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An Overland Flow Sampler for Use in Vegetative Filters

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Abstract. *Vegetative filters (VF) are used to remove contaminants from agricultural runoff and improve surface water quality. Techniques are needed to quantify the performance of VF in realistic field settings. The goal of this project was to develop and test a relatively simple and low cost method for sampling overland flow in a VF. The 0.3 m wide sampler has the capacity to sample a flow rate of 1.3 L/s and a total runoff volume of about 20 000 L. The sampler was tested in the laboratory, in field experiments, and using a simulation model. Overall the sampler split ratio (SR) is 2180. The SR is essentially constant with flow rate in the range of 0.1 to 1.0 L/s. Computer simulations of overland flow using MIKE SHE indicate that the sampler does not cause significant convergence or divergence of flow when sampling at the downstream edge of the VF. Because of the higher roughness in the VF relative to the row-cropped contributing watershed, longer wing walls are needed to avoid flow convergence when sampling at the leading edge of the buffer. The required length of the wingwall is dependent on land slope, flow rate, and the hydraulic roughness of the filter. The runoff volume and runoff hydrographs that were derived from the sampler agreed well with the measurements taken with flow measurement flumes. Equations were developed to help interpret the data collected with the sampler.*

Keywords. Buffers, vegetative filters, samplers, overland flow.

An Overland Flow Sampler for Use in Vegetative Filters

Introduction

Vegetative filters (VF) are used to remove contaminants from agricultural runoff and improve surface water quality. State and federal cost-share funds are available to encourage landowners to install VF. The USDA-National Conservation Buffer Initiative calls for 3.2 million km of buffers to be installed by the year 2002. Numerous experimental plot and modeling studies have quantified the removal of sediments and other non-point source (NPS) contaminants from agricultural runoff by VF. Almost all of these studies have been conducted under controlled settings, including artificial sheet flow conditions, and using expensive, labor-intensive measurement systems. There is a critical need for simple, low-cost measurement systems that can be used to assess VF performance under realistic field conditions. A simple runoff measurement device would help to quantify and sample overland runoff and contaminant transport while accounting for spatially variable patterns of runoff from fields as they occur in nature.

Contaminants are carried in overland runoff both in solution and attached to sediment. To quantify the removal of a contaminants by a VF, the amount of sediment trapped in the VF as well as the loss of dissolved chemical must be measured. The removal of dissolved chemical from overland runoff is, for the most part related to the amount of water infiltration in the VF. Suspended solids are trapped in the VF because the hydraulic retardance of the vegetation reduces velocity which leads to sediment settling. Forbes et al. (1994) developed sediment boxes or traps that can be placed at the inlet and outlet of VF to quantify the sediment removal. The inlet of these 0.3 m wide boxes is placed at the soil surface so that all flow must go through them and all sediment contained in this runoff sample is presumably retained in the box for measurement after a runoff event. No quantification of infiltration or removal of dissolved contaminants is possible with this system. Sheridan et al. (1996) used Gieb-type multi-slot flow splitters to collect approximately 10 percent of the water that enters the sampler. Robinson et al. (1996) used a V-trough method for splitting flow with each segment of the trough splitting the inlet flow into that section by ½. The concept of these flow splitting samplers, which operate by gravity alone, is to reduce the sampled volume enough so that the reduced volume will fit into a reasonably sized tank for measurement of water quantity and quality.

Many VF are placed in riparian zones which characteristically have gently sloping terrain. Having adequate head or fall for sampling is a problem in this setting. This problem can by overcome by collecting the runoff in a sump and then pumping the water to a higher elevation where it can be split and sampled (Willis et al., 1969; Sourtani et al., 1993; and Ngandu and Mankin, 2002). Ngandu and Mankin (2002) adapted the V-trough splitter technique by using a sump and DC powered pump to sample 1/64th of the flow from a 1 m wide sampling section.

The flow and volumetric capacity of sampling are key design considerations for samplers. The sampler developed by Ngandu and Mankin (2002) can sample a maximum rate of about 0.4 L/s.

The water in their sampler ultimately passes through 6 flow splitting segments before it is split 1 part in 64.

Design Objectives

The goal of this project was to develop and test a relatively simple and low cost method for sampling overland flow in a VF. The sampler was designed to meet flow and capacity requirements for a 25-year 3-hour storm in eastern Nebraska. Rainfall depth is 8.9 cm. For a SCS Runoff Curve Number of 75, a field slope of 1 %, and a field length of 600, peak flow was estimated using HEC-HMS (USCE, 1998) to be 4.7 L/s/m and the runoff depth was 3.8 cm. The resulting runoff volume is 23000 L/m. With a sampling width of 0.3 m, the sampler must handle a minimum flow rate and volume of 1.4 L/s and 7000 L, respectively.

