

Study areas included two center pivot irrigated sites in Nebraska. Each site has a no-till and tilled field. The first site is located in Fillmore County, southeast Nebraska. The study area contains Crete silty clay loam soil with a slope of approximately 1%. The second site is located in south central Nebraska in Phelps County. This site contained Holdrege silt loam soil with a slope of 0.4%. Both sites contain two corn/soybean rotation fields. Each location consists of a field that is cultivated at least once in the spring before planting, and one practicing long term continuous no-till. These operations have been consistent for at least seven years. The no-till and tilled fields at each site were paired to match in planting date, crop hybrid, land slope, and soil type.

4.2 Vadose Zone Samples

In 2009, data were collected after planting. Three holes were cored from each field using UNL's Geoprobe hydraulic sampler, which provided five 1.5 m samples to a depth of 7.5 m. The core diameter was 3.75 cm. In the lab, the 1.5 m sections were analyzed every 0.3 m for texture, bulk density, organic matter, water retention, and hydraulic conductivity. From properties gathered in the lab, water content graphs were developed for Fillmore County and Phelps County sites. Because of compression from probing, the water content equated from the lab measured high bulk density at the Fillmore County site. Pedotransfer functions from Saxton and Rawls (2006) estimated the bulk density to account for this discrepancy. From the adjusted bulk density, water content was then determined.

To illustrate the water transfer rate in the vadose zone, a nitrate analysis on the 3-4.5 m layer in the vadose zone was performed (Katupitiya et al., 1997). The nitrate levels were measured every 0.15 m. Peaks of nitrate, representing total migration for a year, exhibited the yearly movement of pore water. Darcy's velocity was obtained by using the water content in the 3 - 4.5 m core and the pore water velocity. The volumetric water content graphs paired with the percolation rates, which were derived from the nitrate samples, potentially could determine the flux beneath the root zone.

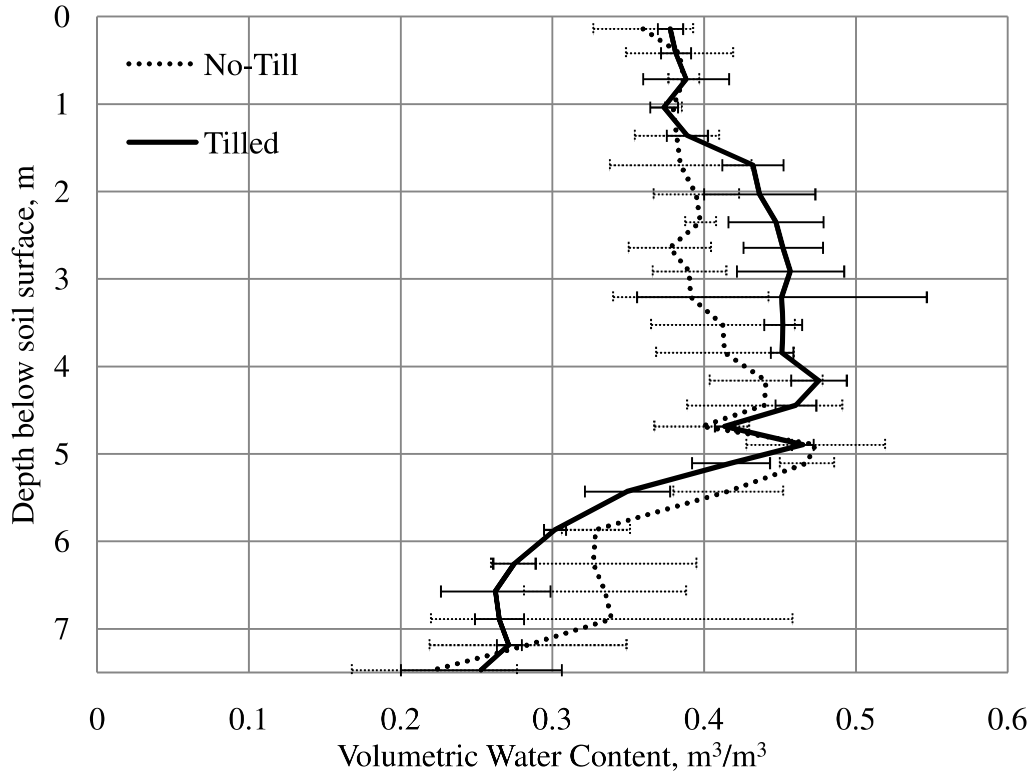
A water content difference between tilled and no-till was analyzed below the root zone to the depth of water movement since current tillage systems began, the years being estimated by v_p. Average water content values, θ_v, are listed in Table 4.1. Water had moved 4 m in Fillmore and 6 m in Phelps since the no-till systems were established. Based on this depth for analysis, a significant difference was found in volumetric water content at the Fillmore site, with tilled having a higher water content as shown in Figure 4.1. Average volumetric water contents were 0.39 and 0.38 m^3/m^3 for tilled and no-till, respectively. The second site showed a similar trend, although not significant, with 0.30 m^3/m^3 found for tilled and 0.28 m^3/m^3 for no-till as displayed in Figure 4.3. These results are similar to the research done by Shipitalo et al. (2000) and Katuitiya (1995) that examined the effect of preferential flow directly below the root zone and found no significant difference between tilled and no-till field water contents.

