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Modeling of Two-Dimensional Overland Flow in a Vegetative Filter

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Abstract. Water transports sediment and other pollutants through vegetative filters. It is often assumed that the overland flow is uniformly distributed across the vegetative filter, but this research indicates otherwise. The objective of this study was to model the two-dimensional overland water flow through a vegetative filter, accounting for variation in microtopography, infiltration, and surface roughness. Overland flow was monitored in two areas (east and west grid) of an established vegetative filter. The two areas were surveyed in detail to determine the spatially varying microtopography. Soil hydraulic properties were gathered at the site to represent the spatial variation in soil hydraulic properties. Runoff from four irrigation events was monitored. The inflow rate, outflow rate, and maximum depth of flow were measured at multiple locations. Simulation of the flow processes was performed using the physically based, distributed model, MIKE SHE. Simulations were performed with constant and variable topography and constant and variable soil hydraulic properties. The variable topography significantly impacted the outflow hydrographs for both the areas. The variable soil hydraulic properties impacted the outflow hydrographs with greater impact in the west grid area than the east grid area. The outflow rate at the downstream edge of the vegetative filter varied with position along the downstream edge of the filter indicating flow is not uniformly distributed in the vegetative filter.

Keywords. Vegetative filters, grass filters, overland flow, MIKE SHE

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Introduction

With the increase in concern about water pollution by sediment and other pollutants, the use of vegetative filters as a best management practice has grown. This increased use is in part due to the National Conservation Buffer Initiative implemented by the USDA Natural Resources Conservation Service. While there has been a significant amount of research performed on plot-scale vegetative filters and on vegetation or simulated vegetation in a laboratory setting, very little information is available on water flow and sediment transport within "field scale" vegetative filters.

In modeling water flow through vegetative filters it is often assumed that the flow is uniformly distributed. REMM (Lowrance et al., 2000) and VFSMOD (Munoz-Carpena et al., 1999), which are models that simulate processes that occur in vegetative filters, use the assumption of uniformly distributed overland flow. Helmers et al. (2001) found that the surface water flow was not uniformly distributed in the vegetative filter described in this paper. If flow is not uniformly distributed there are likely areas of converging and diverging flow. Areas of converging flow indicate flow concentration. Dillaha et al. (1989) state that vegetative filters that are characterized by concentrated flow should be less effective for sediment removal than filters with shallow, uniformly distributed flow. Flow concentration could impact filter performance due to variation in flow velocities and flow depths. Tayfur et al. (1993) state that soil erosion and sediment transport studies are highly influenced by the local depth of water flow and the velocity fields of the water flow.

To evaluate the impact of flow concentration on filter performance, the multi-dimensional surface water flow must be described. In this study, multi-dimensional water flow through a vegetative filter is modeled using the physically based, distributed hydrologic model MIKE SHE (Refsgaard and Storm, 1995). MIKE SHE can account for variation in microtopography, infiltration, and surface roughness. The objective of this study was to model surface water flow in a vegetative filter using MIKE SHE and evaluate the impact of variable soil hydraulic properties and topography on the surface water flow in a vegetative filter. The results of this investigation will be used in evaluating the performance of vegetative filters relative to surface water movement.

Site Description

The field experiments were conducted during the summer of 2001 at a filter strip established in the spring of 1999 in central Nebraska near Stromsburg, Nebraska further described as the 99 Buffer. The site is the same site described by Helmers et al. (2001). Vegetation in the filter strip consists of big bluestem (*Andropogon gerardii*), Indiangrass (*Panicum virgatum*), and switchgrass (*Sorghastrum nutans*). The area upstream from the filter strip is a furrow-irrigated field with furrow lengths of approximately 670 m. The average slope in the direction of flow is almost 1% in the filter strip. The cross-slope is about 0.1%. The field, including the filter, had been graded for furrow irrigation many years prior to this project. The flow length through the buffer is approximately 13 m. Two areas in the filter strip were investigated in detail.

The areas are designed as the east and west grids, respectively. The topography of the east grid is shown in Figure 1 and the topography of the west grid is shown in Figure 2.

Materials and Methods

The contours on the topographic maps shown in Figures 1 and 2 were developed using the computer program Surfer, version 6.04 by Golden Software, using the kriging interpolation scheme. The location and elevation data (x-y-z coordinates) for these maps was obtained during the fall of 2001 using a total station (Nikon DTM-520 Total Station) with measurements points on a 1.5 m grid in the 13x15 m area and on a 3 m grid outside the 13x15 m area. Additionally, measurements (x-y-z coordinates) were taken at the locations of the sampling equipment at the site. The locations of the sampling equipment are also shown in Figures 1 and 2 for the east and west grid, respectively. The sampling equipment consisted of depth pegs, overland flow samplers, and mini-overland flow samplers.

Soil samples were obtained from the 99 Buffer in October 2000. A total of 26 samples were gathered to characterize the soil hydraulic properties at the site. The undisturbed samples were contained in a ring with an inside diameter of 8.25 cm and a length of 7.5 cm. Of the 26 samples taken five of the soil cores were disturbed by earthworm or ant activity during storage so they were discarded. The following tests were performed on the 21 soil samples (11 from the east grid and 10 from the west grid):

- Multi-step steady state outflow for determining soil water retention (at capillary pressures of 1 kPa, 4kPa, 10kPa, and 33 kPa). In addition, the method of Rawls et al. (1982) was used to estimate soil water retention at capillary pressures of 20 kPa, 60kPa, 100 kPa, 200 kPa, 400 kPa, 700 kPa, and 1000 kPa.
- Thermocouple psycrometry was used to determine the water content at a capillary pressure of 1500 kPa (also needed for Rawls et al. (1982) technique).
- Percent sand, silt, clay and organic matter tests were performed for use in the method of Rawls et al. (1982).
- Soil bulk density
- Satiated conductivities were determined using the falling head method.

The soil hydraulic data will be used for modeling infiltration and variability in infiltration in the vegetative filter.

A representative or average soil water retention curve was used to represent all locations within the filter area. We believe that the spatial variability in infiltration can be reflected by variable satiated conductivity. The Shapiro-Wilk test statistic W in the SAS System for Windows, version 8.02, was used to test the normality of a given set of data. Both the van Genuchten (1980) and Brooks and Corey (1964) methods for representing the soil water retention curves were fit to the data. The satiated water content and the residual water content values from the van Genuchten method were used in determining the parameters for the Brooks and Corey method. The curve fitting process to determine the parameters for these methods was completed using SigmaPlot Version 5.0.

The runoff from irrigation was monitored during the summer of 2001. A total of four irrigation events were monitored. The runoff was measured with 60° V-notch trapezoidal flumes and with in-buffer overland flow samplers. The overland flow samplers, which sample a 0.3 m wide section, have been developed during the course of this research project (Eisenhauer et al., 2002). The outflow was measured at three points along the exit from each grid. The inflow to the filter was measured using three overland flow samplers at the entrance to the filter and multiple flumes positioned in furrows approximately 30 m upstream of the filter entrance. The positions and the identification number of the overland flow samplers are shown in Figures 1 and 2 for the east and west grid, respectively. During the 1st three irrigation events (July 18, August 2, and August 13) a total of five flumes were installed for monitoring flow into each grid area. During these three events, the number of furrows where water was run ranged from 11 to 15 with water being run in every other furrow (all non-wheel track furrows except the guess rows). The flumes were installed in five non-wheel track furrows. For the 4th event (August 23 for west grid and August 24 for east grid), 11 furrows were monitored in each grid area with water being run in just these 11 furrows. In this case, water was run in both non-wheel track and wheel track furrows but not guess furrows, so 11 furrows in a 13 furrow section were watered.