Description of the Sampler

Several alternative designs were developed and tested in year 2000. The current version is shown in Figures 1 and 2. As with the samplers of Willis et al. (1969), Sourtani et al.(1993), and Ngandu and Mankin (2002), a sump and pump are used to lift the water to a higher elevation before the water is split for sampling. Wing walls for minimizing flow divergence and convergence extend 0.5 m upstream of the sump and are place 0.3 m apart and parallel with the flow direction. The wing walls are made of 18 gauge galvanized steel. The 0.46 m diameter by 0.91 m long polyvinylchloride (PVC) sump extends 0.76 m below grade. To remove floating debris, the sump contains a basket screen made of 0.15 m diameter PVC well screen with 1.5 mm slotted openings. The sump pump is powered by a 12V marine battery. The pump capacity is about 1.3 L/s. Two electrodes, spaced vertically 0.3 m apart, control the pump start and stop cycles. Water and contaminants are pumped from the sump into three pairs of orifice-sample tube assemblies placed in series with each other. Each assembly consists of a pair of orifices made of stainless steel, one smaller than the other. The discharge from the smaller orifice flows into the sample tube while the flow from the larger orifices is discharged back to the VF. Since the discharge from the larger orifices in Assemblies A and B can be relatively large and erosive, a corrugated plastic tube is used to convey the water back to the surface of the VF. Vent holes were placed in the upper portion of the tubes to prevent siphoning. The sample tubes are made of PVC pipe. The orifice-sample tube assemblies are designated as assemblies A, B, and C. The size of each orifice and tube sizes and volumes are shown in Table 1. An orifice assembly is illustrated in Figure 3. An 80 mesh strainer is positioned upstream of Assembly C to prevent plugging of these smaller orifices.

The sampler is designed to work as follows. For relatively small runoff events, the split sample is retained in Tube A. For larger runoff events, the split samples are retained in Tubes A and B. For events with runoff volume that exceed the capacity of Tubes A and B, a split of the runoff flows to Tube C. Following a runoff event, the volume of water in each tube is measured and a representative water sample is collected from each tube. With these data, the known characteristics of each splitter assembly, and the necessary equations for analysis, the runoff volume and mass of contaminant runoff can be determined. HOBO® State data loggers are used to record each pump cycle. The volume pumped during each cycle is 54 L. The runoff hydrograph can be developed from the pump cycling data.

The samplers are installed at the leading and downstream edge of the VF. A skid-steer loader equipped with a 0.46-m auger was used to bore the holes for the sump. About 3 person-hours were required per sampler for installation. Originally we felt that the friction between the borehole wall and the sump would be enough to hold the sumps in place. However, we did have problems several times with the sumps floating. In these cases we had to use stakes and wire to keep the sumps in place.

Equations for Data Interpretation

To interpret the results from sampler data, equations were developed for the sampler mass balance. Assuming a 4-stage sampler (3 orifice-sample tube assemblies plus the sump) and a large enough event for flow into Tube C, the volume of runoff per sampled width can be estimated as:

$$V_r = V_s + V_A (SR_A) + V_B (SR_A\ SR_B) + V_C (SR_A\ SR_B\ SR_C) \qquad (1)$$

where: V_r = volume of water runoff through the sampling width,

V_s = volume in the sump,

V_A = capacity of sample tube A,

V_B = capacity of sample tube B,

V_C = volume remaining in sample tube C, and

SR_A, SR_B, and SR_C = split ratios of orifice assemblies A, B, and C, respectively.

The split ratio is defined as

$$SR = \frac{V_{in}}{V_{out}} \qquad (2)$$

where: SR = split ratio for a given assembly,

V_{in} = volume that enters a given assembly, and

V_{out} = volume that flows to the sample tube for a given assembly (from the smaller orifice).

For soluble contaminants, the mass of contaminant runoff is estimated by

$$M_{rs} = C_s V_s + SR_A \{C_A V_A + SR_B [C_B V_B + SR_C (C_C V_C)]\}$$

where: M_{rs} = mass of soluble contaminant runoff

C_S, C_A, C_B, and C_C = concentration of contaminant in the sump and sample tubes A, B, and C, respectively.

The mass of runoff of suspended solids is estimated as

$$M_{rp} = M_{sp} + \frac{}{E_A} \quad (4$$

where: M_{rp} = mass of suspended solids runoff,

M_{sp} = mass of suspended solids in the sump, and

E_A = trapping efficiency of Tube A.

Obviously to apply Equations 1-4 the parameters SR_A, SR_B, SR_C, and E_A must be estimated. SR parameters will be discussed in the next section. Experiments to evaluate E_A are currently being planned.

