NEW FURROW FLUME FOR HIGH SEDIMENT LOADS

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ABSTRACT. *Measurement of water flow in furrows from either irrigation or rainfall is difficult when significant soil erosion occurs. It can be accomplished with flumes that back up flow in the furrow, which for moderate to steeply sloping fields causes only small changes in furrow water depth and thus has little influence on the water flow measurement. However, the ponding of water upstream from a flume can have a significant impact on the movement of sediment down the furrow. In one research study, measured sediment transport through the flume was reduced 40% over that measured in a furrow with only a non–constricting metal form that matched the furrow shape. A new furrow flume has been designed that overcomes the limitations of current v–shaped flumes or trapezoidal RBC flumes that cause significant backwater during furrow irrigation. This new flume has a trapezoidal shape with only a side contraction. It was designed to keep flow velocities high over the full range of flow conditions. This new flume is commercially available and has been working successfully in the field for three seasons.*

Keywords. *Flumes, Weirs, Flow measurement, Erosion, Sediment transport, Furrow irrigation.*

Flow measurement in open channels has evolved over the 20th century from art to science. Early flow measuring flumes and weirs relied exclusively on laboratory calibration. Generally, the practitioner was faced with selecting from available devices for a particular need. Selections were not always perfect. In the past several decades, the ability to mathematically model the behavior of flumes and weirs allows us to design flumes for a particular application, matching the flume's hydraulic behavior to that of the channel.

Flumes and weirs work on the principal of critical depth, a condition under which the energy of the flow is a minimum for a particular rate of flow. If the flow passes through critical depth, then there is a unique relationship between the flow rate and the flow energy. A flow measurement is made by relating the flow energy, represented by the upstream depth, to the flow rate. Using boundary–layer theory, Replogle (1975) was able to relate the total flow energy in the flume throat (where flow is at critical depth) to the upstream water level by computing energy losses (not true losses, but conversions to heat, etc.) and accounting for velocity distributions, provided that the flume met certain dimensional specifications, and in particular a sufficiently long throat. This allows these flumes (and weirs) to be computer calibrated. Many older, laboratory–calibrated flumes do not meet these dimensional specifications, and thus are not amenable to computer calibration. Further, these older flumes with short throats are also more subject to submergence by downstream tailwater.

The difficulty with placing a flume or weir in a furrow to make flow measurements is that a drop in the water surface elevation across the structure is required in order to obtain critical flow in the throat. Because of energy recovery, the amount of drop is actually very small for any given flow rate. If the furrow is sufficiently steep, then the backwater effect caused by placing the flume in the channel will propagate only a short distance upstream. However, because the rate of water flow changes during an irrigation event, it is often difficult to match the flow conditions over the full range of flows. In practice what usually occurs is a flume set to match high flows will cause too much change in upstream level at low flow, or if set for low flows, will not allow critical flow to occur at high flows due to downstream submergence.

Adding to this difficulty in our application is the desire to measure sediment flow through the flume with reasonable accuracy. In order to do this, we use a scoop that fits the downstream section of the flume. The scoop is placed in the flow until it fills. When removed, it should contain all water and sediment that passed through the flume during that short period of time, collecting both suspended load and bed load. If the flume is placed too low, the high downstream backwater makes collection of this sample difficult and may compromise its accuracy.

The purpose of this paper is to present the design of a new furrow flume that is specifically geared toward measurement of water and sediment flows in small furrows, typical of sloping furrow irrigation systems where erosion is a concern.

LONG–THROATED FLUMES AND BROAD–CRESTED WEIR

Flumes and weirs have been in use for flow measurement for more than one hundred and fifty years. The concept of critical depth and our ability to calculate it date back almost one hundred years. By the 1950's, the dimensional requirements for these weirs were more–or–less understood. Yet

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these concepts were not fully exploited to design flumes and weirs to match channel conditions until the 1970's, thanks largely to our ability to design these structures with the computer. This led to the development of a large number of standard structures for lined canals, including a number of portable flumes (See Clemmens et al 2001 for details on theory and its historical development).

For the calibration of flumes and weirs, we rely on an energy balance. For a given flow rate, the energy of flow is a minimum at critical depth. The equation for critical depth is

$$Q = \sqrt{gA_c{}^3/(\alpha_c B_c)} \qquad (1)$$

where Q is flow rate or discharge, g is acceleration of gravity, A is cross–sectional area, B is top width of flow, α is the velocity distribution coefficient, and subscript c refers to the throat section. (At critical flow, the velocity distribution is very close to uniform, with α_c nearly unity). Proper design of a critical depth measuring device forces critical depth to occur in a region of the flume where the flow lines will be straight and roughly parallel. This results in a hydrostatic pressure distribution so that we can compute the total energy of the flow from knowledge of the flow depth and cross section shape and dimensions. For a given flow depth in the throat, there is only one flow rate possible (assuming hydrostatic pressure and a nearly uniform velocity distribution). With a known flow rate and energy head, one can compute the upstream water depth from the energy equation (with the calculation of a small head loss between the two locations).