MIKE-SHE is a deterministic, distributed and physically based model that allows for simulation of all major hydrological processes occurring in the land phase of the hydrologic cycle (Refsgaard and Storm, 1995). The water movement module (WM) is the main module of MIKE SHE and the portion used as a part of the investigation described within. The WM module of MIKE SHE solves the equations of continuity and conservation of momentum in two horizontal directions to describe the overland flow process. The conservation of momentum equations are solved using the diffusive wave approximation. The Strickler/Manning-type law is used for the friction slope with a Strickler roughness coefficient input at each computational location. Infiltration is described using one-dimensional vertical flow by solving Richards equations. The unsaturated zone and overland flow components of MIKE SHE were used for this study.

As discussed above, MIKE SHE is being used to model multi-dimensional overland flow in a vegetative filter. For the simulations a discretization of 0.762 m was used to represent the model domain. This size discretization was used to correspond to furrow widths, which allowed for variable inflow to the filter from the furrows. MIKE SHE allows for separate flow areas so since for most of the events water was applied in every other furrow inflow could be separated to more closely simulate the field conditions of flow entering the filter. Since MIKE SHE does not allow direct input of overland flow, time-varying precipitation was introduced on a planar area upstream of the filter to produce time-varying inflow to the vegetative filter. Precipitation was introduced on an area with a width of 0.762 m and a length of 6.1 m at a minimum distance of 6.1 m upstream of the filter to produce inflow to the filter. The slope of the domain upstream of the filter was about 1%. The time-varying precipitation was introduced to reproduce the measured inflow rates at the various locations. At locations where there was not measured data, an average inflow from the measured values was determined and a representative precipitation rate was introduced to produce the average inflow to the filter. The width of the filter (direction perpendicular to the predominate flow direction) used in the simulations was 32 m and the length of the filter (direction parallel to the predominate flow direction) was 14.5 m with additional length upstream of the filter for the rainfall area. The locations of the downstream samplers were approximately 13 m downstream from the upstream filter edge. The roughness was kept constant within the filter for the simulations discussed within. For these simulations the Manning's roughness was 0.1 (Strickler number of 10), which, according to Foster et al. (1980) is in the range of an excellent to dense stand of grass. A portion of the simulations performed had variable topography based on the topography shown in Figures 1 and 2 and a portion had constant topography. For the constant topography cases, there was no-cross slope and a constant slope in the primary direction of water flow. For the east grid the slope was approximately 0.65% and for the west grid the slope was approximately 0.89%.

Results and Discussion

The Shapiro-Wilk test statistic W for normality showed the satiated conductivity to be log-normally distributed. The geometric mean and range of satiated conductivity values are shown in Table 1. For the Brooks and Corey pore size distribution index and the air entry pressure there was little difference in the Shapiro-Wilk test statistic W for normality between non-transformed data and log normal transformed data. The arithmetic mean and the range for the pore size distribution index and the air entry pressure are provided in Table 1. The satiated and residual water content were found to be normally distributed and their arithmetic mean and range are shown in Table 1.

Table 1: Summary of soil hydraulic parameters

Parameter	Mean	Method of Averaging	Range
Satiated hydraulic conductivity	2.38 cm/hr	Geometric	0.358 – 13.3
Pore size distribution index (λ)	0.264	Arithmetic	0.164 – 0.343
Air entry pressure	80.9 cm	Arithmetic	34.4 – 134
Satiated water content	0.388	Arithmetic	0.357 – 0.433
Residual water content	0.065	Arithmetic	0.0 – 0.122

Using SAS, a semivariogram was developed with the log-normally transformed satiated conductivity data and an exponential model was found to best fit the experimental semivariogram. Table 2 summarizes the semivariogram values for the exponential model.

Table 2: Summary of semivariogram model for satiated conductivity

Parameter	Nugget	Sill	Range (m)
Log-normally transformed satiated conductivity (base units cm/hr)	0.20	2.42	25

Using the semivariogram model, the distribution of log normally transformed conductivity was estimated using the kriging interpolation method and then back transformed to produce a distribution of satiated conductivity values. The distribution for the east grid is shown in Figure 3 and the distribution for the west grid is shown in Figure 4. Reviewing Figures 3 and 4 it appears that there is greater variation in satiated hydraulic conductivity in the west grid than in the east grid.

The average pore size distribution index, air entry pressure and satiated and residual content were used to develop an average soil water retention curve to be input into MIKE SHE. In the unsaturated zone component of the model, points on the soil water retention curve are the input into MIKE SHE. The distributions shown in Figures 3 and 4 were used to develop a series of 15 soil profiles with differing satiated conductivities. Each grid cell in MIKE SHE was assigned a different soil profile that would relate back to a satiated conductivity value and the average soil water retention curve. From this, there were 15 different satiated conductivity values and each cell in the filter area would be assigned one of these values depending on its soil profile classification developed from the distributions in Figures 3 and 4. The area upstream of the filter was assigned a soil profile separate from the 15 profiles in the filter. We used an extremely low conductivity so that there was negligible infiltration in this portion of the domain.

Simulation results from the July 18 irrigation event in the east grid and the August 13 irrigation event in the west grid are presented and discussed within. These events were used in part since the inflow for these events seemed to have the lowest variability. The simulations performed as a part of this study and presented within were undertaken to evaluate the impact of variable infiltration and microtopography on surface water flow in a vegetative filter.

As discussed above, since time-varying inflow cannot be directly input into MIKE SHE the time varying inflow was developed using time-varying precipitation upstream of the filter. Figures 5 and 6 compare the measured inflow rate and the modeled inflow rate at various locations in the east and west grids, respectively. As a can be seen from these figures, this method for representing inflow produces modeled inflow rates close to the measured flow rates.

The simulations for the east grid for the July 18, 2001 event are summarized in Figures 7 and 8. Figure 7 shows outflow hydrographs from various positions on the downstream edge of the filter. The positions are at the locations of samplers E-S-1, E-S-2, and E-S-3. Results considering variable and constant soil hydraulic properties and topography are shown. As illustrated in Figure 7 the variable topography impacted the outflow hydrograph by increasing the outflow at the location of samplers E-S-2 and E-S-3 and decreasing the outflow at the location of sampler E-S-1. This is especially noticeable for the case at the location of E-S-2. For the E-S-1 and E-S-2 locations the variable soil hydraulic properties had little impact on the outflow hydrograph, but there was slightly greater impact at the E-S-3 location. Reviewing the outflow hydrographs at the sampler locations show there is variation in flow along the downstream edge of the filter with the greatest outflow rate occurring at sampler E-S-2. Contours for the depth of overland flow in the east grid are shown in Figure 8 for the July 18, 2001 event. The variable topography had a significant impact on the depth of overland flow when compared to the constant topography case.