Experimental Results

Split Ratios. Laboratory tests were conducted to determine the SR for each orifice assembly and the variability of the SR as flow rate changes. The data were collected by measuring the volume of discharge from the larger and smaller orifices over a known time period. The results are illustrated in Figure 4 and summarized in Table 2. These results are for the range of flows tested. The SR is relatively constant with changing flow rate with the average SR being 10.3, 18.6, and 11.4 for Assemblies A, B, and C, respectively. During these tests, the larger and smaller orifices of each assembly were at the same elevation except those for Assembly C. To obtain a uniform and consistent split in Assembly C we found that the discharge pipe from the smaller orifice has to be 1.8 mm lower than the discharge pipe from the larger orifice. We believe that this is because of the effects of surface tension on the depth of flow in the pipe on the downstream side of the smaller orifice.

Using the SR obtained here, Equation 1 and the volumetric capacity of each tube, the volume of runoff that will exactly fill each sample tube were calculated. The results are shown in Table 2.

Runoff Hydrograph. The samplers have been applied at two VF study sites in Nebraska including the site described by Helmers et al. (2001). At this site, inflow to the VF is from a furrow-irrigated field. With selected furrows runoff is measured with a 60° V-notch flow measurement flume before it enters the sampler in the same furrow on the upstream edge of the VF. For several irrigation runoff events, a hydrograph was developed for the flumes by recording head and time at regular intervals during a runoff event. The logged data of sump pump operation was also used to develop a runoff hydrograph for the overland flow sampler. In Figure 5 we illustrate the runoff hydrograph obtained by the two methods during one event. The flume and overland flow sampler methods produced essentially equal hydrographs. In Figure 6 we illustrate the accumulated volume of runoff, calculated using trapezoidal integration of the hydrograph, based on the flume data and the overland flow sampler data. Again, the results from the two methods appear to agree well.

Flow Convergence and Divergence

One concern regarding the application of the overland flow sampler is the potential of biased data because of either flow convergence or divergence in the vicinity of the sampler. This is of particularly concern at the upstream edge of a VF. If water is leaving a field whose hydraulic roughness is less that the roughness of the VF, the water will pond at the entrance to the VF. If a sampler is located at this point, it could act as a drain because of the lower resistance to flow through the sampler compared to flowing through the VF.

We simulated overland flow using MIKE SHE to evaluate the potential problem of convergence. 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) that we used is the main module of MIKE SHE. 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. MIKE SHE allows for separate overland flow areas so that there is not flow between adjoining cells. To simulate flow to a sampler, separate overland flow areas were defined on either side of the intended location of the sampler to represent the presence of wing walls with each separate area having a width equal to the grid discretization. If the sampler width was one discretization in width and the wing walls were one discretization wide then if no convergence of flow occurred one might expect twice as much flow into the sampler due to the effect of the width of the wing wall. For the cases where the sampler was positioned at the upstream edge of the VF, the boundary of the domain was in the cell directly downstream of the sampler location. This differed from the rest of the VF domain and allowed for simulation of water flow leaving the system through the sump. For these cases the wing walls extended from the downstream edge of the VF to upstream of the sampler location. The distance that the wing walls extended upstream depended on the condition being considered. For some cases where the sampler was positioned at the upstream edge of the VF the wing walls were extended a fairly large distance (up to 10 m) upstream of the sampler location. Simulations were performed for field and VF slopes of 1 and 5%, Manning's roughness in the field of 0.04, roughness in the VF of 0.1 and 0.2, and flow length through the VF of 5 and 15 m. Rainfall intensities were 25 and 50 mm/h. The grid discretization used for all the simulations was 1 m.

At the downstream edge of the VF there was little convergence of flow. In fact, some of these simulations with the sampler positioned on the downstream edge of the VF had negative values for convergence which indicated a slight divergence of flow (<10%). This may possibly be due to the width effect of the wing walls in the MIKE SHE simulations. In the simulation the wing walls had a finite width, one grid spacing, while in reality the wing wall width is almost negligible. Thus, in the simulation, the flow in one grid spacing was blocked and forced to flow either through the sampler or outside of the sampler. This could cause the simulated flow to diverge away from the sampler.

When reviewing the simulations for the overland flow sampler at the upstream edge of the VF, there was significant convergence to the sampler in some conditions. The results are summarized in Figure 7. For the cases when the slope was 5% there was negligible convergence but when the slope of 1% there was convergence. Positioning the upstream edge of the wing walls further upstream into the field area reduced the convergence. In effect this was positioning the sampler upstream of the VF. It is evident that for the lower slope conditions the distance upstream to position the sampler is related to the ratio of the wing wall length (distance upstream of VF edge to the edge of the wing wall) and the approximate distance upstream from the filter edge to reach the normal depth of flow in the field area. We call this length ratio the dimensionless wing wall length. The distance to normal depth in the field is the distance of a horizontal line that projects upstream from the water surface elevation at normal depth at the VF entrance to the point of intersection with the water surface at normal depth in the field. From the analysis performed, to minimize convergence of flow to the overland flow sampler especially in low slope conditions the sampler may need to be positioned upstream of the VF-field edge.

