Technical Report

CRWR 223

RECIRCULATING FURROW INFILTROMETER DESIGN GUIDE

CENTER FOR RESEARCH IN WATER RESOURCES
BUREAU OF ENGINEERING RESEARCH

College of Engineering
The University of Texas at Austin
Austin, Texas

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Recirculating Furrow Infiltrometer Design Guide

by

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Prepared under the auspices of the

W-163, Surge Flow Surface Irrigation
USDA Cooperative Regional Research Project

February 1989

CENTER FOR RESEARCH IN WATER RESOURCES

Bureau of Engineering Research • College of Engineering
The University of Texas at Austin • 10100 Burnet Road • Austin, Texas 78758-4497

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1. INTRODUCTION AND APPLICATIONS

Determination of infiltration parameters is critical for the design and operation of efficient furrow irrigation systems. The complexity of the physical processes which govern infiltration in furrows, and the nonhomogeneous, anisotropic conditions which often exist in irrigated fields, have hindered the development of an infiltration theory which can accurately predict infiltration rates based on easily measured soil parameters. Therefore, the practicing irrigation engineer continues to depend on direct measurement of infiltration using infiltrometers or volume balance methods for determining field infiltration during continuous flow or surge flow furrow irrigation. Volume balance methods use advance, surface storage, inflow, and outflow data collected during an irrigation event to determine the infiltration parameters. Elliott and Eisenhauer (1983) outline the details of several volume balance methods for continuous flow irrigation. Latortue (1984) outlines a volume balance technique for estimating infiltration and surface storage for surge flow irrigation. The infiltration parameters determined from these methods are likely to be more representative of average field conditions than data obtained from an infiltrometer.

Infiltrometer tests have been extensively used for several decades and have the advantage over volume balance methods in that data analysis requirements are not as great. Infiltrometer data are usually collected from a small areal sample of the irrigated field. Thus, infiltrometer data can be significantly affected by the random and structured spatial variability of soil infiltration characteristics. Nonetheless, field experiments using a recirculating infiltrometer can be designed to test theoretical hypotheses concerning both continuous and surge flow infiltration. Several infiltrometer tests, each with a systematic change in an experimental parameter (such as flow rate), can be performed in a small section of field. This group of tests, each in close proximity and randomly ordered so as to minimize structural spatial variability, assists in analyzing the effect of an experimental parameter (such as flow rate) on infiltration. Such tests can also be carried out using volume balance tests, but with considerably more effort. Because of the small amount of labor required, infiltrometer tests are often used for both applied and experimental infiltration data collection.

Double ring and blocked furrow infiltrometers are commonly used in surface irrigation research. However, as Walker and Willardson (1983) noted, these infiltrometers do not reflect the hydraulic characteristics of an actual irrigation. Thus, the flowing or recirculating infiltrometer, which simulates the hydraulics of an irrigation, is often the preferred infiltrometer for use in furrow irrigation infiltration measurement. In determining surge flow infiltration, a recirculating infiltrometer is a necessity due to the relationship between flowing water and the surge flow infiltration phenomena.

The recirculating furrow infiltrometer (RFI) can be used for measurement of both continuous flow and surge flow infiltration. The operation of the RFI is similar for both of these applications, the primary difference being that the inflow during surge flow tests is periodically interrupted and the water stored on the surface of the soil is allowed to drain. Analysis of continuous flow RFI data is straightforward and analogous to analysis of ring and blocked furrow test data. However, surge flow RFI data require determination of the amount of water stored on the soil surface, infiltration during advance, and recession of water within the test section.

Furthermore, the RFI can be used for measuring infiltration and investigating the effect of wetted perimeter, stream velocities, and sediment transport on infiltration. This versatility makes the RFI useful to both practicing and research engineers and technicians. The objective of this report is to identify and outline some of the field procedures, data analysis methods, and design suggestions for the recirculating, or flowing, furrow infiltrometer. This report can also be used as a field guide for construction and operation of recirculating infiltrometers.

2. CONFIGURATIONS

Three recirculating infiltrometer configurations are outlined in this section. These configurations cover the major types of RFI currently used in irrigation research. Typically, an RFI is custom manufactured by the individual researcher; thus, each infiltrometer has particular features. However, these three configurations represent the major differences between RFI designs and should serve as a basis for most custom designs.

All RFI systems have five components in common: 1) a water storage reservoir; 2) an upstream head box; 3) a downstream sump box; 4) a pump(s) to recirculate water; and 5) hoses and valves connecting items 1 through 5. The primary difference among these three configurations is the pumping system used to recirculate water. The first configuration consists of a single centrifugal pump (SC), the second of a single screw pump (SS), and the third uses two centrifugal pumps (TC). The merits and disadvantages of each of these configurations are discussed in sections 2.1 through 2.3.

2.1 Single Centrifugal Pump RFI

The single centrifugal pump (SC) RFI is the simplest in design and operation of the three RFI configurations. The schematic of this RFI is shown in Figure 1. The centrifugal pump recirculates water between the downstream sump and the upstream head box, and a constant water level in the downstream sump is maintained using a float valve which is supplied by gravity flow from the supply reservoir.

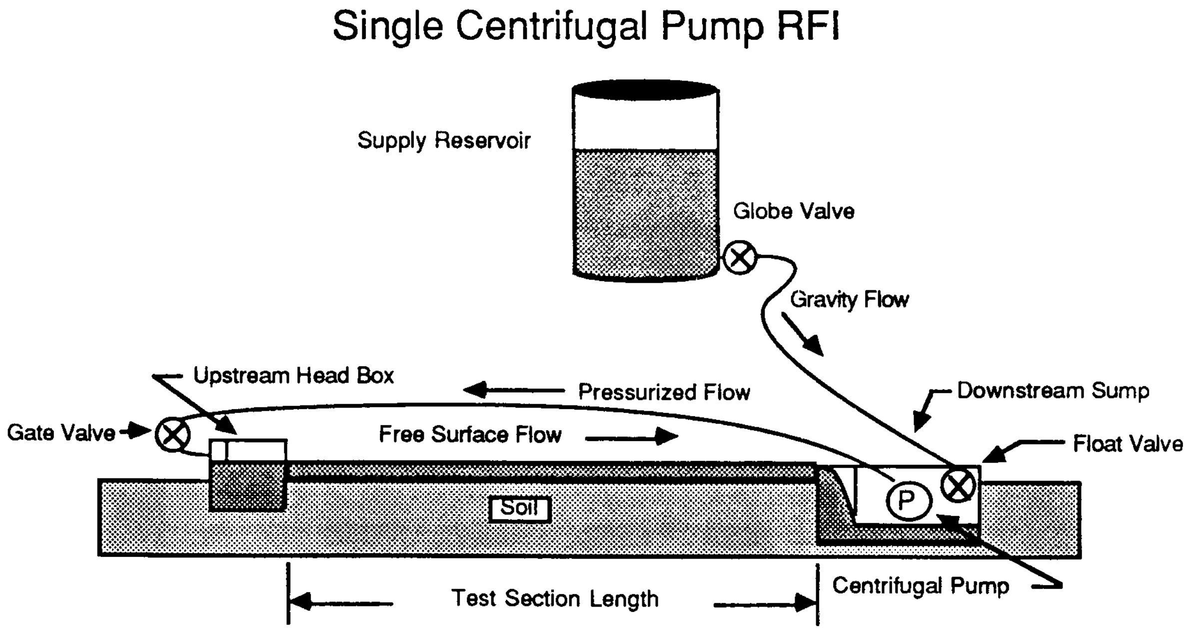

Figure 1. Single Centrifugal Pump RFI - Flow Diagram

The primary advantages of this system are low power requirements, low cost, and simplicity of operation. However, the accuracy of SC RFI in determining infiltration rates is often limited by the accuracy with which the downstream sump water level is maintained by the water level valve and the gravity-controlled water supply line. Additional valves, piping, and/or constant head reservoirs are also necessary to control the recirculating water flow rate and to measure the volume of runoff after inflow of water has stopped. Because of these disadvantages, it may be difficult to accurately determine the infiltration rates, averaged over small time periods, which are often required to analyze surge infiltration. The components of the SC RFI are outlined in the following paragraphs.