Figures 9 and 10 show results of the simulations for the August 13, 2001 event in the west grid area. The outflow hydrographs at the locations of samplers W-S-1, W-S-2, and W-S-3 are shown in Figure 9. Reviewing the hydrographs in Figure 9 reveal that both the variable soil hydraulic properties and the variable topography impacted the outflow hydrographs. For sampler W-S-2, the variable topography increases the outflow rate compared to the constant topography. The constant soil hydraulic property case resulted in a greater outflow rate at location W-S-2 compared to variable soil hydraulic properties. At the location of sampler W-S-3 the variable topography cases had lower outflow than the constant topography cases and the constant soil hydraulic property cases have a lower outflow rate than variable soil hydraulic property cases. Compared to the conductivity distribution in Figure 4, assuming constant soil hydraulic properties would result in greater conductivity upstream of sampler W-S-3 and lower conductivity upstream of sampler W-S-2. These observations of the effect of conductivity variability correspond with the observations from the outflow hydrographs in that it would be expected if conductivity decreases infiltration would decrease and runoff would increase and vice versa. From Figure 9, the outflow rate varies at different locations along the downstream edge of the filter with the peak outflow rate occurring at the location of sampler W-S-2. Contours for the depth of overland flow in the west grid are shown in Figure 10. As was the case for the east grid simulations, the variable topography case resulted in greater variation in depth of flow than the constant topography case for the west grid simulations.

The modeling results did not consider the impact of variable roughness in surface water flow in a vegetative filter. This factor will be considered in future modeling. Photographs of emerging vegetation were taken after the spring controlled burn in 2001 for use in accounting for variable vegetation density. Also the impact of change in roughness as the velocity and depth of flow changes throughout the event may have an effect on simulated outflow hydrographs and will be investigated. The results presented within have not been compared with data from the field experiments at the 99 Buffer. Calibration and validation will be performed in future modeling work to further evaluate the ability to simulate the multi-dimensional surface water flow.

Results from the overland flow modeling show that there are areas of variable flow in the 99 Buffer. This variation in flow may impact the performance of the filter relative to sediment trapping since sediment transport is highly influenced by the depth and velocity of the water flow (Tayfur et al. 1993). The impact of variable surface water flow on sediment trapping in a vegetative filter will be investigated in future phases of this research.

Summary and Conclusions

The objective of this study was to model surface water flow in a vegetative filter and evaluate the impact of variable soil hydraulic properties and topography on the surface water flow. Two areas in a vegetative filter established in 1999 in central Nebraska were monitored for surface water runoff using 60° V-notch trapezoidal flumes and in-buffer overland flow samplers. The two areas were designated the east and west grids. The flow length through the filter is approximately 13 m with an average slope in the primary direction of flow of about 1% and a cross-slope of about 0.1%. Multi-dimensional surface water flow was modeled using the physically based, distributed hydrologic model MIKE SHE. The variable topography was based on a detailed survey performed at the site and the variable soil hydraulic properties were based on laboratory tests performed on undisturbed soil samples obtained from the site. The variable soil hydraulic properties were represented with a variable satiated hydraulic conductivity and a constant soil water retention curve. The satiated hydraulic conductivity was found to be log-normally distributed. Simulations were performed with MIKE SHE for the July 18, 2001 event in the east grid and the August 13, 2001 event in the west grid using both constant and variable topography and soil hydraulic property conditions.

Based on the simulations performed the variable topography significantly impacted the outflow hydrographs for both the east and west grid areas. For both areas the variable topography case had a greater peak outflow rate at the location of the center sampler (samplers E-S-2 and W-S-2) than for the constant topography case. At the location of samplers E-S-1, W-S-1, and W-S-3 the constant topography cases had a greater outflow rate than the variable topography cases. The variable soil hydraulic properties in general had less impact on the outflow hydrographs in the east grid than the west grid. This is understandable since there was less variation in the satiated hydraulic conductivity in the east grid than in the west grid. From these simulations both variable topography and variable soil hydraulic properties impacted the outflow hydrographs and the depth of overland flow in the filter. Also, the simulations showed that the outflow rate varied with position along the downstream edge of the filter indicating the flow is not uniformly distributed in the vegetative filter even though inflow was relatively uniformly distributed at the upstream edge.

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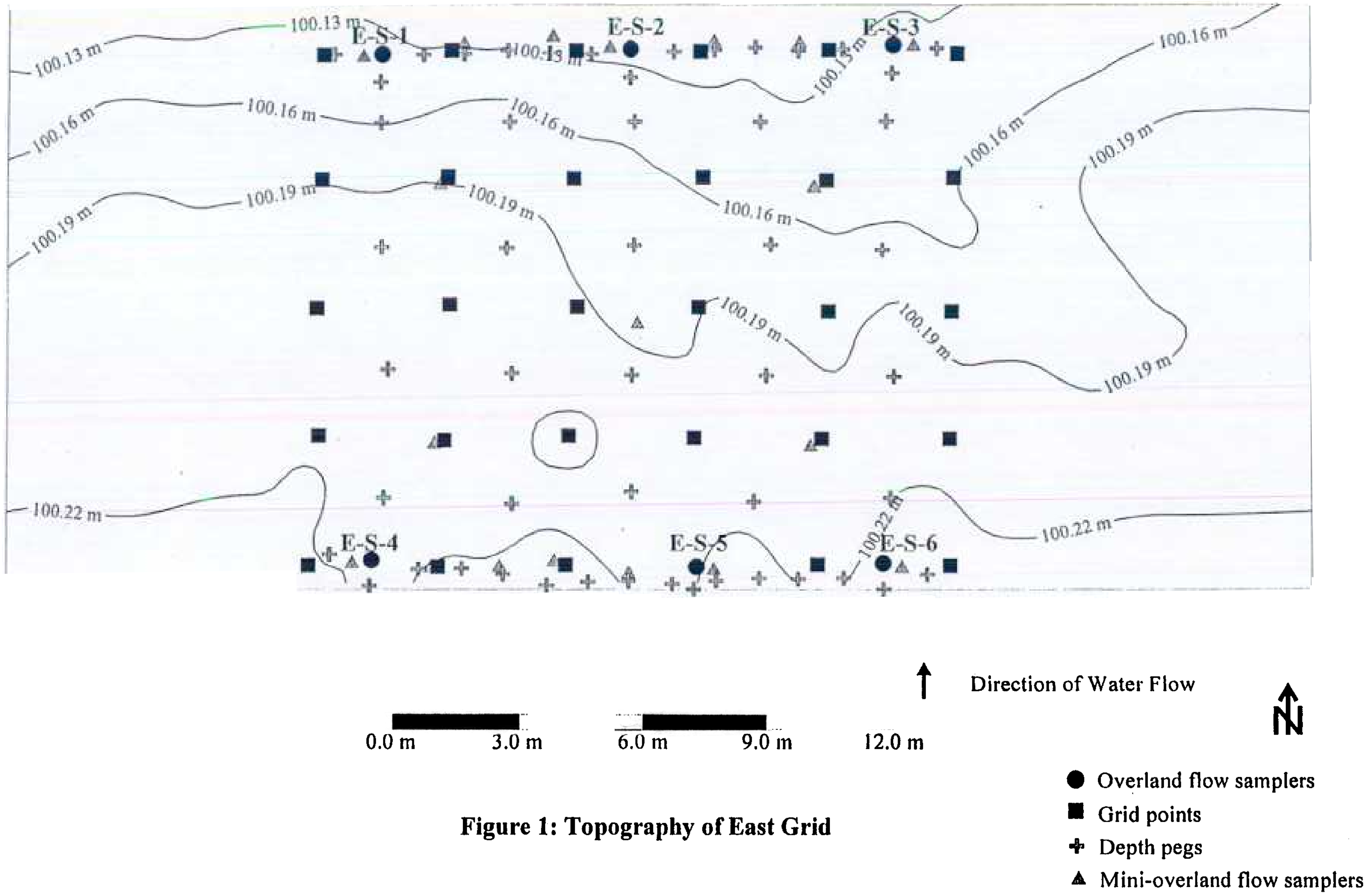