The water movement into the vadose zone is given in Table 4.1. The three cores from each field were used to determine an average rate of vertical water movement, v_p. Values were 0.53-0.58 m yr-1 in no-till and 0.43-0.97 m yr-1 for tilled. Katuitiya (1995) mean pore velocity values were in range of the data in this study. Even though tillage systems are long-term, percolation rates were comparable over the 7.5 m depth. Figures 4.2 and 4.4 display satiated hydraulic conductivity in the vadose zone.

Table 4.1. Water movement into vadose zone using nitrate analysis. θ_v is the average

Site	Plot	θ_v, m^3/m^3	Average v_p, m/yr
Fillmore	No-till	0.38	0.53
	Tilled	0.39	0.43
Phelps	No-till	0.28	0.58
	Tilled	0.30	0.97

volumetric water content in the vadose zone. v_p denotes mean pore water velocity.



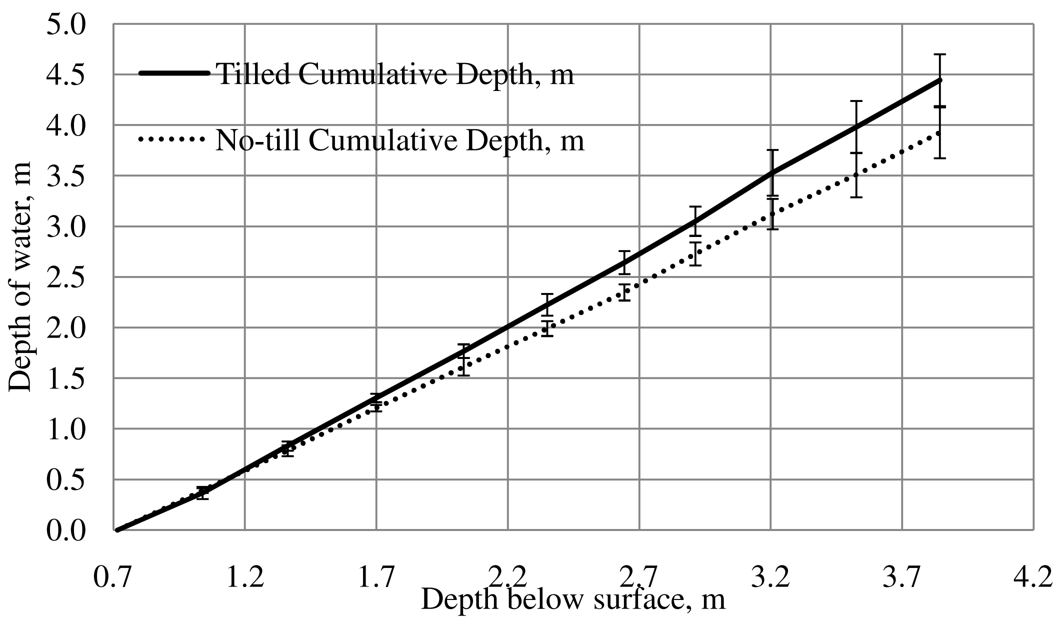


Figure 4.1. Fillmore County volumetric water content under tilled and no-tilled fields and Fillmore cumulative water depth in the vadose zone