Supply Reservoir. The supply reservoir should be large enough to meet the expected volume of water which will infiltrate during the test. Typically, this reservoir holds between 55 and 200 gallons. A 3/4-inch gate valve and hose are used to convey the water to the float valve in the downstream sump. Valves and hoses smaller than 3/4-inch should be avoided because they may restrict the flow rate during the first part of the test when the infiltration rate is very large.

Upstream Head Box. The purpose of the upstream head box is to reduce flow velocity and align the flow with the channel. The head box should be designed to meet these criteria, to prevent any leakage around the box, and yet be easy to install. Typically, the head box sits a few inches down in the soil. A cutoff plate which extends five or more inches into the soil is installed on the front of the box to prevent water from seeping under and around the box.

Centrifugal Pump. A 1/20 horsepower, (12 VDC) or 1/3 horsepower, (115 VAC) centrifugal sump pump can be used to recirculate water. A submersible pump is recommended but not required. If a submersible pump is used, it must be able to operate when only partially submerged without overheating. The pump should be wired to operate continuously with an on/off switch located away from the sump.

Downstream Sump and Flow Valve. The downstream sump should be capable of holding the volume of water needed to prime the sump pump without backing water into the furrow (typically 2 to 5 gallons). This sump must be installed into the soil a sufficient depth (typically 5 to 9 inches) to allow for weir controlled flow into the sump. An adjustable weir is installed at the inlet to the sump to provide a means of controlling the flow depth in the furrow. A trash screen and a sluice can be placed between the weir and the pump to provide a means of removing large and floating debris from the water.

2.2 Single Screw Pump RFI

The single screw pump (SS) RFI was designed to minimize the alteration of sediment contained in the recirculated water. The schematics of this infiltrometer are shown in Figures 2a through 2d. The screw pump provides the required lift to the flow with a minimum change in flow velocity and pressure.

The primary advantage of this system is the minimal effect of the pumping system on sediments in the recirculated water. A major disadvantage is the complexity and custom construction of the pump. Also, the SS RFI is similar to SC RFI in that the accuracy of the SS RFI in determining infiltration rates is often limited by the accuracy with which the downstream sump water level is maintained. Additional equipment and measurements are required to determine the volume of runoff which occurs after inflow of water has stopped. Because of these disadvantages, it may be difficult to accurately determine the infiltration rates over small time periods, which is often required to analyze surge infiltration. The components to the SS RFI are discussed in the following paragraphs.

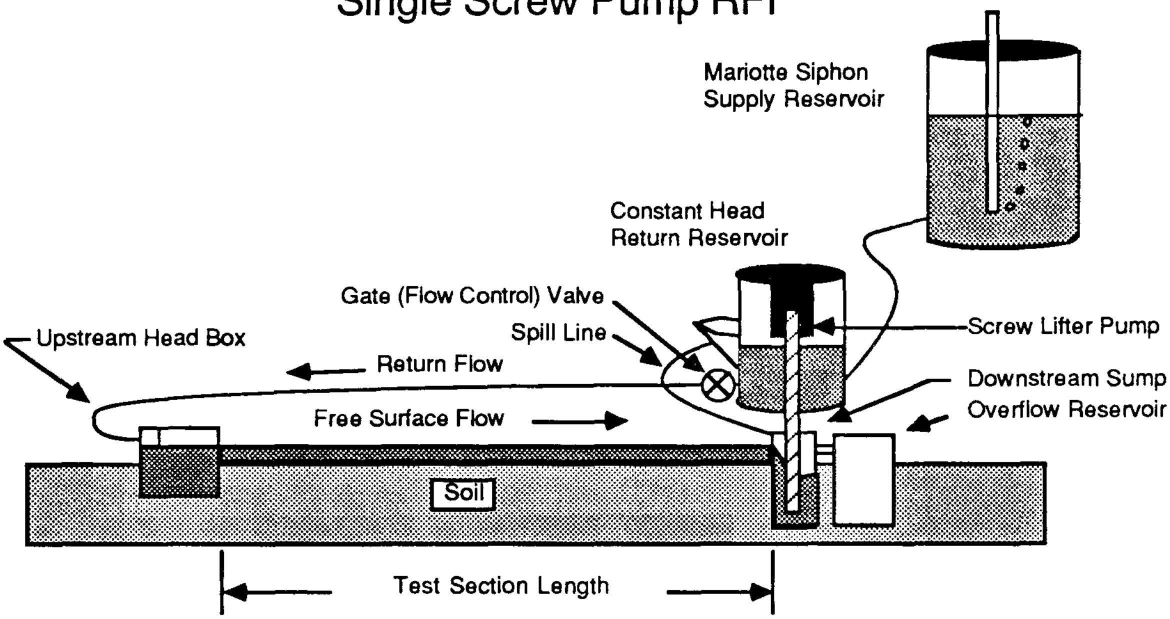

Figure 2a. Single Screw Pump RFI - Flow Diagram

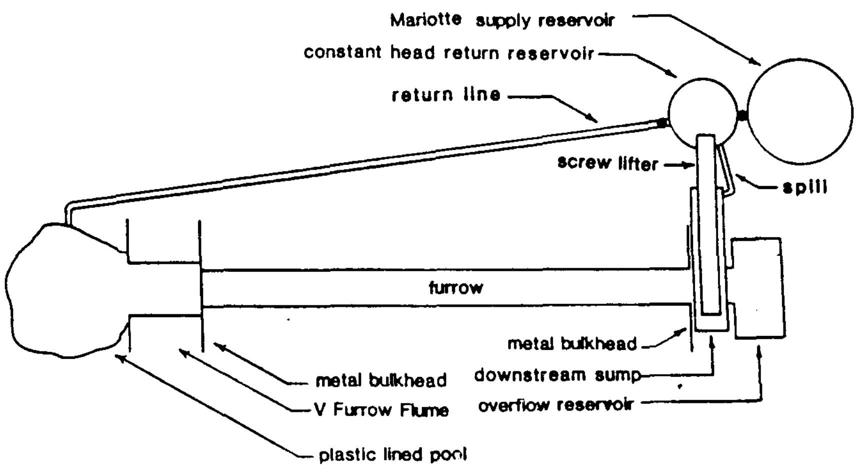

Figure 2b. Single Screw Pump RFI - Plan View

<u>Constant Head Return Reservoir</u>. This item can be made from a section of 10-inch PVC pipe and 3/8-inch PVC sheeting. The bottom is bent into a V shape to direct sediment into the return line. An overflow spill is attached to the side. A 1 1/2-inch gate valve and flexible return tubing are used for the return line. The gate valve is used to control the flow from the constant head reservoir.

<u>Screw Pump</u>. This pump is made from a 6-inch grain auger (5 1/2-inch outside diameter) with a 1/2-inch rubber tubing, split down the length and fit over the outer edge. The auger is mounted in a 6-inch PVC pipe which is split and tightly clamped

around the auger. The screw length is a function of the required lift and flow rate (see Figure 1). A PVC lip ring is glued to the top to prevent water from running back down the outside of the pipe. A brass pin is press fit into the auger center shaft at the lower end of the pump. This pin rides in a nylon bearing mounted in the downstream sump. A pulley is mounted near the top of the screw and is used to connect with the driver. The auger is rotated by rolling the pipe on its axis.