Summary and Conclusions

Vegetative filters (VF) are used to remove contaminants from agricultural runoff and improve surface water quality. Techniques are needed to quantify the performance of VF in realistic field settings. The goal of this project was to develop and test a relatively simple and low cost method for sampling overland flow in a VF. The 0.3 m wide sampler has the capacity to sample a flow rate of 1.3 L/s and a total runoff volume of about 20 000 L. The sampler components include wing walls and a collection sump for capturing overland flow, and a DC powered sump pump. From the sump the water is delivered to orifice-sample tube assemblies (Assemblies A, B, and C) where the water is split into two parts, one part that goes to the sample tube from the smaller orifice and the other part from the larger orifice is delivered back to the VF. The three assemblies are connected in series.

The sampler was tested in the laboratory, in field experiments, and using a simulation model. The split ratio, volume of water into an orifice assembly divided by the water that goes to the sample tube, averaged 10.3, 18.6, and 11.4 for Assemblies A, B, and C, respectively. Thus the sampler is capable of an overall split ratio of 2180. The SR is essentially constant with flow rate in the range of 0.1 to 1.0 L/s. In a field experiment, runoff volume and runoff hydrographs based on the sampler data agreed well with the measurements taken with flow measurement flumes. Equations were developed to help interpret the data collected with the sampler. Computer simulations of overland flow using MIKE SHE indicates that the sampler does not cause significant convergence or divergence of flow when sampling at the downstream edge of the VF. Because of the higher roughness in the VF relative to the row-cropped contributing watershed and the resulting ponding of surface water runoff, longer wing walls are needed to avoid flow convergence when sampling at the leading edge of the buffer. The required length of the wing wall is dependent on land slope, flow rate, and the hydraulic roughness of the VF.

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Table 1. Characteristics of orifice-sample tube assemblies.

Assembly	Orifice Diameter Small	Orifice Diameter Large	Sample Tube Nominal Diameter	Volume Held in Sample Tube
	(mm)	(mm)	(mm)	(L)
A	12.7	34.5	100	
B	3.45	15.1	100	
C	0.81	3.45	150	8.52

Table 2. Summary of split ratio data for orifice assemblies and runoff volumes required to fill each assembly.

Assembly	Average Split Ratio	Standard Deviation	Volume of Runoff Before Field
			(L)
A	10.3	0.247	75
B	18.6	0.308	
C	11.4	0.672	19551