Figure 1: Topography of East Grid

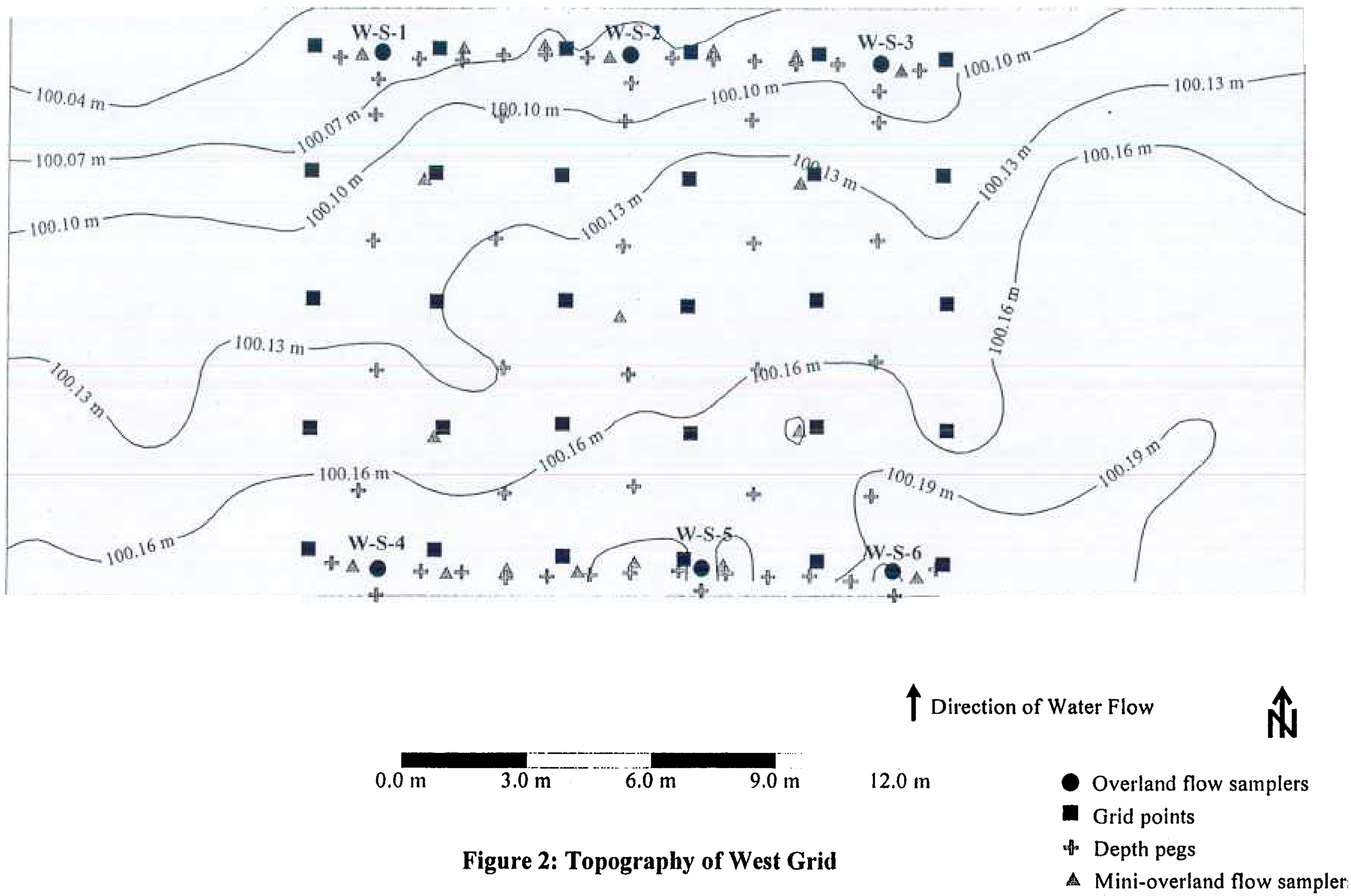


Figure 2: Topography of West Grid

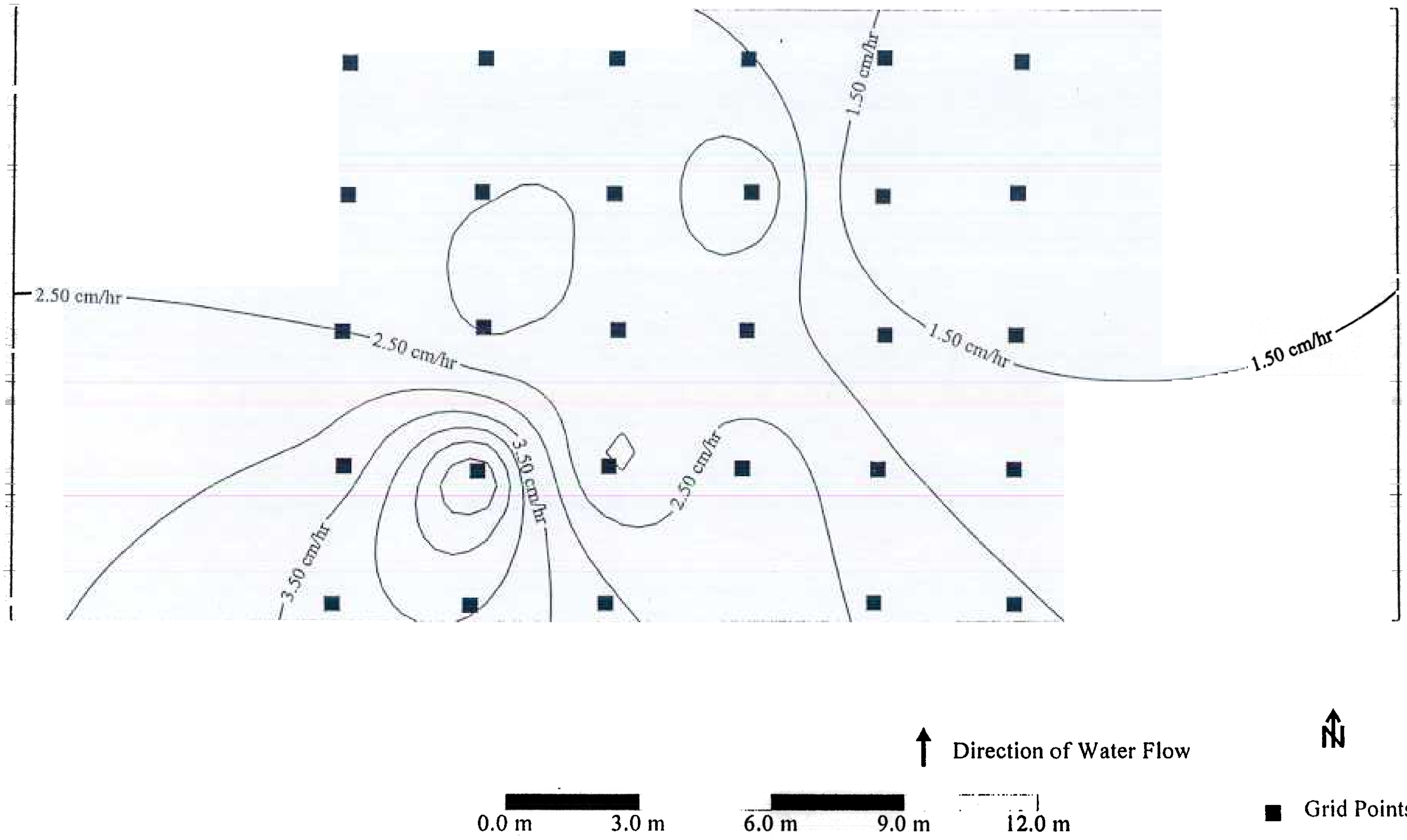


Figure 3: Distribution of Satiated Conductivity for East Grid