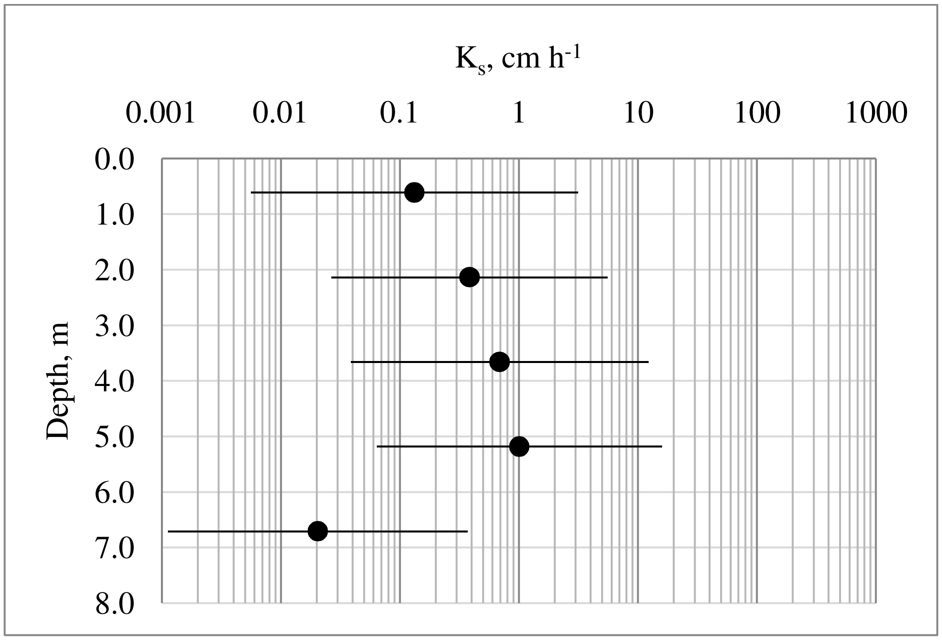
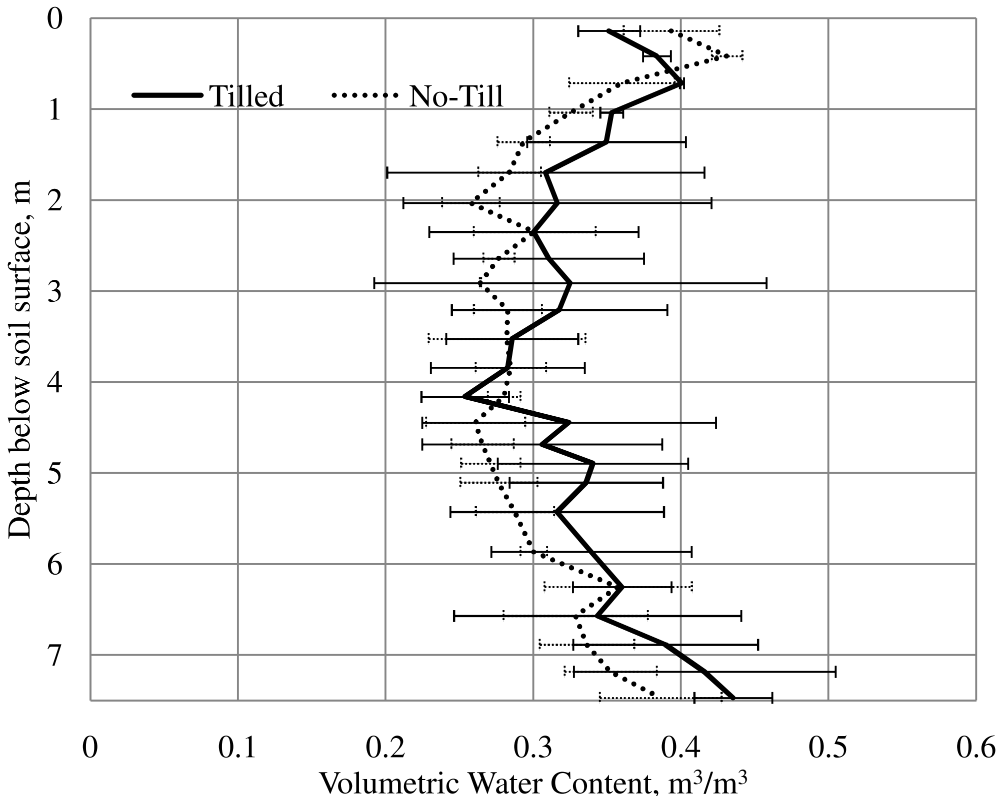


Figure 4.2. Satiated hydraulic conductivity in vadose zone for Fillmore County. 30 samples per geometric mean.
Error bars indicate standard deviation = abs [exp $^{(\ln \bar{y} \pm \ln s_y)}$- geometric mean]