$$h_1 + \alpha_1 v_1{}^2 / 2g = h_c + \alpha_c v_c{}^2 / 2g + h_L \qquad (2)$$

where h is the water depth with reference to the flume throat, v is the average flow velocity, subscript 1 refers to the approach section, and h_L is the head loss between the approach section and the throat. This equation assumes hydrostatic pressure distributions in the approach channel and throat. Calculation of h_L requires that the transitions from the approach channel to the throat are sufficiently gradual that head losses are due to friction and not turbulence associated with flow separation. The approach velocity distribution coefficient for a well–developed velocity distribution in an open channel is typically around 1.04.

The same theory is used for both flumes and weirs. If the flume throat or weir crest is sufficiently long in the direction of flow, the same energy theory can be used. In order to have critical flow in the throat and subcritical flow upstream, the size of the flow area in the throat must be smaller than the size of the flow area upstream. Flumes reduce the flow area by contracting the channel primarily from the side, while weirs contract the channel primarily from the bottom. For a given flow rate, a flume can be designed for a desired upstream water depth. A weir can be designed that gives exactly the same water level for that given flow. The flume and weir would differ in the cross–section dimensions and in the height of the crest above the channel bottom. However, at any other flow rate, the water levels for these two structures would differ. The choice between a weir and flume then is based on the conditions over the range of flows to be considered and ease of construction. We have found weirs much easier to build in existing canals, since the side walls can remain the same and only a weir crest needs to be raised from the bottom. For pre–manufactured portable flumes, this construction advantage for weirs is less important.

A limitation with many of the older, empirically calibrated devices, such as Parshall and cutthroat flumes, is that stream lines are not straight and parallel, pressure is not hydrostatic, and thus we cannot predict the upstream depth for a given rate of flow. Even some of the more useful flumes, such as Palmer–Bowles, Robinson–Chamberlain, etc. can be calibrated by computer, but only up to a certain depth. Once the depth on these flumes gets too great, the flow lines in the throat become curved, the pressures non–hydrostatic, and the calibration varies from that predicted from theory.

The error in discharge for a flume with a throat that is too short to maintain parallel streamlines can be determined experimentally, which allows small portable flumes to handle a wider range of flows for a given flume length. However, the short throat also decreases the ability of the flume to accommodate downstream submergence. When the depth of water downstream from the flume gets too high, critical flow no longer occurs in the throat and the flume is no longer functioning as a measuring structure. Calibration of critical–depth measuring devices under these conditions is highly inaccurate and not recommended. The point at which the downstream water depth causes the flume to no longer function as a measuring device is called the modular limit, defined as the ratio of the downstream to upstream energy head relative to the invert of the flume throat ($ML = H_2/H_1$). At lower downstream water depths, the flow is modular (e.g., functioning as a flow module). At greater downstream depths, the flow is non–modular, and the flume is overly submerged. The head loss on the downstream side of the structure has a large influence on the modular limit. While some frictional head loss exists, a majority of the head loss (energy conversion) is from expansion of the flow. A gradual expansion can greatly reduce the head loss, compared to a sudden expansion.

For rectangular flumes, the worst–case scenario is ML = 0.6 (i.e., downstream head loss is 40% of the upstream energy head). For trapezoidal or parabolic flumes, ML = 0.7, and for triangular flumes, ML= 0.76. With a gradual downstream expansion, ML greater than 90% is possible for any shape. The addition of a gradual downstream expansion increases the length of the overall device, which is often not desirable for a portable device.

In this article, we use the WinFlume software (Clemmens et al., 2001) to assist in designing a flume to satisfy the requirements for furrow erosion studies. The requirements are described below. (http://www.usbr.gov/pmts/hydraulics_lab/winflume/)

FLOW AND SEDIMENT MEASUREMENTS IN FURROWS

Due to the temporary nature of furrows, portable devices are appropriate for flow measurement. One of the difficulties with the use of portable flow measurement devices, such as furrow flumes, is setting the flume at the proper elevation. Setting the flume too high results in an upstream water depth that is too high and backwater effects that extend upstream. This causes a wider wetted perimeter and potentially more infiltration. Of course, the steeper the furrow, the less influence this has. It also reduces the upstream velocity and can cause sediment that is suspended in the stream and moving along the bottom as bed flow to settle out upstream from the flume throat. Generally, once enough sediment has deposited in the furrow upstream from the flume throat, the incoming sediment is passed through as if the flume was no longer there. However, if too much has been deposited, the approach conditions to the flume are different from that used in calibration and additional error is added to the flume readings. Also, setting the flume too high may create erosion downstream as the flow drops from the flume to the soil surface. Installing a flume too high compromises our ability to accurately measure sediment movement in furrows. Installing a flume too low results in non–modular flow conditions, and thus inability to measure flow, and makes collection of sediment samples more difficult. For furrows that are sufficiently steep (e.g., > 0.005 m/m), proper placement of an appropriately sized flume should result in modular flow (not influenced by submergence), because the flume is supposed to be set level and the furrow bottom slopes away.