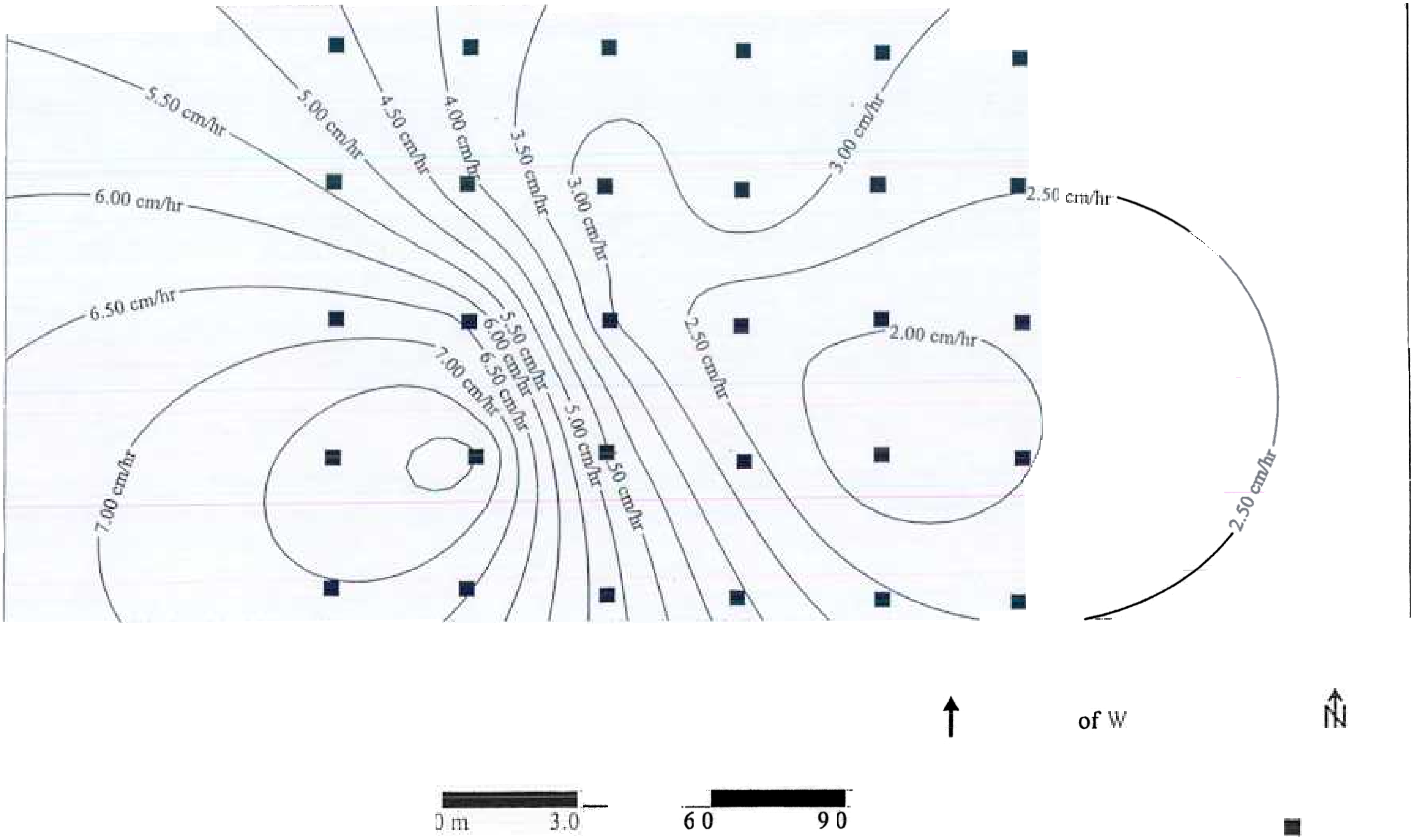


Figure 4: Dis ri ion of Satiated C nd ctivity fo West Grid

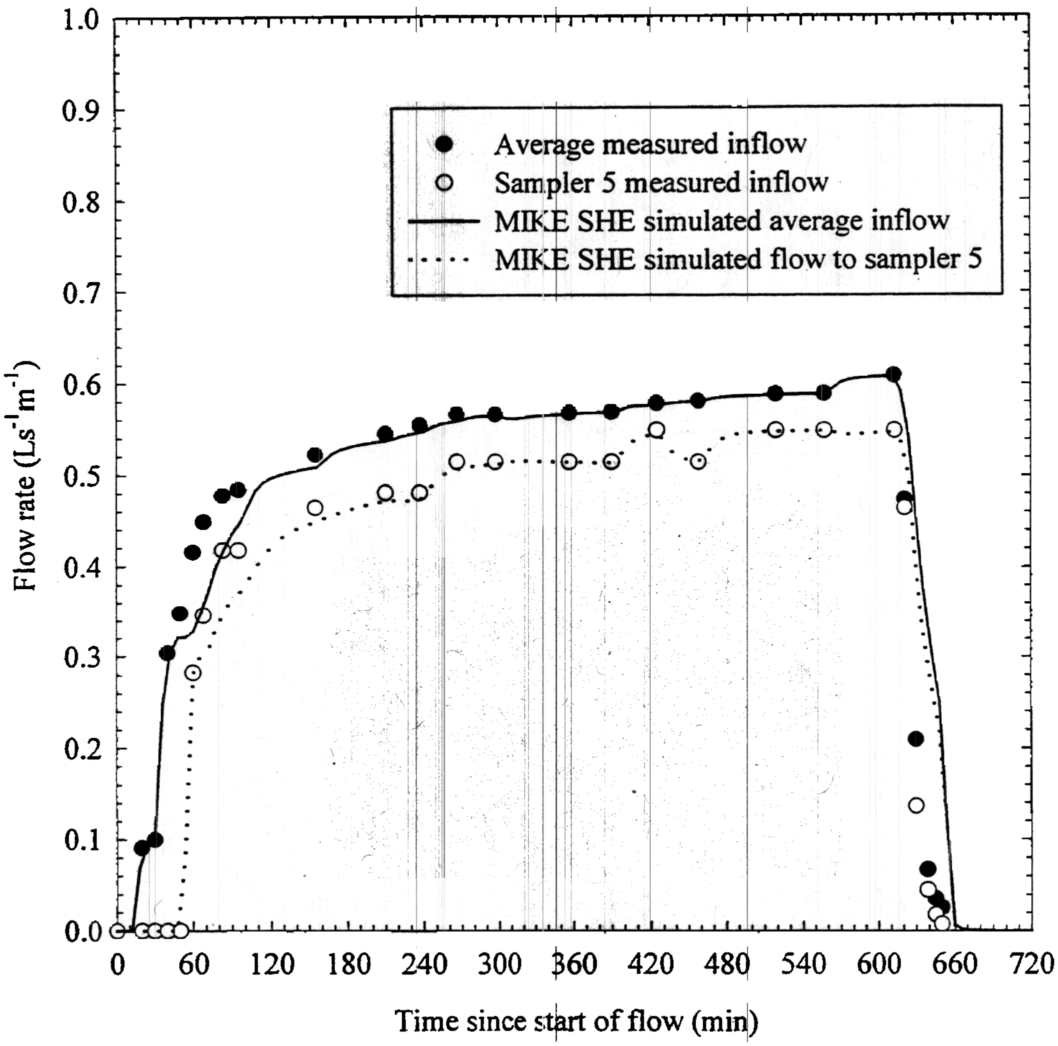


Figure 5: Comparison of Measured Inflow Hydrograph and Inflow Hydrograph from MIKE