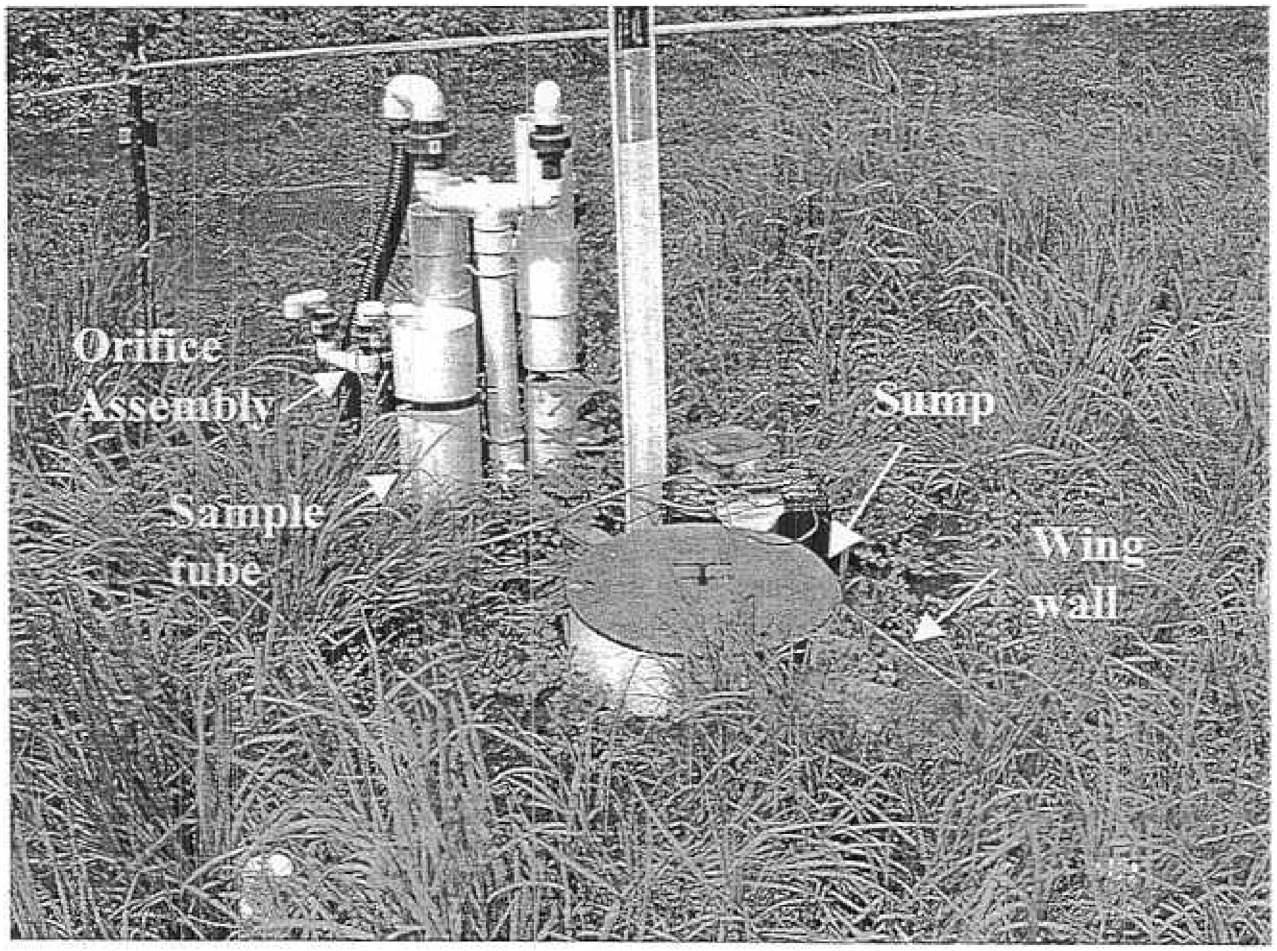

Figure Overland flow sampler installed in field.

Figure 2. Entrance to overland flow sampler.