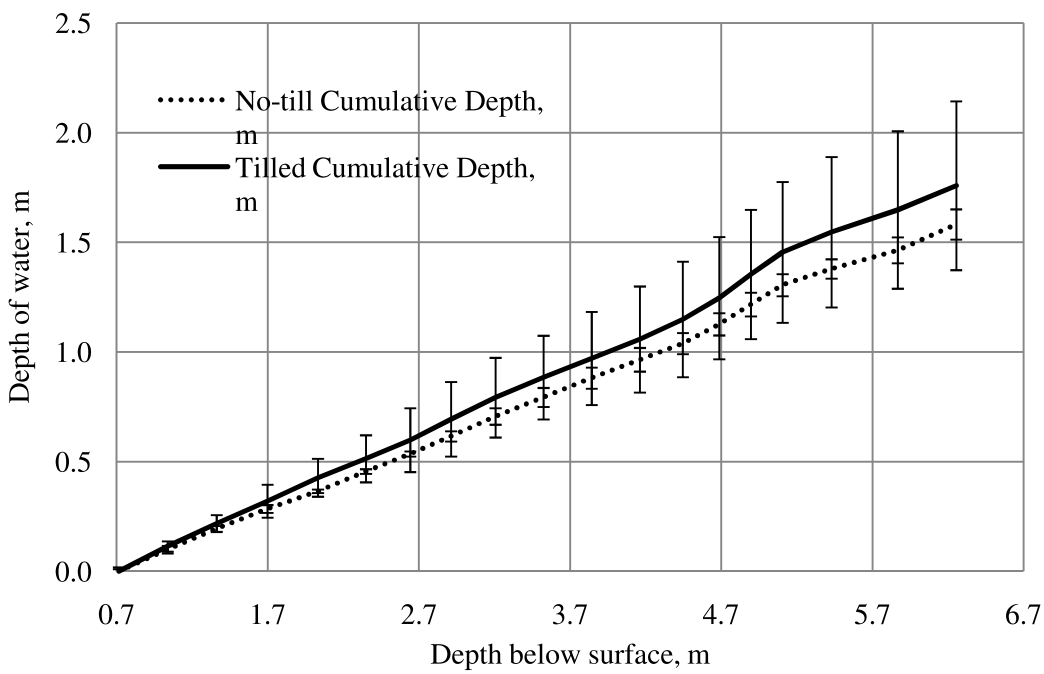


Figure 4.3. Phelps County volumetric water content under tilled and no-tilled fields and Phelps cumulative water depth in the vadose zone.

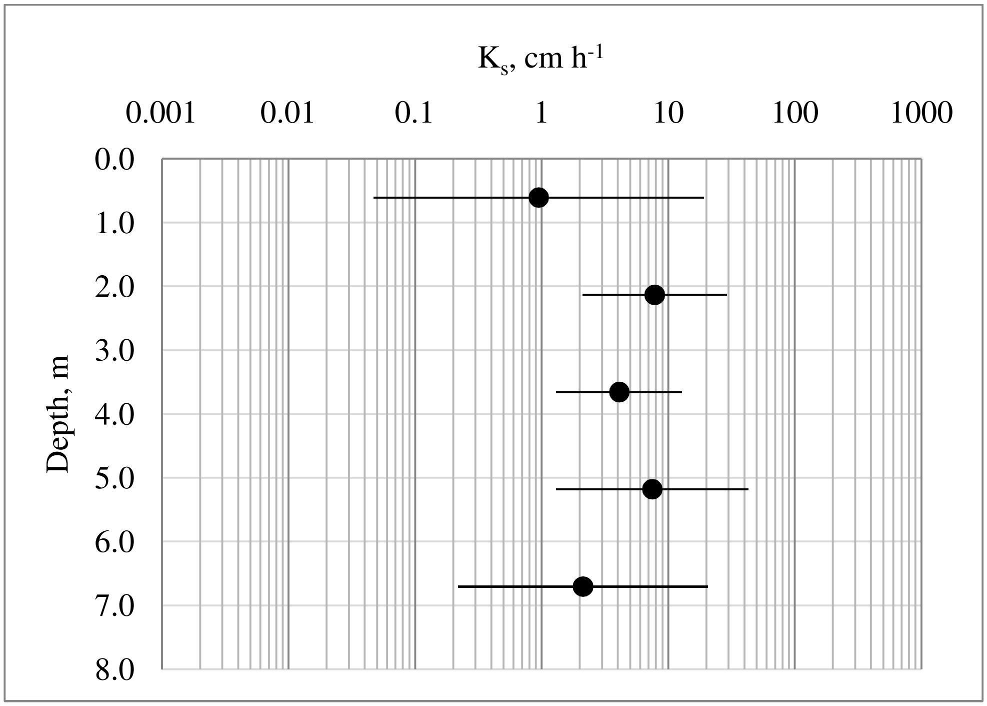


Figure 4.4. Phelps County satiated hydraulic conductivity in the vadose zone. 30 samples per geometric mean.
Error bars indicate standard deviation = abs [exp $^{(\ln \bar{y} \pm \ln s_y)}$- geometric mean]

4.3 References

Katupitiya, A. 1995. Long-term tillage effects on nitrate movement and accumulation and denitrification in the root and intermediate vadose zones. PhD diss. Lincoln, Nebr.: University of Nebraska-Lincoln, Department of Agronomy.

Katupitiya, A., D.E. Eisenhauer, R. B. Ferguson, R.F Spalding, F.W. Roeth, M.W Bobier. 1997. Long-term tillage and crop rotation effects on residual nitrate in the crop root zone and nitrate accumulation in the intermediate vadose zone. Trans. ASAE 40(5): 1321-1327.

Saxton, K.E., and W.J. Rawls. 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Sci. Soc. Am. J. 70: 1569-1578.

Shipitalo, M.J., W.A. Dick, W.M. Edwards. 2000. Conservation tillage and macropore factors that affect water movement and the fate of chemicals. Soil and Till. Res. 53(3-4):167-183.