SHE Simulations, East Grid July 18, 2001 Event

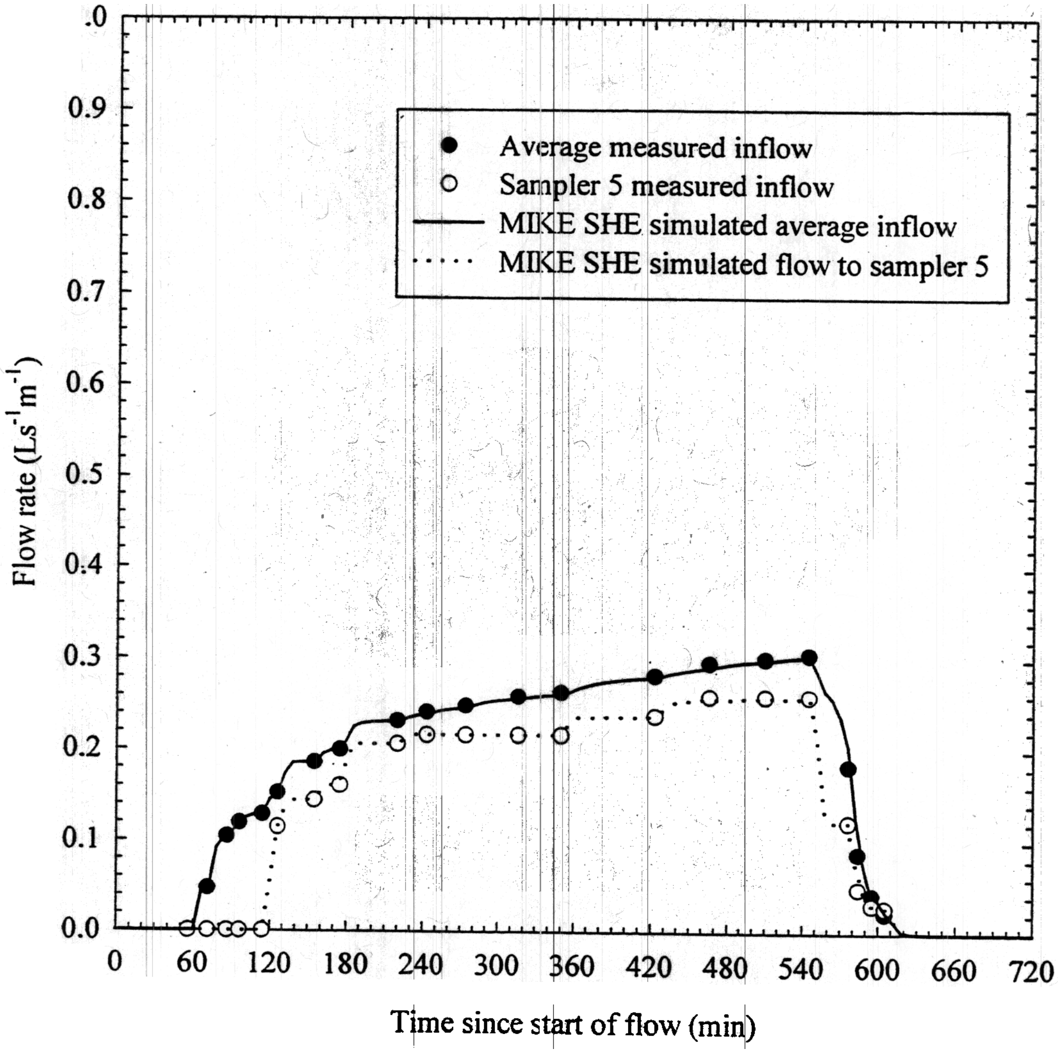


Figure 6: Comparison of Measured Inflow Hydrograph and Inflow Hydrograph from MIKE SHE Simulations, West Grid August 13, 2001 Event