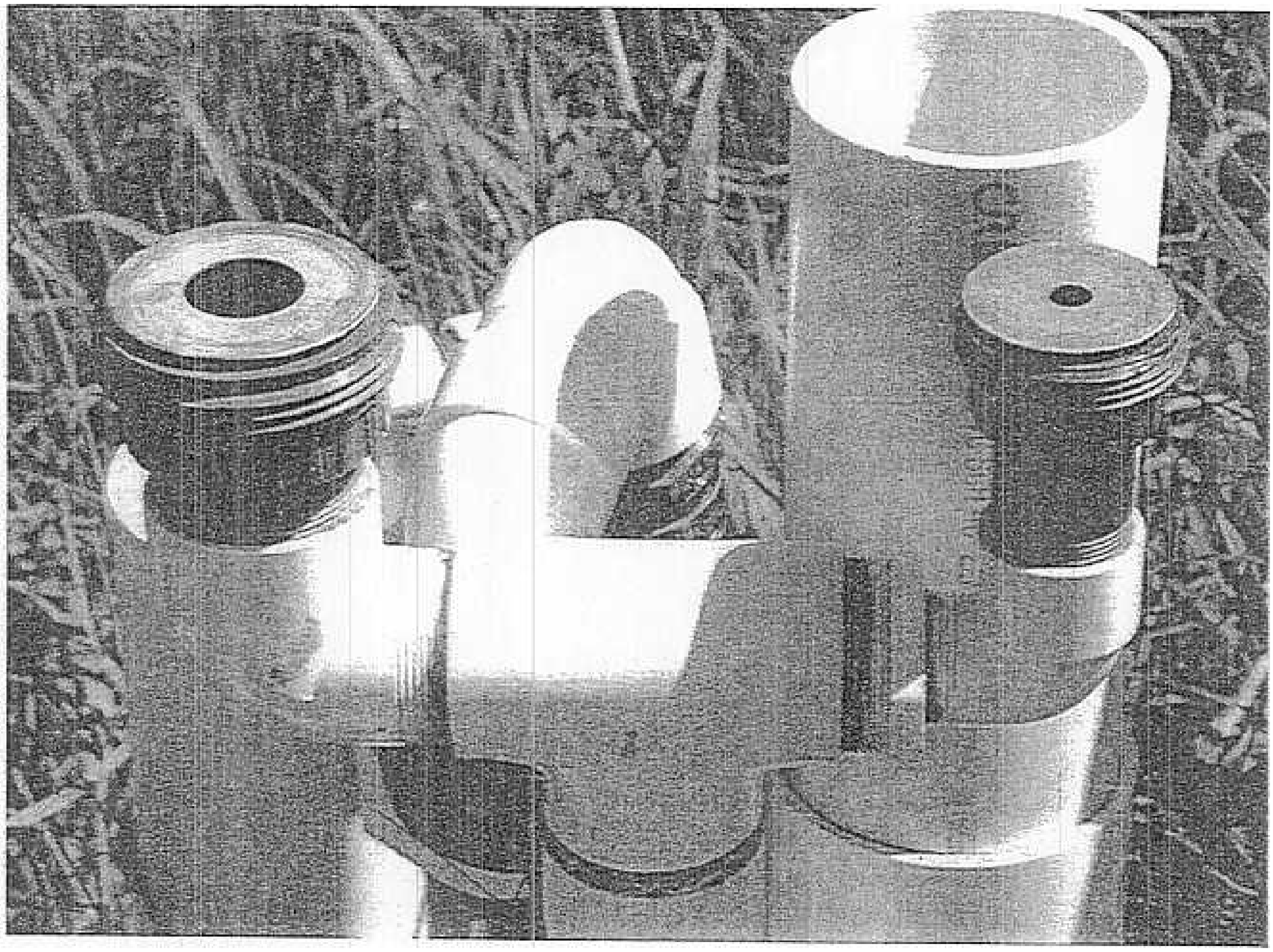

Figure Orifice assembly

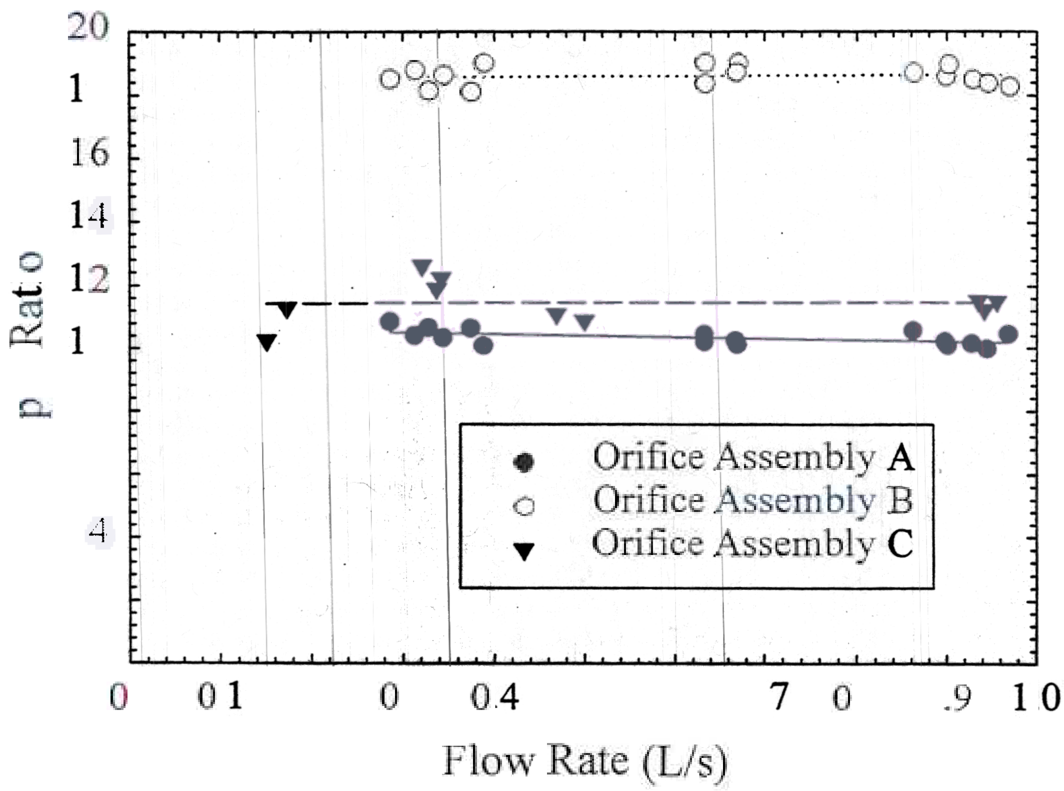

Figure Split ratio for each orifice assembly