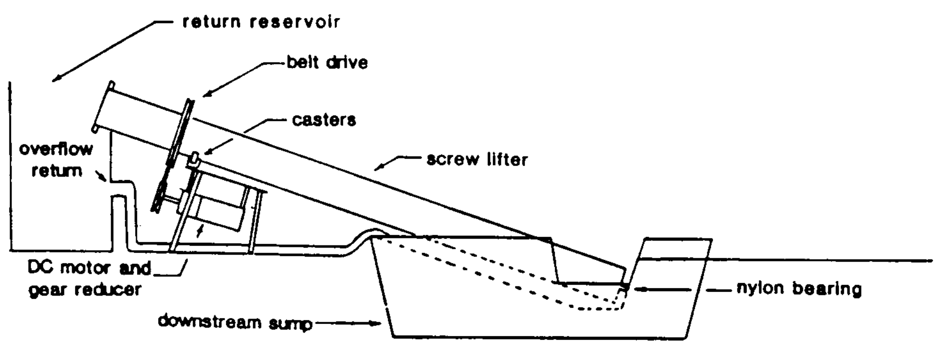

Figure 2c. Single Screw Pump RFI - Profile View of Sump

Driver. The screw pump rides on two rolling casters attached to a three-legged platform. A 1/14 horsepower DC motor with a 35:1 gear reducer is attached under the platform and drives the screw pump with a belt. With a 2:1 pulley diameter ratio, screw speed can be varied between about 110 RPM at 12 VDC and 70 RPM at 8 VDC. The motor draws approximately 5 amps at 12 VDC and will operate off a typical automotive battery at full speed for about 10 hours. The screw capacity, Q (liters/minute), varies inversely with the screw slope, s (percent), and is proportional to the speed, R (RPM). The 6-inch screw flow rate, with between 50 and 90 percent of the inlet submerged, is

$$Q = R\,[1-(s/60)]^{1/2} \qquad (1)$$

Mariotte Siphon Supply Reservoir. This reservoir can be constructed from any cylindrical barrel rigid enough to hold 2 psi suction without collapsing. The reservoir should have a volume great enough to meet the expected infiltration requirements for the test. Typically, a volume between 55 and 200 gallons is sufficient. The outlet of the reservoir is connected to a 3/4-inch gate valve and hose. A 2-inch hole is cut in the top for adding water and is plugged with a rubber stopper during operation. A 1/2-inch acrylic tube bubbler is inserted through the stopper. The bottom of this tube establishes the constant head in the reservoir and thus must be adjusted to the desired water surface elevation in the return reservoir. A manometer is attached to the outside of the Mariotte siphon reservoir for a visual indication of water level. The ends of the manometer can be attached to a differential pressure transducer which is used with an electronic data logger to record water level at periodic time intervals.

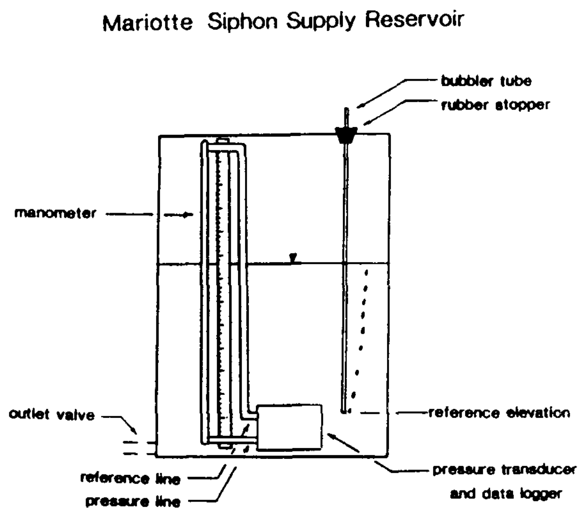

Figure 2d. Single Screw Pump RFI - Supply Reservoir

<u>Downstream Sump</u>. This sump can be made from 16 gauge steel with 1/2-inch angle iron reinforcement at the top front edge. This reinforcement is needed to protect the sump from the hammering required during installation. A bulkhead is attached to the front to reduce leakage. A nylon bearing is attached inside the sump for supporting

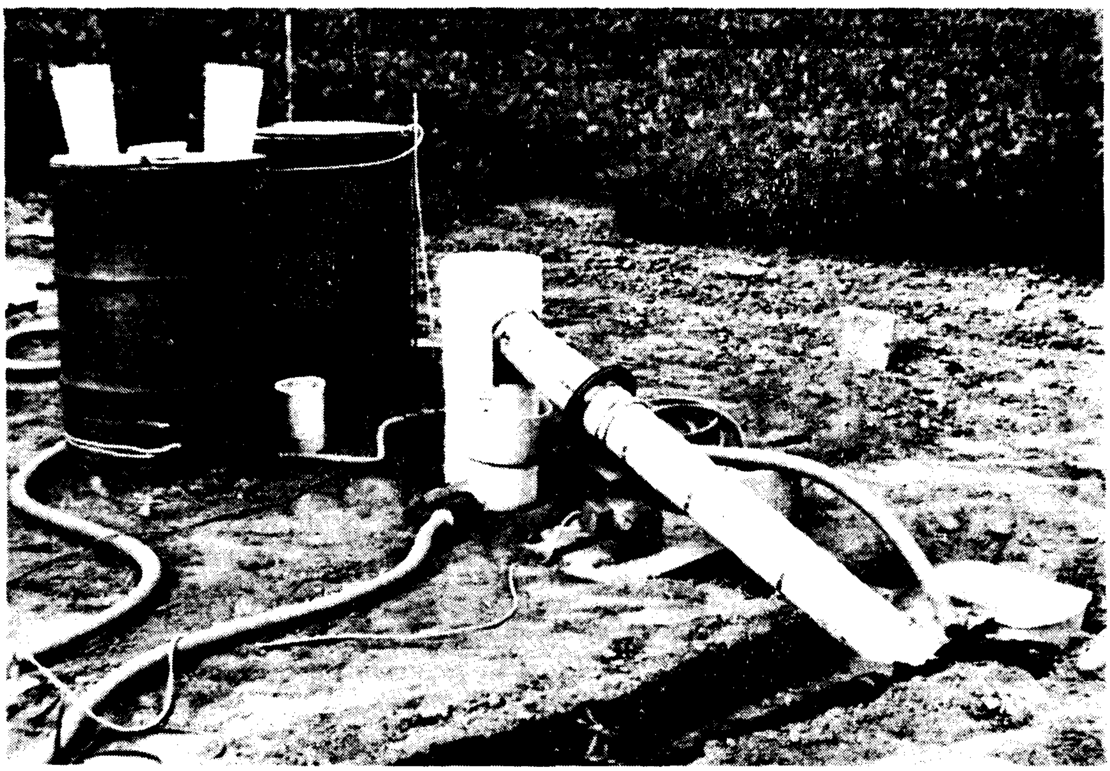

Figure 2e. Single Screw Pump RFI - Photograph

the screw pump. An overflow reservoir is used to drain water from the furrow during surge flow off periods. A metal cutoff plate with a furrow shaped top edge is inserted into the soil against the front of the bulkhead to establish downstream furrow cross-section conditions.

2.3 Two Centrifugal Pump RFI

The two centrifugal pump (TC) RFI differs from the SC RFI and SS RFI in that all recirculated water passes through the supply reservoir prior to being pumped back to the head box. The schematics of this infiltrometer are shown in Figures 3a through 3c. The advantage of this system is the positive control over supply flow rate which enables precise measurement of infiltration rates. Furthermore, the volume of runoff which drains from the furrow after inflow has stopped can be directly measured in the supply reservoir. The disadvantage of the TC RFI is the extra power (cost of generators) and equipment required to use the second pump.