CHAPTER 5 APPENDIX C: STATISTICAL ANALYSIS RESULTS

One Way Analysis of Variance

Data source Field vs Lab Ks

Dependent Variable: log Ks

Normality Test: Failed (P < 0.050)

Test execution ended by user request, ANOVA on Ranks begun

Kruskal-Wallis One Way Analysis of Variance on Ranks Thursday, November 11, 2010, 2:16:04 PM

Data source: Field vs Lab Ks

Group	**N**	**Missing**	**Median**	**25%**	**75%**
Lab	12	0	0.751	0.0872	1.334
Field	48	0	0.788	0.429	1.152

H = 0.00546 with 1 degrees of freedom. (P = 0.941)

The differences in the median values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.941)

Two Way Analysis of Variance

Data source: Fillmore No-till vs. Tilled Ks without Span 3

General Linear Model

Dependent Variable: Log Ks

Normality Test: Passed (P = 0.141)

Equal Variance Test: Passed (P = 0.097)

Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Layer	1	2.841	2.841	22.676	<0.001
Tillage	1	0.999	0.999	7.976	0.009
Layer x Tillage	1	0.0302	0.0302	0.241	0.628
Residual	24	3.007	0.125		
Total	27	6.852	0.254		

The difference in the mean values among the different levels of Layer is greater than would be expected by chance after allowing for effects of differences in Tillage. There is a statistically significant difference (P = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of Tillage is greater than would be expected by chance after allowing for effects of differences in Layer. There is a statistically significant difference (P = 0.009). To isolate which group(s) differ from the others use a multiple comparison procedure.

The effect of different levels of Layer does not depend on what level of Tillage is present. There is not a statistically significant interaction between Layer and Tillage. (P = 0.628)

Power of performed test with alpha = 0.0500: for Layer : 0.997
Power of performed test with alpha = 0.0500: for Tillage : 0.724
Power of performed test with alpha = 0.0500: for Layer x Tillage : 0.0500

Least square means for Layer :

Group	**Mean**
Surf	0.814
Sub	0.171

Std Err of LS Mean = 0.0956

Least square means for Tillage :

Group	**Mean**	**SEM**
NT	0.683	0.102
T	0.302	0.0885

Least square means for Layer x Tillage :

Group	**Mean**	**SEM**
Surf x NT	1.038	0.145
Surf x T	0.590	0.125
Sub x NT	0.328	0.145

Sub x T 0.0130 0.125

All Pairwise Multiple Comparison Procedures (Holm-Sidak method):
Overall significance level = 0.05

Comparisons for factor: **Layer**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
Surf vs. Sub	0.644	4.762	<0.001	0.050	Yes

Comparisons for factor: **Tillage**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
NT vs. T	0.382	2.824	0.009	0.050	Yes

Comparisons for factor: **Tillage within Surf**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
NT vs. T	0.448	2.344	0.028	0.050	Yes

Comparisons for factor: **Tillage within Sub**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
NT vs. T	0.315	1.650	0.112	0.050	No

Comparisons for factor: **Layer within NT**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
Surf vs. Sub	0.710	3.475	0.002	0.050	Yes

Comparisons for factor: **Layer within T**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
Surf vs. Sub	0.577	3.262	0.003	0.050	Yes

Two Way Analysis of Variance Tuesday, March 23, 2010, 10:15:44 AM

Data source: Fillmore No-till vs. Tilled Ks

Balanced Design

Dependent Variable: Log Conductivity Data

Normality Test: Passed (P = 0.219)

Equal Variance Test: Passed (P = 0.227)

Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Tillage Treatment	1	0.00259	0.00259	0.00750	0.931
Depth Treatment	1	11.476	11.476	33.281	<0.001
Tillage Treat x Depth Treatme	1	0.220	0.220	0.638	0.429
Residual	44	15.172	0.345		
Total	47	26.871	0.572		

The difference in the mean values among the different levels of Tillage Treatment is not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in Depth Treatment. There is not a statistically significant difference (P = 0.931).

The difference in the mean values among the different levels of Depth Treatment is greater than would be expected by chance after allowing for effects of differences in Tillage Treatment. There is a statistically significant difference (P = <0.001). To isolate which group(s) differ from the others use a multiple comparison procedure.

The effect of different levels of Tillage Treatment does not depend on what level of Depth Treatment is present. There is not a statistically significant interaction between Tillage Treatment and Depth Treatment. (P = 0.429)

Power of performed test with alpha = 0.0500: for Tillage Treatment : 0.0500
Power of performed test with alpha = 0.0500: for Depth Treatment : 1.000
Power of performed test with alpha = 0.0500: for Tillage Treat x Depth Treatme : 0.0500

Least square means for Tillage Treatment :

Group	**Mean**
T	0.384
NT	0.370

Std Err of LS Mean = 0.120

Least square means for Depth Treatment :

Group	**Mean**
SUB	-0.112
SURF	0.866

Std Err of LS Mean = 0.120

Least square means for Tillage Treat x Depth Treatme :

Group	**Mean**
T x SUB	-0.172

T x SURF 0.941
NT x SUB -0.0515
N T x SURF 0.791
Std Err of LS Mean = 0.170

All Pairwise Multiple Comparison Procedures (Holm-Sidak method):
Overall significance level = 0.05