function sampler flow rate

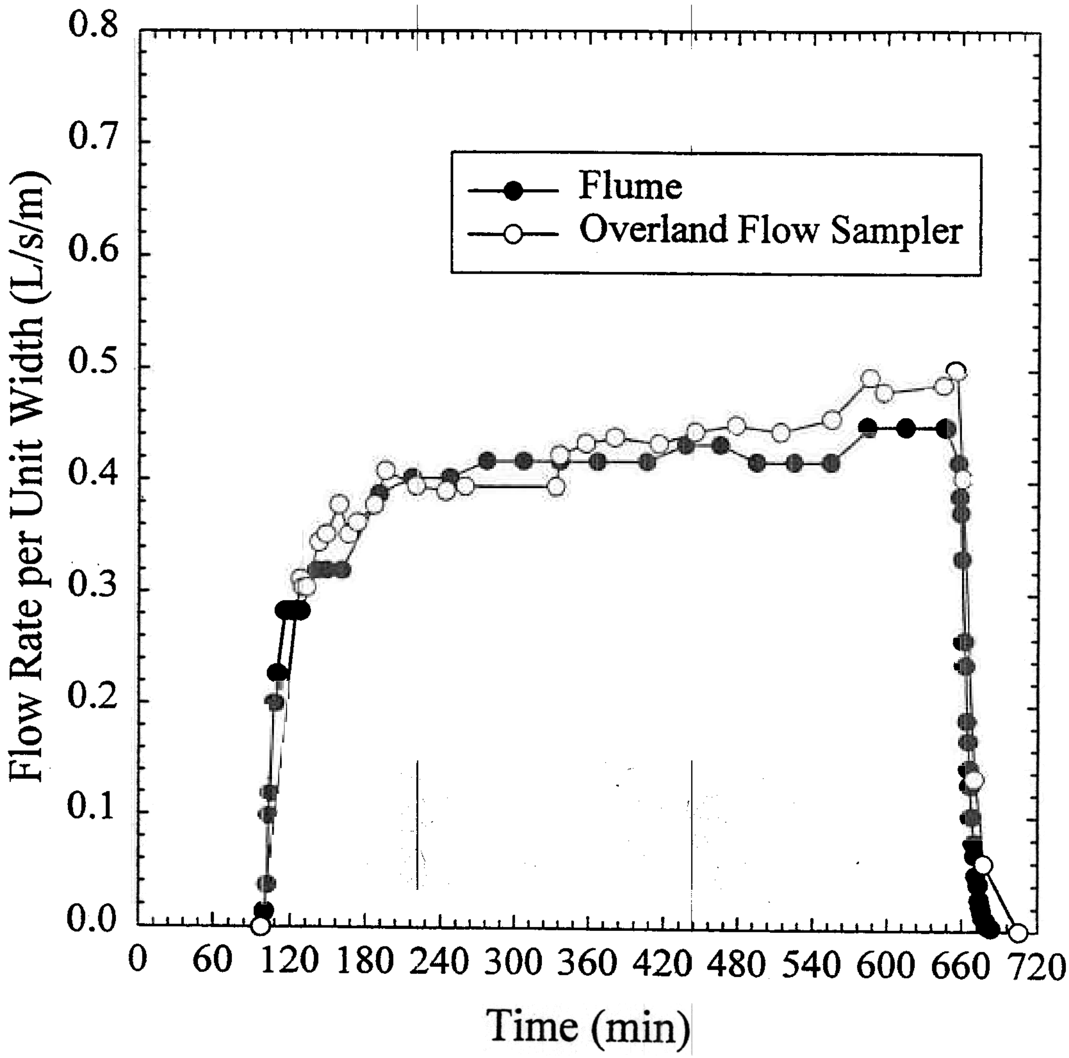

Figure 5. Runoff hydrograph device from V-notch flume and overland flow sampler.