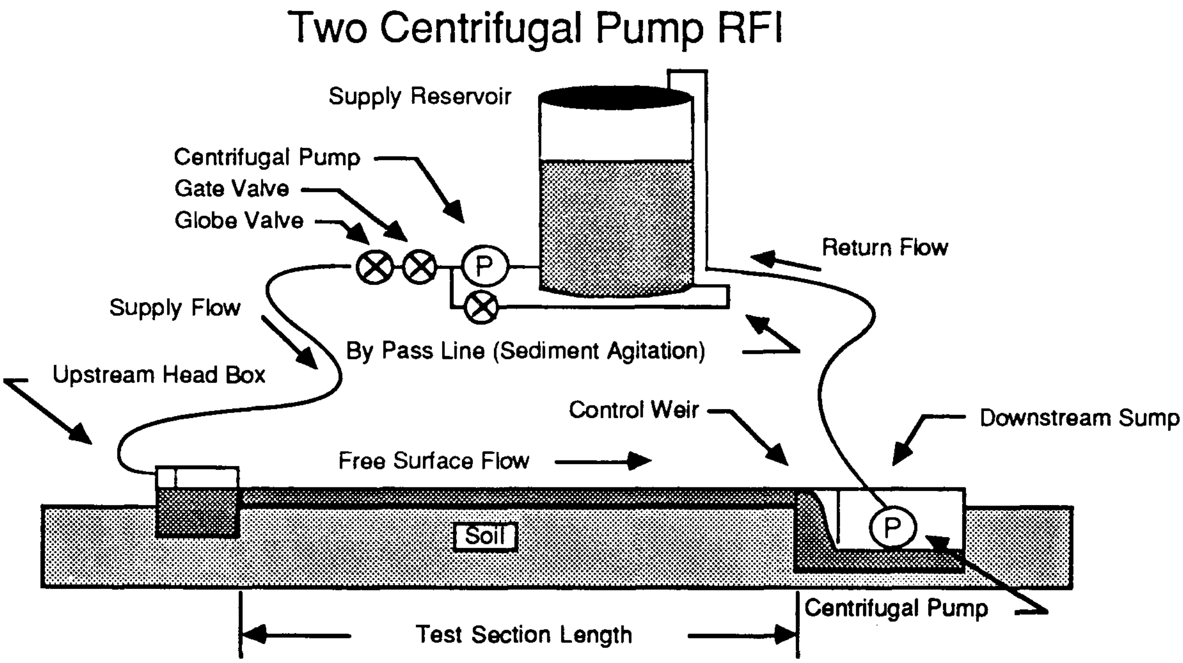

Figure 3a. Two Centrifugal Pump RFI - Flow Diagram

Supply Reservoir. The supply reservoir should be large enough to meet the expected volume which will infiltrate during the test. Typically, this reservoir holds between 55 and 200 gallons. A 3/4-inch or larger outlet and hose are used to connect the reservoir to the supply pump. The return flow from the downstream sump is introduced at the top of the reservoir to prevent back siphoning. A low-level inlet on the reservoir connects the bypass line from the supply pump. The flow from the bypass line is used to agitate sediment which tends to collect on the bottom of the reservoir. Furthermore, the bottom of the reservoir should be tapered to assist in channeling sediment into the outlet. A water level sight tube and pressure transducer can be connected to the outside of the reservoir.

Centrifugal Supply Pump. This pump is typically a one-third horsepower 115 VAC centrifugal pump (swimming pool type). The outlet of the pump is connected to a gate valve and a bypass line. The bypass line provides flow to agitate sediments which tend to collect on the bottom of the reservoir and prevents the supply pump from running dry when the inflow to the furrow is shut off. The gate valve connects to the supply pump and is used to adjust flow rates. The globe valve which is connected to the gate valve is used to shut off inflow to the furrow during surge flow tests.

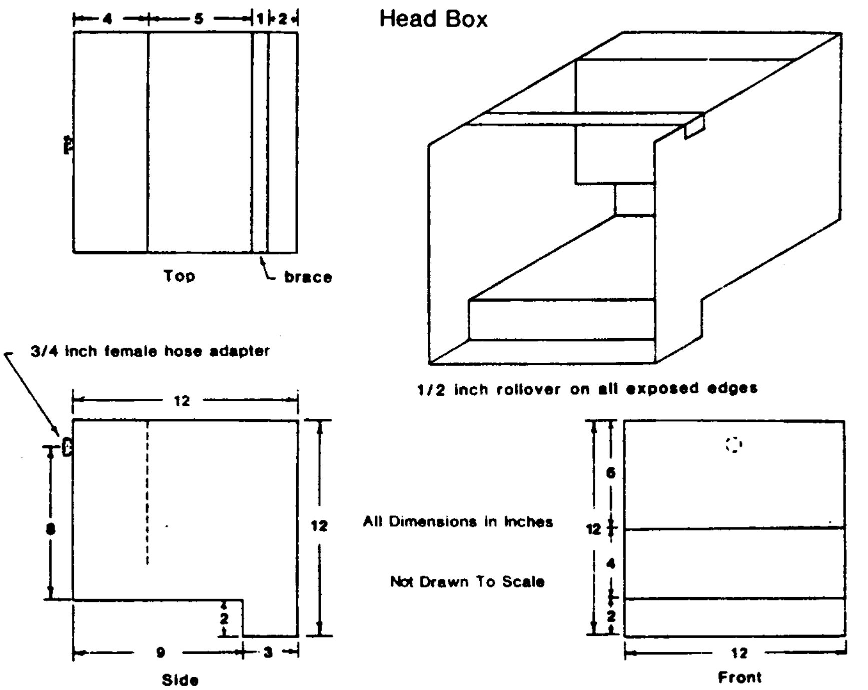

Figure 3b. Two Centrifugal Pump RFI - Head Box

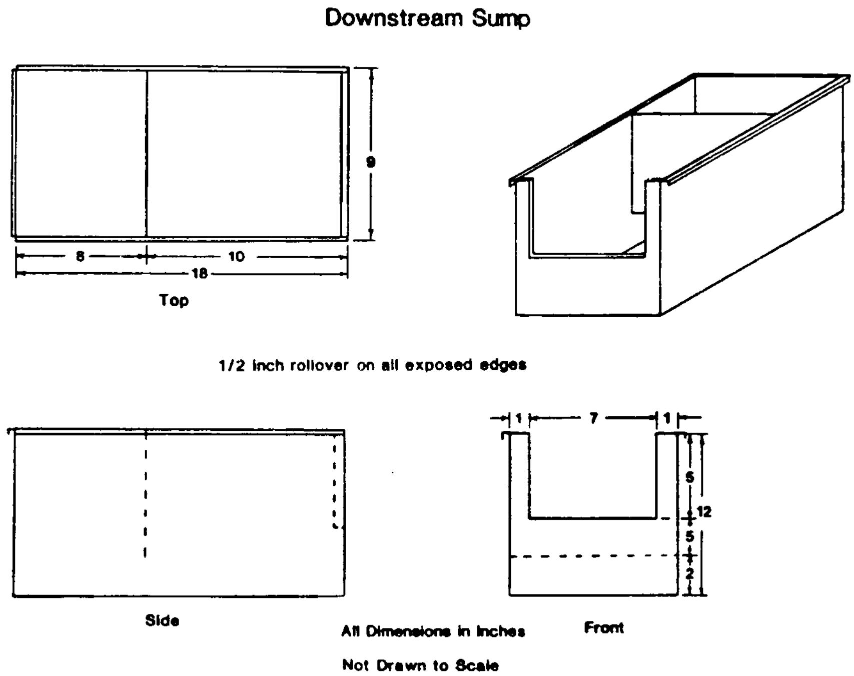

Figure 3c. Two Centrifugal Pump RFI - Downstream

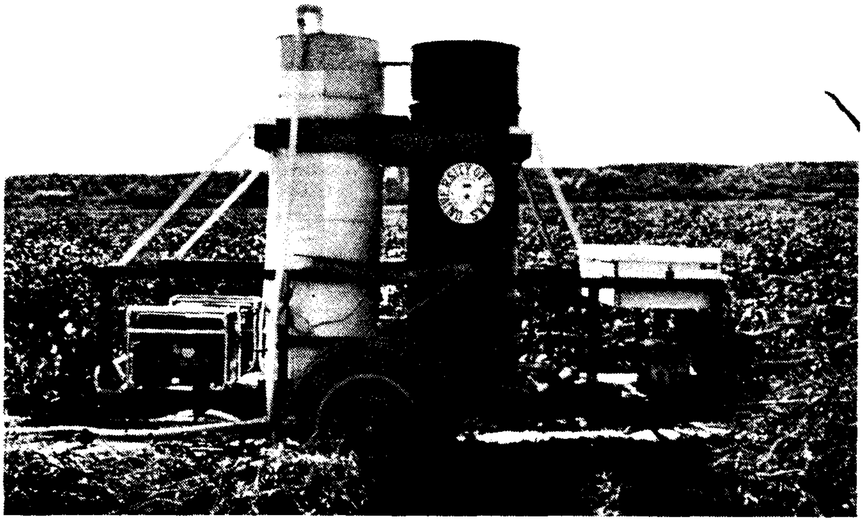

Figure 3d.Two Centrifugal Pump RFI - Photograph

Upstream Head Box. The purpose of the upstream head box is to reduce flow velocities and align flow to the channel. The head box should be designed to meet these criteria, prevent any leakage around the box, and be easy to install. Typically, the head box sits a few inches down in the soil. A cutoff plate which extends 5 or more inches into the soil is installed on the front of the box to prevent water from seeping under and around the box. A recommended design for a head box is shown in Figure 3b.