Comparisons for factor: **Tillage Treatment**

Comparison	Diff of Means	t	Unadjusted P	Critical Level	Significant?
T vs. NT	0.0147	0.0866	0.931	0.050	No

Comparisons for factor: **Depth Treatment**

Comparison	Diff of Means	t	Unadjusted P	Critical Level	Significant?
SURF vs. SUB	0.978	5.769	<0.001	0.050	Yes

Comparisons for factor: **Depth Treatment within B**

Comparison	Diff of Means	t	Unadjusted P	Critical Level	Significant?
SURF vs. SUB	1.113	4.644	<0.001	0.050	Yes

Comparisons for factor: **Depth Treatment within H**

Comparison	Diff of Means	t	Unadjusted P	Critical Level	Significant?
SURF vs. SUB	0.843	3.515	0.001	0.050	Yes

Comparisons for factor: **Tillage Treatment within SUB**

Comparison	Diff of Means	t	Unadjusted P	Critical Level	Significant?
NT vs. T	0.121	0.503	0.617	0.050	No

Comparisons for factor: **Tillage Treatment within S**

Comparison	Diff of Means	t	Unadjusted P	Critical Level	Significant?
T vs. NT	0.150	0.626	0.535	0.050	No

Two Way Analysis of Variance Tuesday, March 23, 2010, 10:17:32 AM

Data source: Phelps No-till vs. Tilled Ks

Balanced Design

Dependent Variable: log transformed

Normality Test: Passed (P = 0.377)

Equal Variance Test: Passed (P = 0.302)

Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Tillage Treatment	1	0.516	0.516	4.723	0.035
Depth Treatment	1	3.700	3.700	33.842	<0.001
Tillage Treat x Depth Treatme	1	0.796	0.796	7.277	0.010
Residual	44	4.811	0.109		
Total	47	9.823	0.209		

Main effects cannot be properly interpreted if significant interaction is determined. This is because the size of a factor's effect depends upon the level of the other factor.

The effect of different levels of Tillage Treatment depends on what level of Depth Treatment is present. There is a statistically significant interaction between Tillage Treatment and Depth Treatment. (P = 0.010)

Power of performed test with alpha = 0.0500: for Tillage Treatment : 0.460
Power of performed test with alpha = 0.0500: for Depth Treatment : 1.000
Power of performed test with alpha = 0.0500: for Tillage Treat x Depth Treatme : 0.693

Least square means for Tillage Treatment :

Group	**Mean**
F	0.508
W	0.301

Std Err of LS Mean = 0.0675

Least square means for Depth Treatment :

Group	**Mean**
S	0.682
SUB	0.127

Std Err of LS Mean = 0.0675

Least square means for Tillage Treat x Depth Treatme :

Group	**Mean**
F x S	0.915
F x SUB	0.102
W x S	0.450
W x SUB	0.152

Std Err of LS Mean = 0.0955

All Pairwise Multiple Comparison Procedures (Holm-Sidak method):

Overall significance level = 0.05

Comparisons for factor: **Tillage Treatment**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
F vs. W	0.207	2.173	0.035	0.050	Yes

Comparisons for factor: **Depth Treatment**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
S vs. SUB	0.555	5.817	<0.001	0.050	Yes

Comparisons for factor: **Depth Treatment within F**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
S vs. SUB	0.813	6.021	<0.001	0.050	Yes

Comparisons for factor: **Depth Treatment within W**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
S vs. SUB	0.298	2.206	0.033	0.050	Yes

Comparisons for factor: **Tillage Treatment within S**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
F vs. W	0.465	3.444	0.001	0.050	Yes

Comparisons for factor: **Tillage Treatment within SUB**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
W vs. F	0.0500	0.371	0.713	0.050	No

T-test Wednesday, March 10, 2010, 11:06:50 AM

Data source: Phelps

Normality Test: Failed (P < 0.050)

Test execution ended by user request, Rank Sum Test begun

Two Way Analysis of Variance Sunday, March 28, 2010, 2:09:34 PM

Data source: Rogers Farm Soybean

Balanced Design

Dependent Variable: Log Transformed Data

Normality Test: Passed (P = 0.076)

Equal Variance Test: Passed (P = 0.970)

Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Tillage Treatment	1	0.163	0.163	0.302	0.589
Depth Treatment	1	0.228	0.228	0.422	0.523
Tillage Treat x Depth Treatme	1	0.635	0.635	1.175	0.291
Residual	20	10.801	0.540		
Total	23	11.827	0.514		

The difference in the mean values among the different levels of Tillage Treatment is not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in Depth Treatment. There is not a statistically significant difference (P = 0.589).

The difference in the mean values among the different levels of Depth Treatment is not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in Tillage Treatment. There is not a statistically significant difference (P = 0.523).