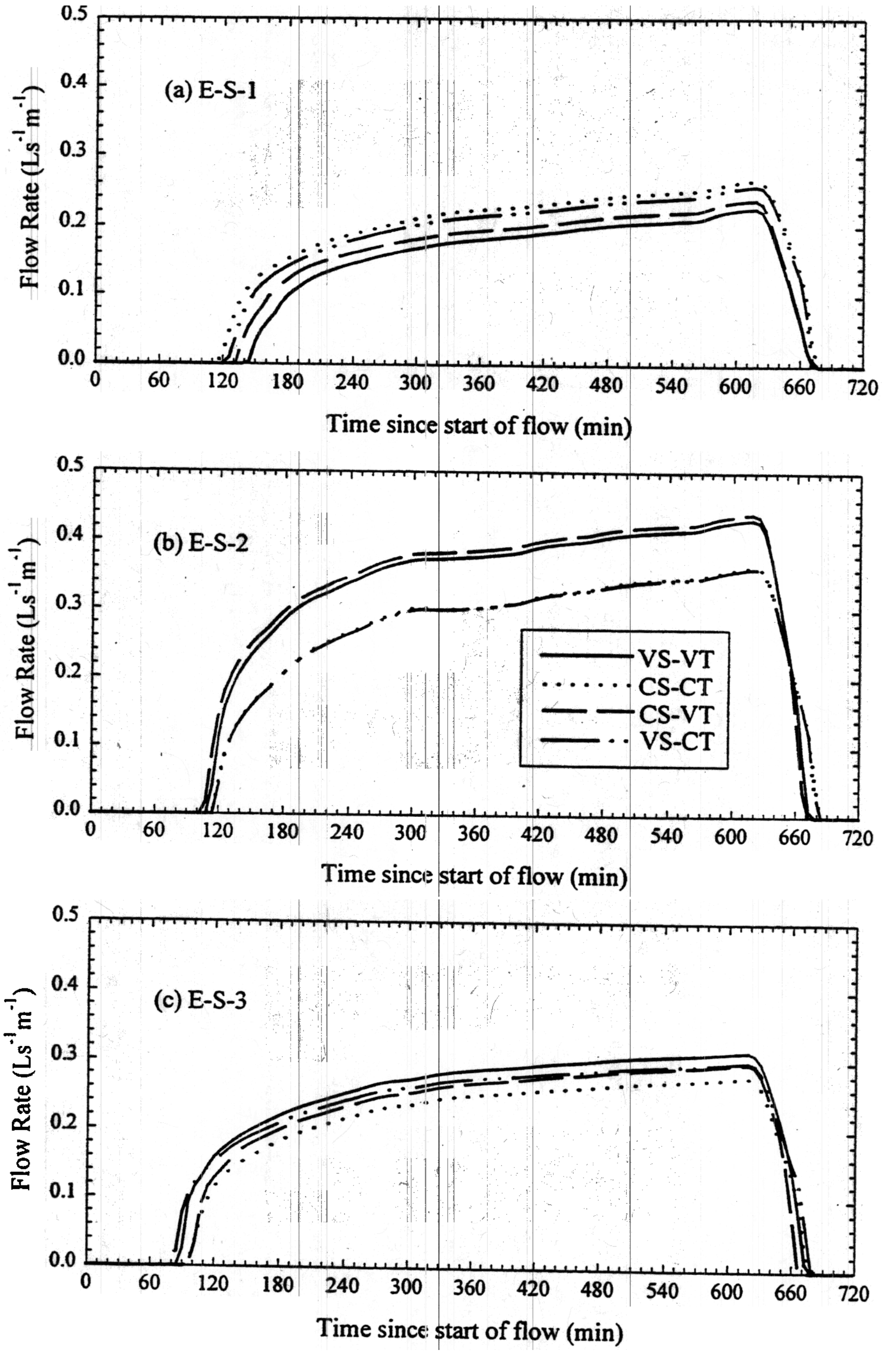
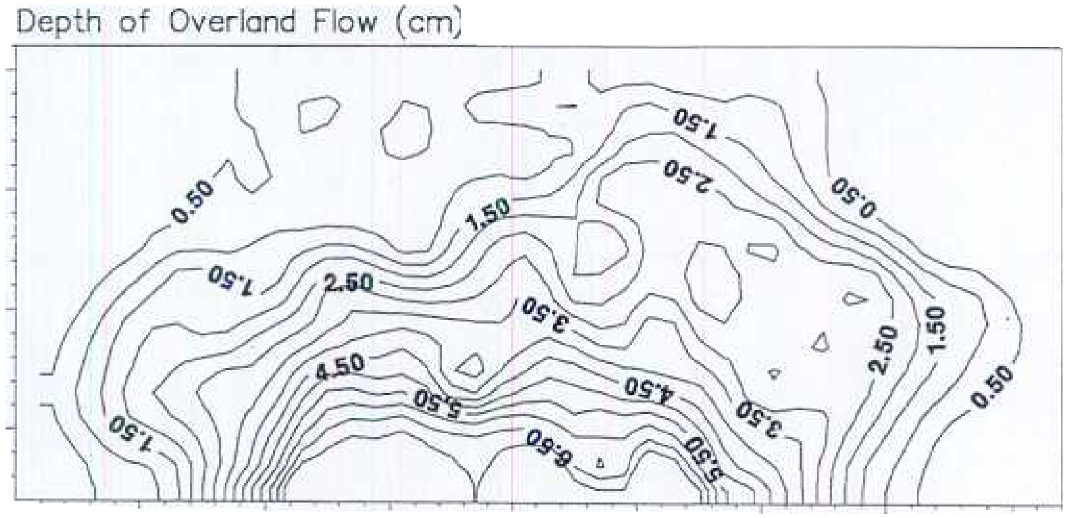
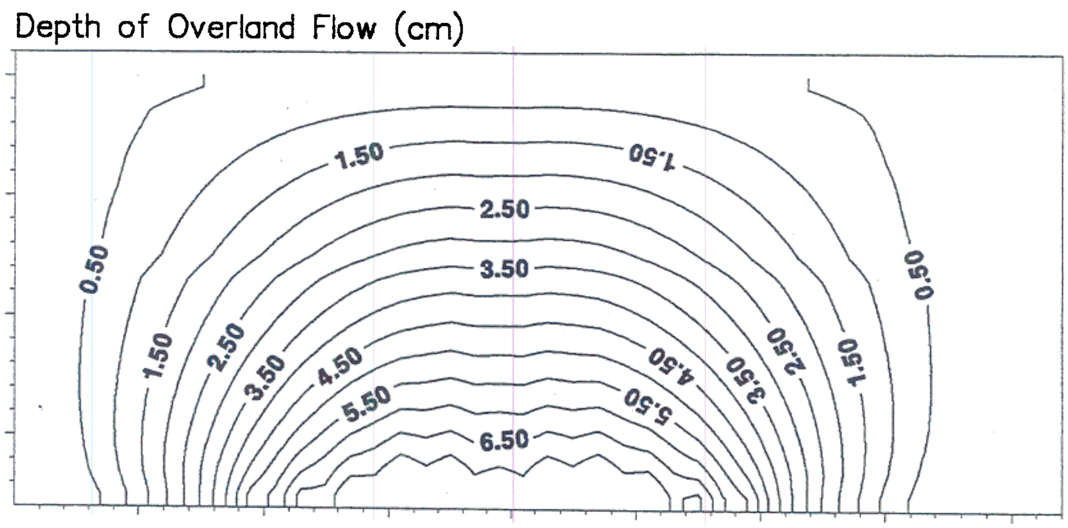


Figure 7: Comparison of Simulated Outflow for Variable and Constant Soil Hydraulic Properties and Topography for East Grid (July 18, 2001) (a) Sampler E-S-1, (b) Sampler E-S-2, and (c) Sampler E-S-3 (CS = constant soil, VS = variable soil, CT = constant topography, and VT = variable topography)



(a) Variable Soil Hydraulic Properties and Topography



(b) Constant Soil Hydraulic Properties and Topography

Figure 8: Comparison of Depth of Overland Flow for Variable and Constant Soil Hydraulic Properties and Topography, East Grid July18, 2001, (a)Variable Soil Hydraulic Properties and Topography and (b) Constant Soil Hydraulic Properties and Topography