Centrifugal Sump Pump. A 1/3 horsepower (115 VAC) centrifugal sump pump is used to return the water to the supply reservoir. A submersible pump is recommended but not required. If a submersible pump is used, it must be able to operate without overheating when only partially submerged. The pump should be wired to operate continuously with an on/off switch located away from the sump.

Downstream Sump and Flow Valve. The downstream sump should be capable of holding the volume of water needed to prime the sump pump without backing water into the furrow (typically 2 to 5 gallons). This sump must be installed into the soil at sufficient depth (typically 5 to 9 inches) to allow for weir-controlled flow into the sump. A removable weir is installed at the inlet to the sump to provide a means of controlling the flow depth in the furrow. A cutoff plate which extends 5 or more inches into the soil is installed to prevent water from seeping under and around the sump. A trash screen and a sluice can be placed between the weir and the pump to provide a means of removing large and floating debris from the water.

2.4 Power Requirements and Equipment Trailers

Power requirements vary considerably among the different RFI con-figurations. In general, the SS RFI uses the least power and the TC RFI uses the most. Furthermore, there are three alternatives for the type of system used to operate the pumps. The most common method is to use 115 VAC pumps powered by a gasoline generator; however, it is also feasible to use automotive batteries with DC pumps or gasoline-powered pumps.

Electric pump/gasoline generator systems are recommended for the SC and TC infiltrometers. This system is conveniently set up on an equipment trailer to provide easy installation and removal from the field. Gasoline powered pumps are often bulky and may produce unstable flow rates due to oscillations in engine RPM. The DC pump/battery system is recommended for the SS RFI. This system may require several batteries during long duration (24-hour) infiltration tests.

Figure 3d is a photograph and Figure 4 is a plan view of a dual (2-system) TC RFI equipment trailer used by Blair (1985). The supply reservoir, supply pump, and gasoline generator are permanently mounted on the trailer. A crossover pickup tool box can be mounted across the front of the trailer to provide storage for the electronic water level data logger and accessories. The supply hoses are stored on garden hose reels mounted near the front on the trailer. This type of RFI equipment trailer allows one person to transport, unload, install, and perform RFI tests and has the advantage of allowing the operator to conduct 2 tests simultaneously. Dedrick et al. (1985), describe a similar version of a SC RFI system trailer.

3. INSTALLATION AND COLLECTION OF DATA

This section provides a general overview of the procedures used to install and operate RFI's. Additional information concerning data analysis is provided in section 4, and information concerning supplementary data is provided in section 5.

3.1 Test Site Location and Infiltration Characteristics

The infiltrometer should be installed in a section of the irrigated field which is representative of average conditions within the field. Because of localized variations in furrow shape and soil texture near the head and tail portions of the field, and higher compaction due to multiple tillage equipment passes near the edges, these locations should be avoided. Ideally, the test section should be located where the soil infiltration characteristics are representative of the entire field. Although a location in the interior of the field is preferred, access to the interior of the field is often restricted because of the size, weight, and power requirements of an infiltrometer. The SC and TC RFI can be easily installed 100 to 200 feet within the perimeter of the field by separating the supply reservoir from the rest of the infiltrometer. This requires long hoses and electrical extension cords. The dual TC RFIs, shown in Fig. 3d, can be installed up to 200 feet from the trailer.

The installer should be aware whether the RFI is being installed in a wheel or nonwheel row. The design of the particular experiments will dictate whether data should be collected in wheel rows or not. If both surge and continuous data are collected, then perhaps it is best to perform all tests in nonwheel rows, unless determination of the effect of wheel rows on infiltration is an object of the experiments.

The length of the furrow test section should be between 10 and 30 feet. The shorter the test section length, the smaller the areal sample is, and the larger the measurement error due to any leakage around the head box and sump. The larger the test section length, the greater is the volume of water required to perform the infiltration test. An estimate of the maximum cumulative infiltrated volume per length of furrow should be made prior to selecting the test section length. This volume can be determined from an estimate of the average infiltration rate of the soil and the duration of the test. The duration should be approximately equal to the maximum infiltration opportunity time for a typical irrigation (12 hours, 24 hours, etc.). The required volume of water is equal to the product of the duration of the test, the average infiltration rate per length, and the length of the test section. Furthermore, the water use during the test should be of similar or identical quality as the actual water used to irrigate the field.

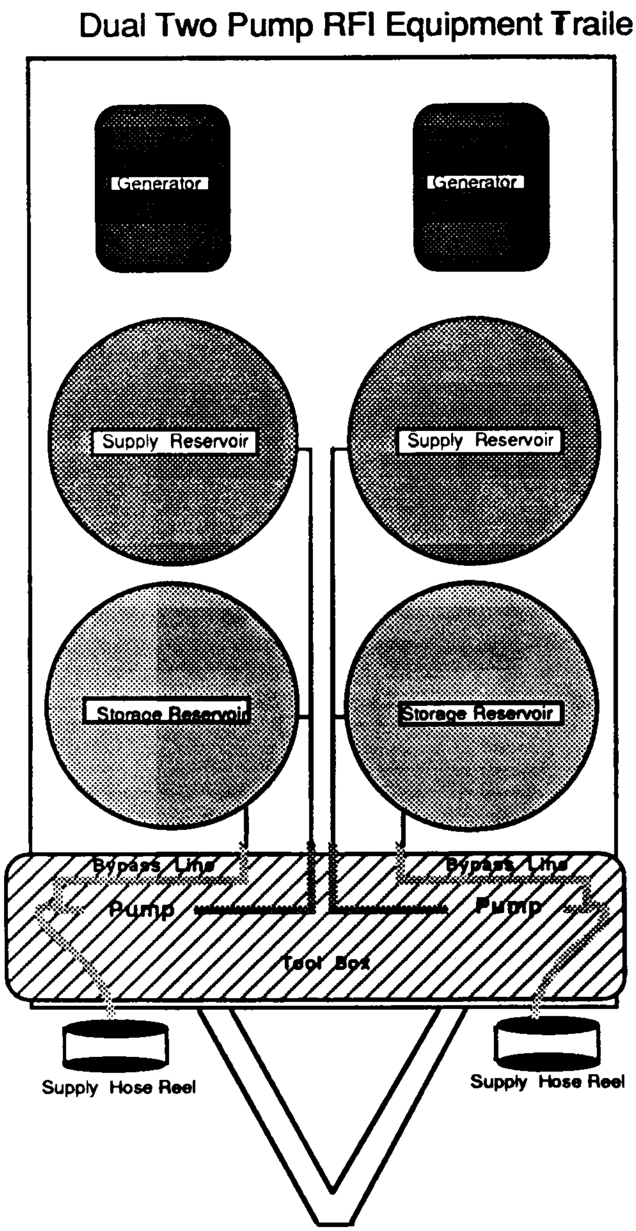

Figure 4. Dual Two Centrifugal Pump RFI Equipment Trailer

3.2 Installation Procedures

Figures 5a through 5g are photographs of the step-by-step procedure used to install a TC RFI. The procedure consists of careful excavation of holes for the head box and sump, installation of the head box and sump, connection and leak testing of the hoses and pumps, measurement of flow rates, and calibration of the water level recording device.

Figure 5a is a picture of the shallow excavation made for the head box in order to provide a level area for it to rest. The front section of the excavation is dug deeper to accommodate the shape of the head box as shown in Figure 3b. After the excavation is complete, the head box is lightly tamped into place. A cutoff plate is then hammered into the soil flush against the head box. Any gaps between the cutoff plate and the head box should be filled with caulking. The soil around the back and sides of the head box is then compacted with a sledge hammer to reduce seepage around and underneath the box. Figure 5b shows the installed head box.

Figure 5c shows the excavated hole for the downstream sump. If the downstream sump is not carefully installed, it will leak excessively during the infiltration test. The sump shown in Figure 3c is slightly narrower than the width of a common square edge shovel, and will fit tightly in a hole dug with a square shovel. After the sump is placed in the hole and back fill is added, the soil around the sump should be tightly packed, using a sledgehammer, prior to and after installing the cutoff plate. Any gaps between the sump and the cutoff plate should be sealed using caulking. Figure 5d shows the installed downstream sump.