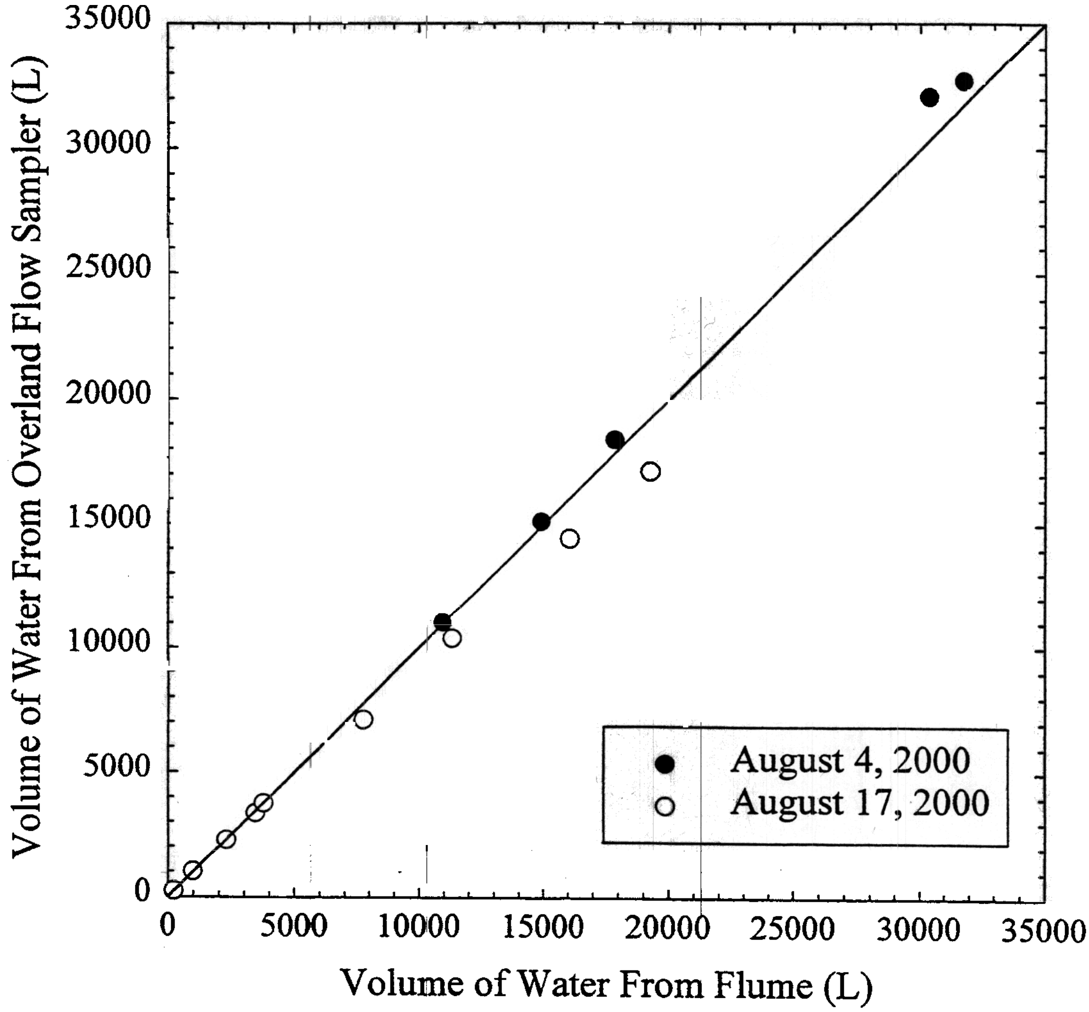

Figure 6. Cumulative runoff volume from V-notch flume and overland flow sampler.

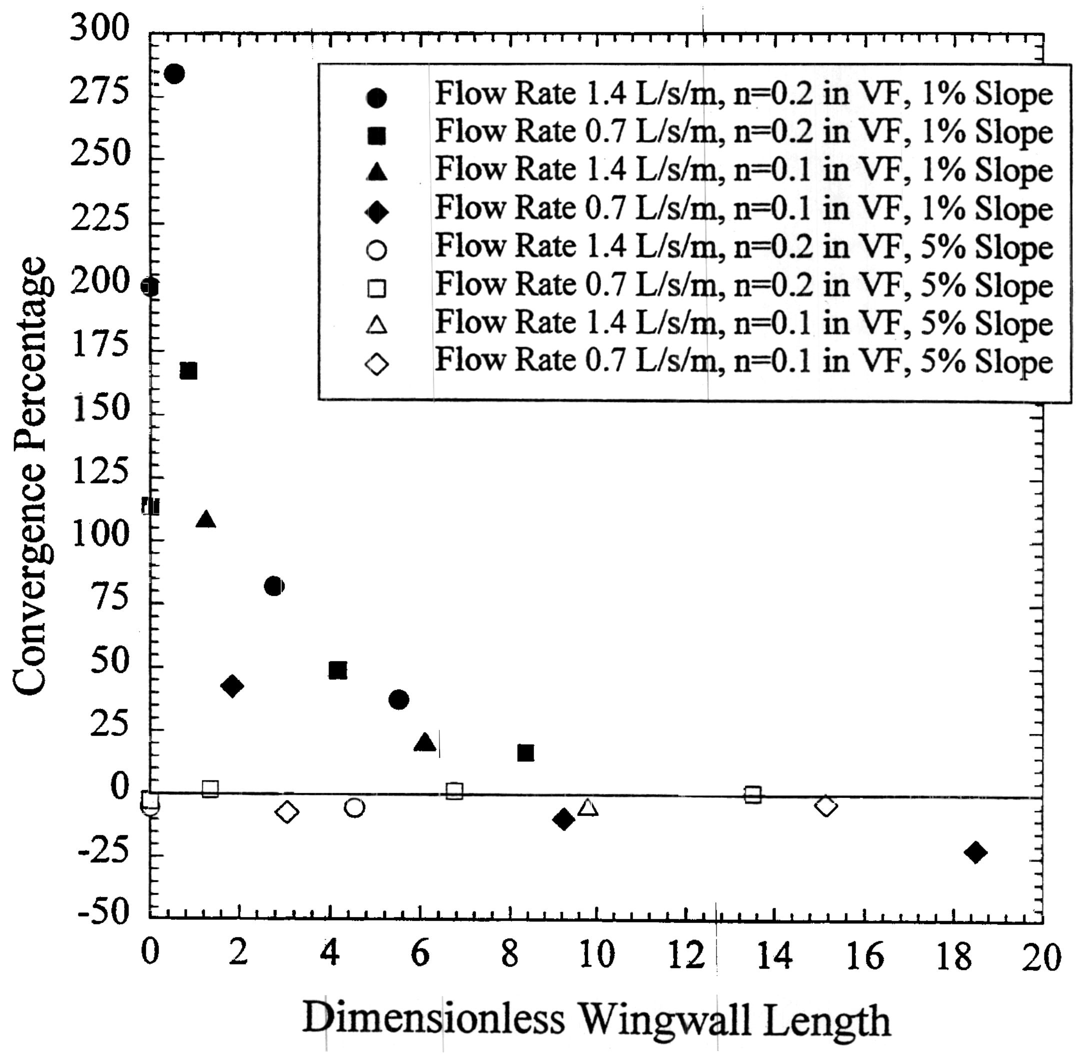

Figure 7. Convergence to overland flow sampler.