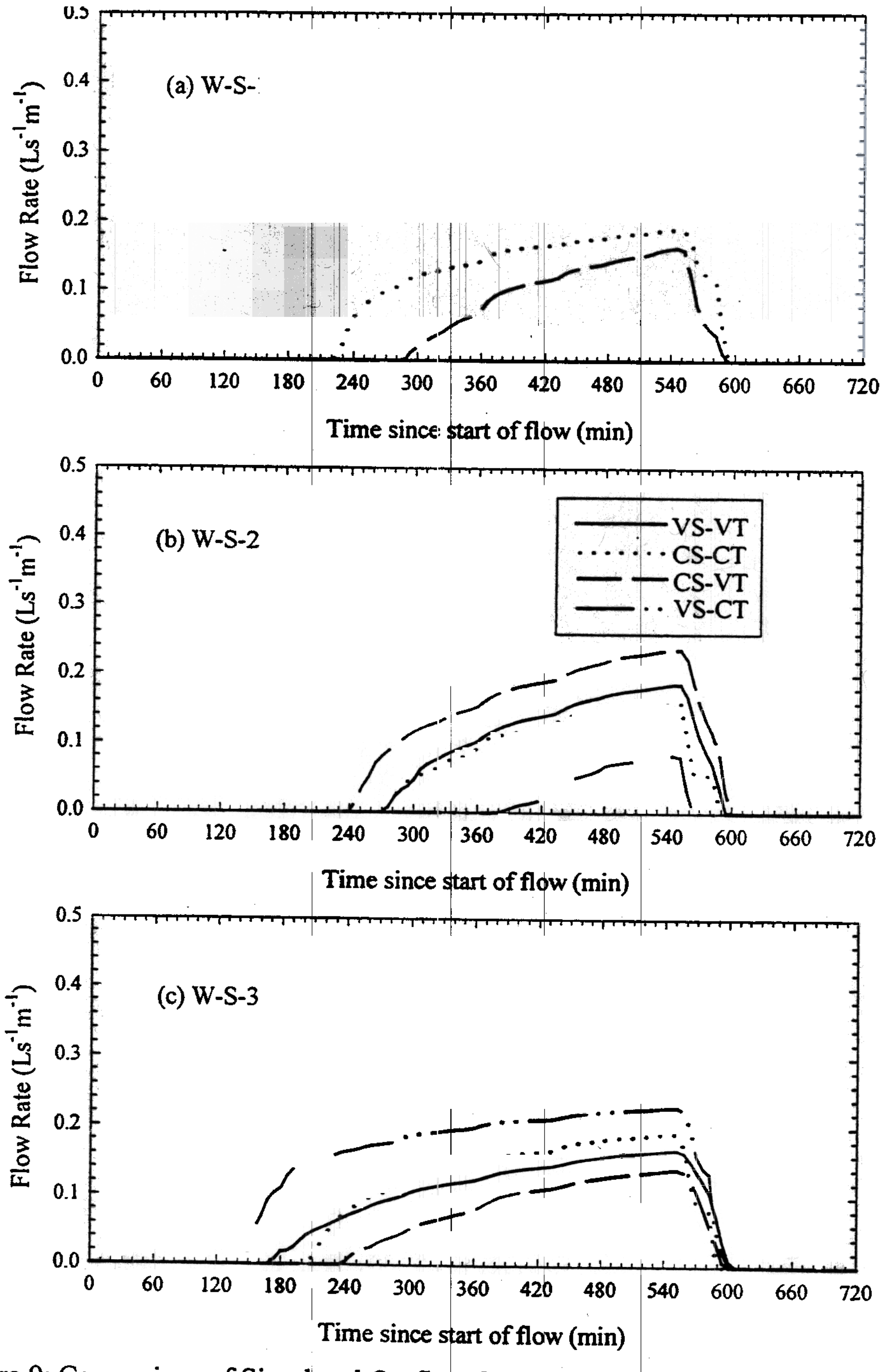
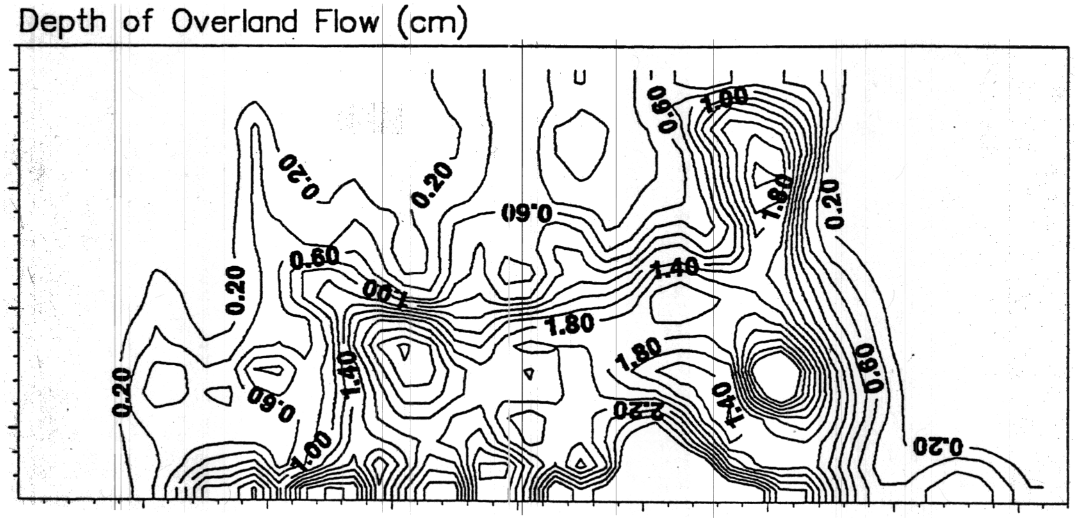
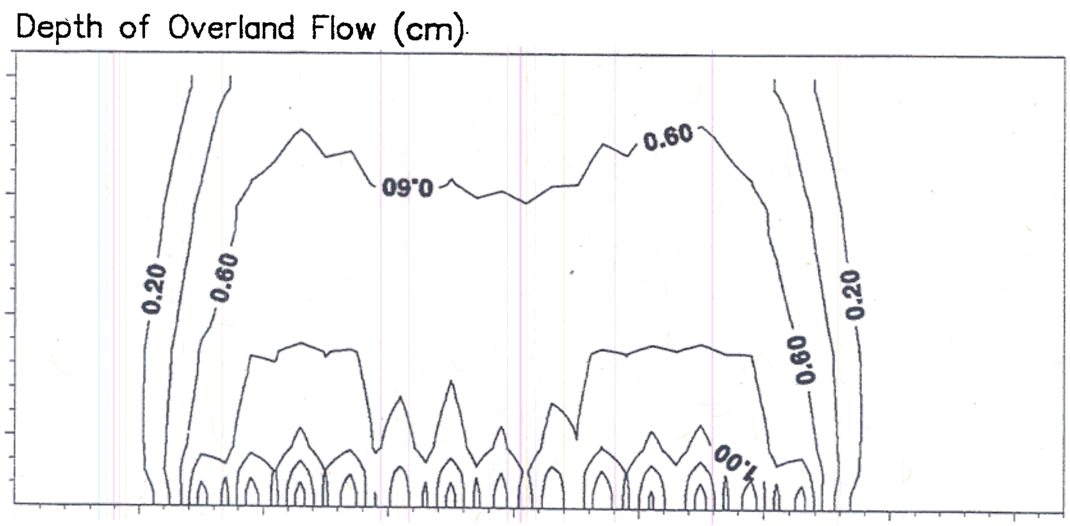


Figure 9: Comparison of Simulated Outflow for Variable and Constant Soil Hydraulic Properties and Topography for West Grid (August 13, 2001) (a) Sampler W-S-1, (b) Sampler W-S-2, and (c) Sampler W-S-3 (CS = constant soil, VS = variable soil, CT = constant topography, and VT = variable topography)



(a) Variable Soil Hydraulic Properties and Topography



(b) Constant Soil Hydraulic Properties and Topography

Figure 10: Comparison of Depth of Overland Flow for Variable and Constant Soil Hydraulic Properties and Topography, West Grid August 13, 2001, (a)Variable Soil Hydraulic Properties and Topography and (b) Constant Soil Hydraulic Properties and Topography