During the excavation of both holes, care should be taken to avoid altering the soil surface between the head box and the sump. This furrow test section should not be walked upon or allowed to have dirt added to or removed from it.

Once the head box and sump are installed, the sump pump and return line can be connected. The supply line to the head box should be temporarily routed directly into the sump. This provides an opportunity to check for any leaks in the pumping system prior to beginning the infiltration test. The flow rate and surface storage of water can be measured while the pumps are running and water is recirculating. The flow rate can be measured using a bucket and stop watch. The surface storage can be measured by lining the furrow with a light plastic tarp (a painter's drop cloth works well) and establishing steady flow in the furrow. Because the plastic tarp prevents infiltration, the volume of water removed from the supply reservoir to fill the tarp lined furrow is an estimate of the volume of water stored on the surface of the furrow. How accurate this estimate is depends on how well the tarp conforms to the shape of the furrow, how much the furrow shape changes after wetting, and how much the flow profile is affected by the tarp. While the tarp is in place and water is flowing, the weir height can be adjusted to obtain the desired flow depth. Once the surface storage has been measured, the inflow should be stopped, water drained from the tarp, and the tarp removed without wetting the soil.

The soil should be initially wetted by letting the water advance from the head box to the sump in a manner similar to an actual irrigation. If the advance velocity is excessive then the soil aggregate stability may be decreased and sediment load increased; if the advance velocity is too low, then sediment load may be less than that which typically occurs during an irrigation. Low advance velocities also complicate efforts to determine the initial infiltration rate of the soil.

Prior to beginning the test, the test section length and furrow cross-sectional shape should be measured. Once the test has begun, measurement of the flow depth and wetted perimeter should be performed. Supplementary data collection methods are discussed in section 5.

3.3 Water Level Measurement and Recording

The rate of change in water level in the supply reservoir is proportional to the infiltration rate of the soil in the test section. The water level can be measured manually, mechanically, or electronically. The manual measurement method is likely the most accurate and is not overly labor intensive for continuous flow tests where readings are only required every hour or two after the first hour of the test. Surge flow infiltration tests require many readings every surge period (which may be for a duration of 30 minutes or less) and tend to be overly labor intensive for the manual measurement method. The manual method can be simplified by taping a strip of paper next to the water level sight tube on the supply reservoir. The water levels and times are marked on this paper during the test. After the test, the paper is removed to measure the difference in water levels.

The mechanical water level recorder creates a strip chart curve of water level versus time. Components to this recorder are a clock-driven chart, a counter weighted float, and a gear mechanism connecting the float with an ink pen. The clock gear in the recorder should provide sufficient resolution to accurately determine changes in volume in the reservoir over 30 to 60 minute periods during continuous flow tests, and 5 to 15 minute periods during surge flow tests. Other accuracy considerations with these recorders are pen thickness, resolution of the water level scale gear, effect of wind on the float counter weight, and hysteresis in the cardioid cam used in some drum recorders.

Electronic water level recorders consist of a transducer and a data logger. The transducer can be a pressure type or a potentiometer type. The potentiometer transducer uses a float and a counter weight similar to a mechanical water level recorder. The pressure transducer converts pressure measured near the bottom of the supply reservoir into an electric voltage or current. The accuracy of water level measurements made using pressure transducers can be affected by a multitude of factors including sensitivity, linearity, zero shift, temperature shift, ratiometricity, and hysteresis. Refer to Benedict (1977) and Sheingold (1980) for details.

The electronic data logger is used to convert the analog voltage or current output of the transducer to a digital value and store the data. The resolution and range of the analog to digital convertor should be matched to the transducer output. In general, a 12-bit convertor, which provides a resolution of 1 in 4096, has sufficient resolution for most transducers. If AC electricity is used to power the pumping system, the the effect of 60 Hz noise on the analog to digital convertor should be considered. The effect of 60 Hz noise can be suppressed by using an analog to digital conversion integration period which is a harmonic of 60 Hz (such as 1/6 or 1/60 of a second).

4. DATA ANALYSIS

This section outlines the methods used to analyze continuous and surge flow RFI data, and the types of measurement errors that may be introduced in the analysis.

4.1 Continuous Flow

Determination of infiltration from infiltrometer data is based on conservation of volume. The time rate of change of the volume of water in the infiltrometer supply reservoir is measured during the infiltration test. Application of conservation of volume to continuous flow recirculating, static blocked furrow or ring infiltrometer tests is straightforward and assumes that the time rate of change of volume in the infiltrometer reservoir is directly proportional to the time rate of change of water infiltrating into the soil. Infiltration rate during continuous flow or static tests is equal to

$$\frac{dZ}{dt} = -c\frac{dS}{dt}$$

where Z is the cumulative infiltrated volume per unit length of test section, t is the infiltration opportunity time, S is volume of water stored in the infiltrometer supply reservoir, and c is a constant equal to the inverse of the furrow section length.

4.2 Surge Flow

Application of conservation of volume to recirculating furrow infiltrometers is considerably more complex for surge flow tests than for continuous flow or static tests. Figure 6 shows the net pumped volume of water during a surge flow recirculating infiltrometer test. The net pumped volume is the measured volume of water pumped out of the infiltrometer reservoir and into the upstream sump, minus the volume pumped into the reservoir from the downstream sump. Determination of infiltration from the net pumped volume requires the analysis of both surface storage of water in the furrow and the volume of water infiltrating during the advance and recession stages of the surge flow. The total amount of water stored on the surface of the soil consists of drainable storage and depression storage.

Application of conservation of volume can be used to determine the cumulative infiltration curve from the net pumped volume curve shown in Figure 6. The cumulative infiltration per unit length at the end of the surge period n is equal to

$$Z_n = \sum_{i=0}^{n} \Delta Z_i \tag{3}$$

where

$$\Delta Z_i = \Delta Z'_i + \Delta Z_{adv,i} + \Delta Z_{rec,i} + S_{dep,i} \tag{4}$$

and $\Delta Z_{adv,0} = 0$. Note that the initial wetting period is the 0^{th} surge period (i=0). The variables in equation (4) are defined in Figure 6 and Table 1. The volume of water per length which is stored in depressions on the soil surface is equal to

$$\Delta Z_{rec,i} + S_{dep,i} = S'_i - S_{drain,\,i} - \Delta Z_{adv,i+1} \tag{5}$$

$$\Delta Z_{adv,\,i+1} \equiv S_o - S'_i \tag{6}$$

The value of $\Delta Z_{adv,i}$ is determined by extrapolation of a curve fit to the data collected just after advance is complete. Figure 6 indicates $\Delta Z_{adv,i}$ by a dotted line at the first of the t_{on} period of the i^{th} surge.

Total surface storage is assumed to be equal to S_o which is measured by covering the furrow test section soil surface with a plastic liner and recirculating water through the furrow. The volume of water stored in the hoses and sumps should be accounted for separately and should not be included in S_o. This assumption is only valid if the plastic liner fully conforms to the furrow bed, the furrow does not change shape or erode during the test, and depth of flow with the liner in place is identical to that with the liner removed. All three of these assumptions are violated to a greater or lesser degree during every test. Total surface storage can also be calculated from furrow profile measurements and either wetted perimeter, top width of the water surface, or depth of flow measurements. Perhaps the most appropriate method for determining total surface storage would consist of measuring the furrow profile and wetted perimeter during every surge period.

4.3 Measurement Errors and Complications

The objective of this section is to provide a brief outline of some types of errors and complications which commonly occur in field infiltrometer data. It is not the intent to provide the reader with rigorous error analysis procedures or examples.

The analysis of field measured infiltration data is complicated by: 1) the spatial variability of the soil; 2) the measurement accuracy of the experimental equipment; 3) the statistical error involved in determination of infiltration equation coefficients; and 4) the effect of wetted perimeter and sediment load. Estimation and minimization of these potential errors in infiltration determination are necessary for confident comparison of surge and continuous flow infiltration tests.