The effect of different levels of Tillage Treatment does not depend on what level of Depth Treatment is present. There is not a statistically significant interaction between Tillage Treatment and Depth Treatment. (P = 0.291)

Power of performed test with alpha = 0.0500: for Tillage Treatment : 0.0500
Power of performed test with alpha = 0.0500: for Depth Treatment : 0.0500
Power of performed test with alpha = 0.0500: for Tillage Treat x Depth Treatme : 0.0652

Least square means for Tillage Treatment :

Group	**Mean**
T	1.118
NT	0.954

Std Err of LS Mean = 0.212

Least square means for Depth Treatment :

Group	**Mean**
SUB	0.939
SURF	1.133

Std Err of LS Mean = 0.212

Least square means for Tillage Treat x Depth Treatme :

Group	**Mean**
T x SUB	1.184
T x SURF	1.053

NT x SUB 0.693
NT x SURF 1.214
Std Err of LS Mean = 0.300

All Pairwise Multiple Comparison Procedures (Holm-Sidak method):
Overall significance level = 0.05

Comparisons for factor: **Tillage Treatment**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
T vs. NT	0.165	0.550	0.589	0.050	No

Comparisons for factor: **Depth Treatment**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
SURF vs. SUB	0.195	0.650	0.523	0.050	No

Comparisons for factor: **Depth Treatment within T**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
SUB vs. SURF	0.130	0.307	0.762	0.050	No

Comparisons for factor: **Depth Treatment within NT**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
SURF vs. SUB	0.520	1.226	0.234	0.050	No

Comparisons for factor: **Tillage Treatment within SUB**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
T vs. NT	0.490	1.155	0.262	0.050	No

Comparisons for factor: **Tillage Treatment within SURF**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
NT vs. T	0.160	0.378	0.709	0.050	No

Two Way Analysis of Variance Sunday, March 28, 2010, 2:04:31 PM

Data source: Rogers Farm Corn

Balanced Design

Dependent Variable: Log Transformed Data

Normality Test: Failed (P < 0.050)

Equal Variance Test: Passed (P = 0.528)

Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Tillage Treatment	1	1.297	1.297	5.895	0.025
Depth Treatment	1	0.0424	0.0424	0.193	0.665
Tillage Treat x Depth Treatme	1	0.484	0.484	2.201	0.153
Residual	20	4.399	0.220		
Total	23	6.222	0.271		

The difference in the mean values among the different levels of Tillage Treatment is greater than would be expected by chance after allowing for effects of differences in Depth Treatment. There is a statistically significant difference (P = 0.025). To isolate which group(s) differ from the others use a multiple comparison procedure.

The difference in the mean values among the different levels of Depth Treatment is not great enough to exclude the possibility that the difference is just due to random sampling variability after allowing for the effects of differences in Tillage Treatment. There is not a statistically significant difference (P = 0.665).

The effect of different levels of Tillage Treatment does not depend on what level of Depth Treatment is present. There is not a statistically significant interaction between Tillage Treatment and Depth Treatment. (P = 0.153)

Power of performed test with alpha = 0.0500: for Tillage Treatment : 0.553
Power of performed test with alpha = 0.0500: for Depth Treatment : 0.0500
Power of performed test with alpha = 0.0500: for Tillage Treat x Depth Treatme : 0.170

Least square means for Tillage Treatment :

Group	**Mean**
NT	1.017
T	1.481

Std Err of LS Mean = 0.135

Least square means for Depth Treatment :

Group	**Mean**
SUB	1.207
SURF	1.291

Std Err of LS Mean = 0.135

Least square means for Tillage Treat x Depth Treatme :

Group	**Mean**
NT x SUB	1.117

NT x SURF	0.917
T x SUB	1.297
T x SURF	1.665

Std Err of LS Mean = 0.191

All Pairwise Multiple Comparison Procedures (Holm-Sidak method):
Overall significance level = 0.05

Comparisons for factor: **Tillage Treatment**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
T vs. NT	0.465	2.428	0.025	0.050	Yes

Comparisons for factor: **Depth Treatment**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
SURF vs. SUB	0.0841	0.439	0.665	0.050	No

Comparisons for factor: **Depth Treatment within NT**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
SUB vs. SURF	0.200	0.739	0.469	0.050	No

Comparisons for factor: **Depth Treatment within T**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
SURF vs. SUB	0.368	1.360	0.189	0.050	No

Comparisons for factor: **Tillage Treatment within SUB**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
T vs. NT	0.181	0.668	0.512	0.050	No

Comparisons for factor: **Tillage Treatment within SURF**

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
T vs. NT	0.749	2.766	0.012	0.050	Yes

One Way Analysis of Variance
Data source: Phelps Sand

Normality Test: Failed (P < 0.050)

Test execution ended by user request, ANOVA on Ranks begun

Kruskal-Wallis One Way Analysis of Variance on Ranks Thursday, March 25, 2010, 10:27:05 AM

Data source: Data 1 in Notebook1

Group	N	Missing	Median	25%	75%
Phelps NT Sand	24	0	22.000	18.000	24.000
Phelps Tilled Sand	24	0	26.000	24.000	27.000

H = 16.027 with 1 degrees of freedom. (P = <0.001)

The differences in the median values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = <0.001)

To isolate the group or groups that differ from the others use a multiple comparison procedure.