Spatial variability likely accounts for a majority of the differences in infiltration data for continuous flow infiltration tests which are performed under nearly identical conditions. Spatial variability has predominantly three components: 1) the random effects on infiltration such as macropores and localized heterogeneity in soil or furrow geometry; 2) the reduction in infiltration in compacted (wheel rows) versus noncompacted furrows; and 3) trend and large-scale discontinuity in the field soil texture. Estimation of the third type of spatial variability is possible using the geostatistical techniques discussed by Bautista and Wallender (1983). However, this type of analysis requires a large number of field tests.

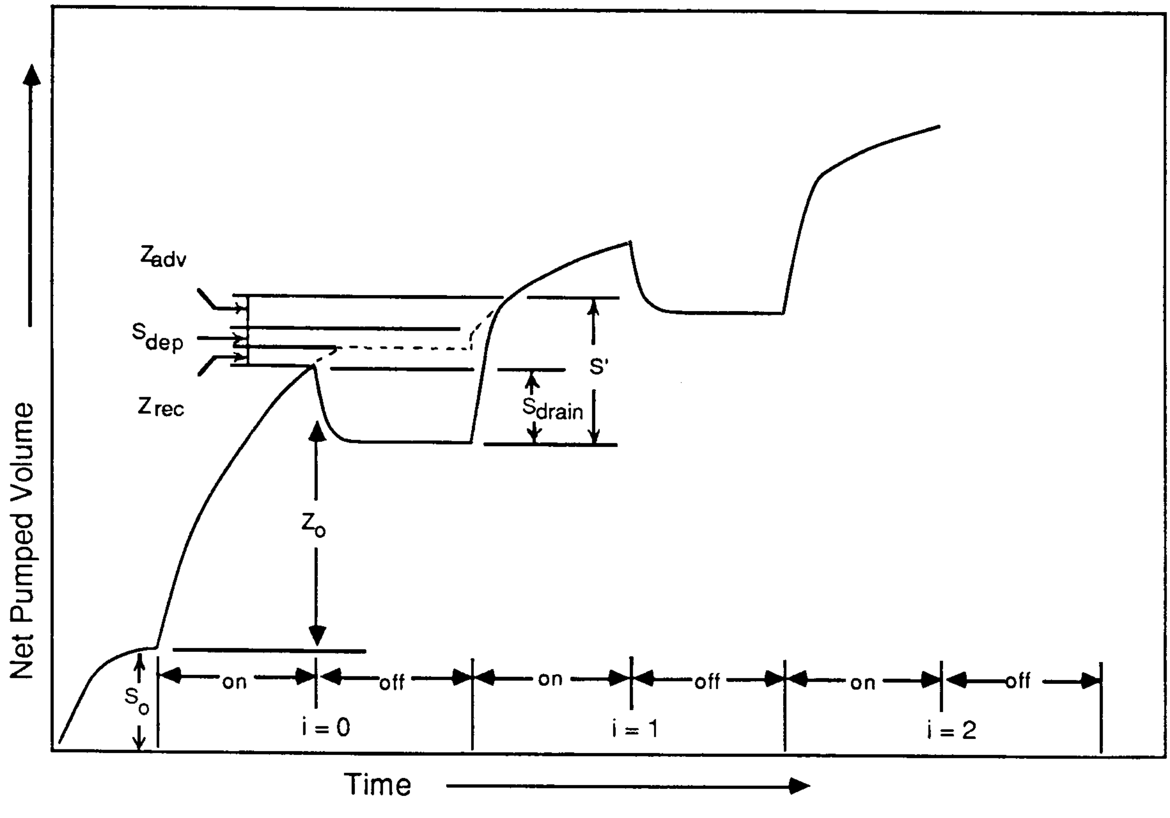

Figure 6. Typical RFI Surge Flow Test Results

Parameter	Defined as
S_o	Total surface storage measured as the volume of water pumped into the plastic covered furrow test section.
$S_{drain, i}$	The measured amount of water pumped back into the reservoir at the end of the i^{th} surge.
S_{dep}	The calculated amount of water stored in surface depression in the furrow test section.
ΔZ_{adv}	The calculated amount of water which infiltrates during advance and stabilization period at the beginning of the second (i=1) and every subsequent surge flow period.
ΔZ_{rec}	The calculated amount of water which infiltrates during the recession and drainage period at the end of every surge flow period minus S_{dep}.
ΔZ_i	The calculated amount of water which infiltrated during i^{th} surge flow period.

Table 1. Calculated and Measured Infiltration and Storage Parameters

Measurement accuracy is dependent on the type of equipment used, test procedures, and data analysis techniques. Sensors used in electronic data collection systems are subject to temperature shift, repeatability, hysteresis, linearity, null shift, ratiometricity, and sensitivity errors. Determination of these types of errors usually requires laboratory calibration of the transducer in a temperature-controlled environmental chamber. These procedures are beyond the scope of this paper and the reader is referred to Benedict (1977) for additional information concerning measurement, definitions, and causes of these types of errors. Product specifications list maximum expected errors.

Total error and calibration checks for null shift and sensitivity can be determined by comparing visual readings with transducer output during the tests if the data collection is properly designed.

Laboratory tests of the RFI data collection system used by Blair (1985) yielded a composite cumulative infiltration RMS error of approximately ±5 liters, or about 1% of the total infiltrometer reservoir volume. This composite measurement error is absolute, thus the relative error in cumulative infiltration decreases as cumulative infiltrated volume increases, or equivalently as the test section length increases and/or the average infiltration rate of the soil increases. Long test section lengths can reduce measurement error; however, they require proportionately larger infiltrometer reservoir volumes and increase the volume of infiltration which occurs during the advance and recession phases for surge flow tests. Infiltration rates during the advance and recession phase cannot be directly measured using an infiltrometer and must be estimated by analysis of surface storage in the furrow.

The absolute measurement error in average infiltration rates for small time periods (10 to 60 minutes) may be smaller than that for cumulative infiltration because the effect of null shift error is less significant over this small time period. Infiltration rate measurement is primarily a function of transducer sensitivity error and resolution, and the length of the furrow test section. However, any temporal instabilities or oscillations of the water level in the supply reservoir may cause significant error in infiltration rate measurement. One common cause of oscillations in the water level using the SC RFI is the temporal variation in downstream sump water level due to hysteresis in the water supply float valve. The Mariotte siphon supply reservoir used in the SS RFI can produce a similar error due to an oscillation of the differential pressure inside the reservoir caused by surface tension effects on the bubbling tube. Furthermore, any unwanted variation in the pumping system power supply voltage can cause the flow rate to change, which in turn causes the volume of water stored on the surface of the furrow to vary. Thus, it is often difficult to accurately determine infiltration rates averaged over small time periods, even though it is possible to accurately measure the water level in the supply reservoir.

Additional errors can be introduced in recirculating infiltrometer data from leakage of water around the upstream and downstream sumps, seepage into adjacent furrows, inflow rate variations, or ignoring the volume of water stored on the surface of the furrow, in the sumps, and in the supply and return hoses. These errors can be significant. However, if care is taken in the installation and operation of the infiltrometer, all volumes of water are properly accounted for, and little seepage into adjacent furrows occurs, these errors are usually quite small compared to other measurement errors.

5. SUPPLEMENTARY DATA AND CONSIDERATIONS

Collection of cumulative infiltration data should be supplemented with hydraulic data, furrow geometry data, and soil information. This additional data is useful for both applied and research purposes. For example, wetted perimeter and furrow geometry are required input for some furrow irrigation computer simulation models. Most of the supplementary data are easy to measure, and there is little reason not to obtain them. Figure 7 shows a field data form which can be used to record this data.

5.1 Wetted Perimeter and Flow Depth

Samani (1983), Strelkoff and Souza (1984), and Blair and Smerdon (1985) reported that infiltration in some furrows is affected by the cross-sectional wetted perimeter. Several infiltration equations have been proposed by these authors to account for this effect; thus, it is highly recommended that wetted perimeter data be collected for all RFI tests.

The wetted perimeter should be measured at several longitudinal locations within the furrow test section using a cloth or vinyl measuring tape. The flow depth in the middle of the furrow and/or the top width of the stream along with the furrow profile data can be used as a substitute for direct wetted perimeter data.

5.2 Furrow Cross-Sectional Shape

A rill meter, as shown in Figure 8, can be used to measure the cross-sectional furrow shape. Most furrows are fairly uniform and only one or two measurements of furrow shape may be required per test. However, some furrows are highly irregular and several profiles must be measured to obtain an average.

Site Location: ______________ Test Id: ________ Date: ________

Infiltrometer Supply Reservoir Diameter: ______________
Flow Rate: ______________ Duration of Test: ______________

Water Level Transducer Calib.	Surge Flow Data
Depth: ______ Voltage: ______ Depth: ______ Voltage: ______ Depth: ______ Voltage: ______	Cycle Time: ______________ Cycle Ratio: ______________ Number of Cycles: __________

Soil and Water Data

Soil Texture: ______________
Soil Moisture Content: ________
Bulk Density: ______________
Dominant Clay Mineral: ________
Soil CEC: ______________
Soil $CaCO_3$: ______________

Water EC: ______________
Water SAR: ______________
Water TDS: ______________

Plant Residues: ______________
____

Wetted Perimeter Data

Head to Sump	1	2	3	4	5	Units
Wetted Perimeter						
Longitudinal Distance						

Flow Depth

	1	2	3	4	5	Units
Center Line Depth						
Longitudinal Distance						

Cross-Section Profile Data

Longitudinal Location (Distance from Head Box): ______________

Left (facing downstream) Right

	1	2	3	4	5	6	7	8	9	10	Units
Depth											
Transverse Distance											

Figure 7. Recirculating Furrow Infiltrometer Test Field Form

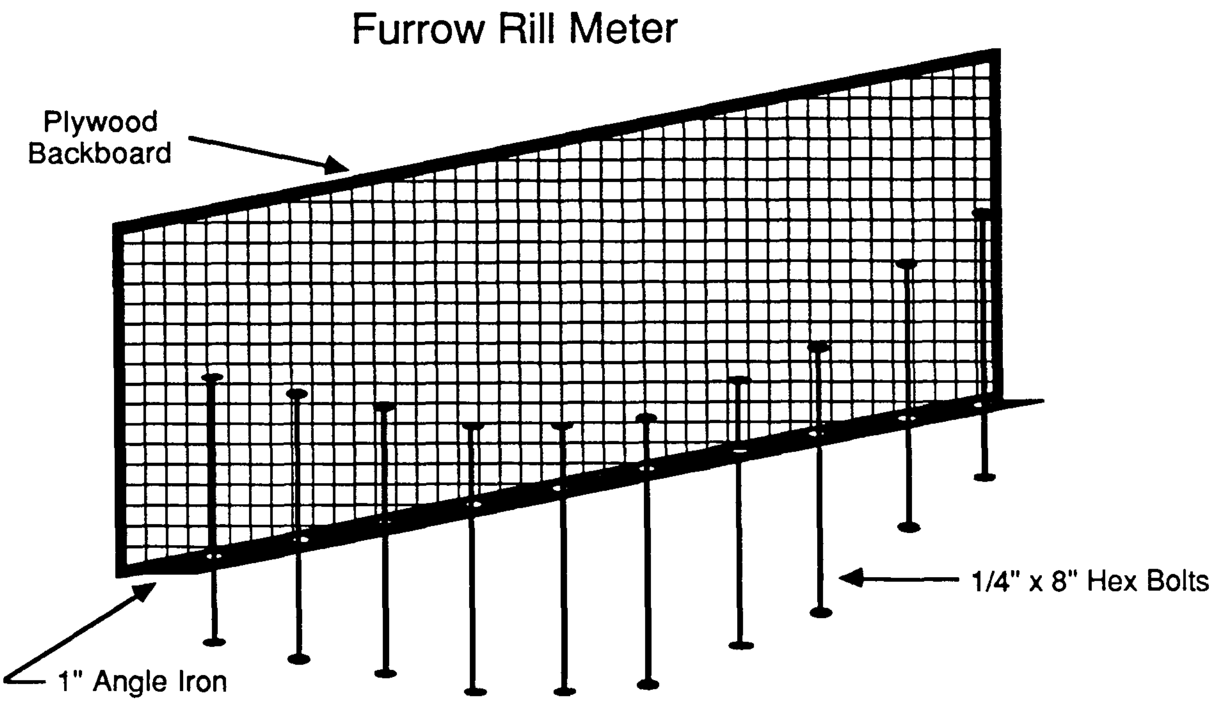

Figure 8. Furrow Rill Meter

5.3 Surface Storage

As discussed in sections 3.2 and 4.2, the surface storage of water in the furrow should be measured prior to wetting the furrow. During surge flow tests, the downstream weir should be removed at the end of each flow period and allowed to drain. This volume of drained water should be measured and recorded. The TC RFI returns this drained water directly to the supply reservoir; thus, this volume can be determined directly from water level data.

5.4 Soil and Water Characteristics

Additional information concerning the chemical or mineral constituents of the soil and water should be obtained through laboratory analysis. This information, as recommended by Letey (1983), is outlined in Table 2.

	Water Quality
Primary Importance:	Electrical Conductivity (EC) Amount of Sodium, Magnesium, and Calcium Amount of Bicarbonate
Secondary Importance:	Amount of Potassium, Chloride, and Sulfate (SO_4)
	Soil Properties
Primary Importance:	Texture, Cation Exchange Capacity (CEC) Calcium Carbonate ($CaCO_3$) Content Exchangable Cations (Na, Ca, Mg, K) Dominant Clay Mineral Initial Soil Moisture Content Soil Bulk Density
Secondary Importance:	Soil Organic Matter Content
	Plant Residues
A descriptive statement on the presence (if any) of plant residues such as stubble should be made.	

Table 2. Soil and Water Characteristics Important in Infiltration

6. REFERENCES

Benedict, R.P. (1977). *Fundamentals of temperature, pressure, and flow measurement.* Wiley and Sons, New York.

Blair, A.W., and E.T. Smerdon. (1985). "Evaluation of empirical equations describing the effect of wetted perimeter on infiltration in furrows." ASCE Irrigation and Drainage Specialty Conference Proceedings, San Antonio, Texas.

Blair, A.W. (1985). "Modeling infiltration and hydrodynamic effects on surge flow surface irrigation," thesis presented to The University of Texas at Austin, Austin, Texas, in partial fulfillment of the requirements for the degree of Doctor of Philosophy, pp. 73-76.

Dedrick, A.R., L.A. Hardy, A.J. Clemmens, J.A. Replogle, and L.M. Clemmens. 1985. "Trailer Mounted flowing furrow infiltrometer," Applied Engineering in Agriculture, ASAE1(2):79-83.

Elliott, R. L., and D.E. Eisenhauer. (1983). "Volume balance techniques for measuring infiltration in surface irrigation." ASAE Paper No. 83-2520, ASAE, St. Joseph, Michigan, 21 pp.

Latortue, H.F. (1984). "Volume balance models for continuous and surge flow furrow irrigation," thesis presented to Texas A&M University, College Station, Texas, in partial fulfillment of the requirements for the Master's Degree.

Letey, J. (1983). Personal correspondence to USDA W-163, University of California at Riverside, Soil and Environmental Sciences, 1 p.

Samani, Z.A. (1983). "Infiltration under surge flow," thesis presented to Utah State University, Logan, Utah, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Sheingold, D.H. (1980). *Transducer interfacing handbook.* Analog Devices, Norwood, Massachusetts, 231 pp.

Strelkoff, T., and F. Souza. (1984). "Modeling the effect of depth on infiltration in furrows." *Journal of Irrigation and Drainage*, ASCE, 110(4), 375-387.

Walker, W.R., and L.S. Willardson. (1983). "Infiltration measurements for simulating furrow irrigation." Proceedings of the National Conference on Advances in Infiltration, ASAE, St. Joseph, Michigan, pp. 241-248.

Wallender, W.W., and E. Bautista. (1983). "Spatial variability of water distribution under furrow irrigation." ASAE Paper No. 83-2574, ASAE, St. Joseph, Michigan, 21 pp.

7. ACKNOWLEDGMENTS

This research was partially funded by the United States Department of the Interior - U.S. Geological Survey, Reston, Virginia, 1985 Water Resources Research Program Grant 14-08-001-G1129 and U.S. Department of Agriculture, Agricultural Research Service, Kimberly, Idaho. This report was prepared under the auspices of the Western Regional Research Committee on Surge Flow Irrigation.