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparison	Diff of Ranks	q	P<0.05
Phelps Tilled vs Phelps NT Sand	383.000	5.584	Yes

Note: The multiple comparisons on ranks do not include an adjustment for ties.

One Way Analysis of Variance

Data source: Phelps Clay

Normality Test: Failed (P < 0.050)

Test execution ended by user request, ANOVA on Ranks begun

Kruskal-Wallis One Way Analysis of Variance on Ranks Thursday, March 25, 2010, 10:27:57 AM

Data source: Data 1 in Notebook1

Group	**N**	**Missing**	**Median**	**25%**	**75%**
Phelps NT Clay	24	0	21.000	20.000	22.500
Phelps Tilled Clay	24	0	20.000	19.000	20.500

H = 7.388 with 1 degrees of freedom. (P = 0.007)

The differences in the median values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = 0.007)

To isolate the group or groups that differ from the others use a multiple comparison procedure.

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparison	**Diff of Ranks**	**q**	**P<0.05**
Phelps NT Clay vs Phelps Tilled	260.000	3.791	Yes

Note: The multiple comparisons on ranks do not include an adjustment for ties.

One Way Analysis of Variance

Data source: Fillmore Sand

Normality Test: Passed (P = 0.064)

Equal Variance Test: Passed (P = 0.108)

Group Name	**N**	**Missing**	**Mean**	**Std Dev**	**SEM**
Fillmore NT Sand	24	0	21.333	2.777	0.567
Fillmore Tilled Sand	24	0	19.375	1.907	0.389

Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Between Groups	1	46.021	46.021	8.112	0.007
Residual	46	260.958	5.673		
Total	47	306.979			

The differences in the mean values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = 0.007).

Power of performed test with alpha = 0.050: 0.752

All Pairwise Multiple Comparison Procedures (Holm-Sidak method):
Overall significance level = 0.05

Comparisons for factor:

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
Fillmore NT vs. Fillmore Til	1.958	2.848	0.007	0.050	Yes

One Way Analysis of Variance

Data source: Fillmore Clay

Normality Test: Passed (P = 0.207)

Equal Variance Test: Failed (P < 0.050)

Test execution ended by user request, ANOVA on Ranks begun

Kruskal-Wallis One Way Analysis of Variance on Ranks Thursday, March 25, 2010, 10:33:59 AM

Data source: Data 1 in Notebook1

Group	N	Missing	Median	25%	75%
Fillmore NT Clay	24	0	25.000	20.000	28.000
Fillmore Tilled Clay	24	0	22.000	20.000	22.000

H = 4.451 with 1 degrees of freedom. (P = 0.035)

The differences in the median values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = 0.035)

To isolate the group or groups that differ from the others use a multiple comparison procedure.

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparison	Diff of Ranks	q	P<0.05
Fillmore NT C vs Fillmore Till	203.000	2.960	Yes

Note: The multiple comparisons on ranks do not include an adjustment for ties.

One Way Analysis of Variance

Data source: Rogers Farm Sand

Normality Test: Failed (P < 0.050)

Test execution ended by user request, ANOVA on Ranks begun

Kruskal-Wallis One Way Analysis of Variance on Ranks Thursday, March 25, 2010, 10:23:47 AM

Data source: Data 1 in Notebook1

Group	**N**	**Missing**	**Median**	**25%**	**75%**
RF NT Sand	24	0	17.500	16.500	21.000
RF Tilled Sand	24	0	17.000	15.000	18.000

H = 4.947 with 1 degrees of freedom. (P = 0.026)

The differences in the median values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = 0.026)

To isolate the group or groups that differ from the others use a multiple comparison procedure.

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparison	**Diff of Ranks**	**q**	**P<0.05**
RF NT Sand vs RF Tilled Sand	212.000	3.091	Yes

Note: The multiple comparisons on ranks do not include an adjustment for ties.

One Way Analysis of Variance
Data source: Rogers Farm Clay

Normality Test: Passed (P = 0.586)

Equal Variance Test: Passed (P = 0.445)

Group Name	N	Missing	Mean	Std Dev	SEM
RF Tilled Clay	24	0	28.458	3.989	0.814
RF NT Clay	24	0	29.583	4.529	0.925

Source of Variation	DF	SS	MS	F	P
Between Groups	1	15.188	15.188	0.834	0.366
Residual	46	837.792	18.213		
Total	47	852.979			

The differences in the mean values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.366).

Power of performed test with alpha = 0.050: 0.047

The power of the performed test (0.047) is below the desired power of 0.800.
Less than desired power indicates you are less likely to detect a difference when one actually exists.
Negative results should be interpreted cautiously.