Measurement of sediment in furrows has proven to be a challenge. While suspended loads can be relatively easily measured with water samples, sampling bed–load sediment is much more difficult. Part of the difficulty is being able to separate the bed load from the furrow bed when taking the sample. One approach has been to place metal forms in the bottom of the furrow that have roughly the same shape as the furrow. The water and bed load material either pond upstream or pass through this form. These are generally placed on the furrow bottom so that little if any water or sediment ponds upstream. A scoop of the same cross–section shape as the form is then used to collect water and sediment samples. The scoop is built with an open end where the water enters and a closed end, which prevents water from flowing through. The scoop is placed on the form and when full, it is lifted up bringing all water and sediment with it. The idea is to collect all water and sediment for a short period of time. As long as this is done quickly, the backwater effects from the water trapped in the scoop will not change the inflow to the flume. With critical flow in the throat of a flume, sample collection just downstream should result in the appropriate proportion of water and sediment. With backwater, one has to be more careful in how the scoop is placed into the flow. In general, as long as the downstream water depth is not too great, this is a manageable task.

EXISTING FURROW FLUMES

In the Pacific Northwest, the Powlus–V furrow flume is commonly used to measure furrow flows (Robinson and Chamberlain, 1960). These flumes have been used in studies of furrow erosion, as well (Trout 1996; Westermann et al. 2001). This flume is made so that it can be placed in a small unlined channel, such as a furrow. As such it includes a section of upstream and downstream channel in addition to the flume throat, and gradual converging and diverging transitions. It has trapezoidal approach and tailwater sections, as shown in figure 1, and a v–shape, made by contracting the approach section from the side, that is, the inverts of the trapezoid and v–shapes are at the same elevation. The head–discharge relationship is shown in figure 2 and table 1. Here the head is shown in terms of water depth relative to the invert of the upstream approach section. For this flume, the upstream depth and head on the flume (relative to the crest) are the same. This flume is commercially available in fiberglass (Honkers Supreme, Twin Falls, Idaho). Above about half the calibrated depth, this flume no longer functions as a long–throated flume and high tailwater levels can have a significant influence on the calibration.

Clemmens et al. (1984) introduced a series of small RBC flumes that have been used to measure furrow flows. These flumes are constructed with a uniform cross section into which a bottom contraction is placed. This makes the side–walls for the approach channel, throat, transitions, and tailwater channel the same. These have been manufactured out of both sheet metal and fiberglass, with the latter version commercially available (Plastifab, Tualatin, Oreg.). The relationship between upstream water level and discharge is shown in figure 2 for the smallest of these flumes (50–mm throat width). For this flume, the crest height is 25 mm above the upstream channel invert (i.e., the actual head on the weir is 25 mm smaller than the value shown in fig. 2).

MEASUREMENT REQUIREMENTS FOR EROSION STUDIES

Selection from among available flumes is based on the hydraulic characteristics of the site and the flow measurement needs. For furrow erosion studies, it is important that the flume cause minimal change in the water depth in the furrow upstream from the flume throughout the range of flow rates. Because furrow flow rates increase from zero to the inflow value, a flume with no bottom contraction is preferred, as discussed later. However, it is also better if the flume does not cause the upstream water level to rise significantly higher than it would have without the flume. To examine the tradeoffs in design, selection and installation of flumes, we use an example from recent furrow erosion studies conducted at Kimberly, Idaho. For flume design, the water level in the existing channel without a flume or weir in place becomes the tailwater level for the flume or weir.

DEFINING TAILWATER CONDITIONS

For the relatively steep slopes (>0.005 m/m) where erosion is a concern, backwater effects from flow constrictions do not extend very far upstream and the flow in the furrow is usually close to normal depth, that is, the depth is based on local flow rate and not based on backwater from downstream conditions. Under such conditions, we can use the Manning equation to relate depth to discharge, provided that we know the flow cross section and boundary roughness. It is relatively easy to measure the depth, cross section, and flow rate at a location. The following form of the Manning equation is useful for extrapolating information at one flow rate to other flow rates:

$$S^{1/2}/n = Q/AR^{2/3} \qquad (3)$$

where S is the bottom slope, n is the Manning roughness coefficient, Q is the flow rate, A is flow cross–sectional area, and R is the hydraulic radius, defined as area divided by wetted perimeter. All units are in meters and seconds. If we assume that the term on the left hand side of equation 3 is constant, then we can determine a relationship between discharge and depth, since the denominator of the right hand

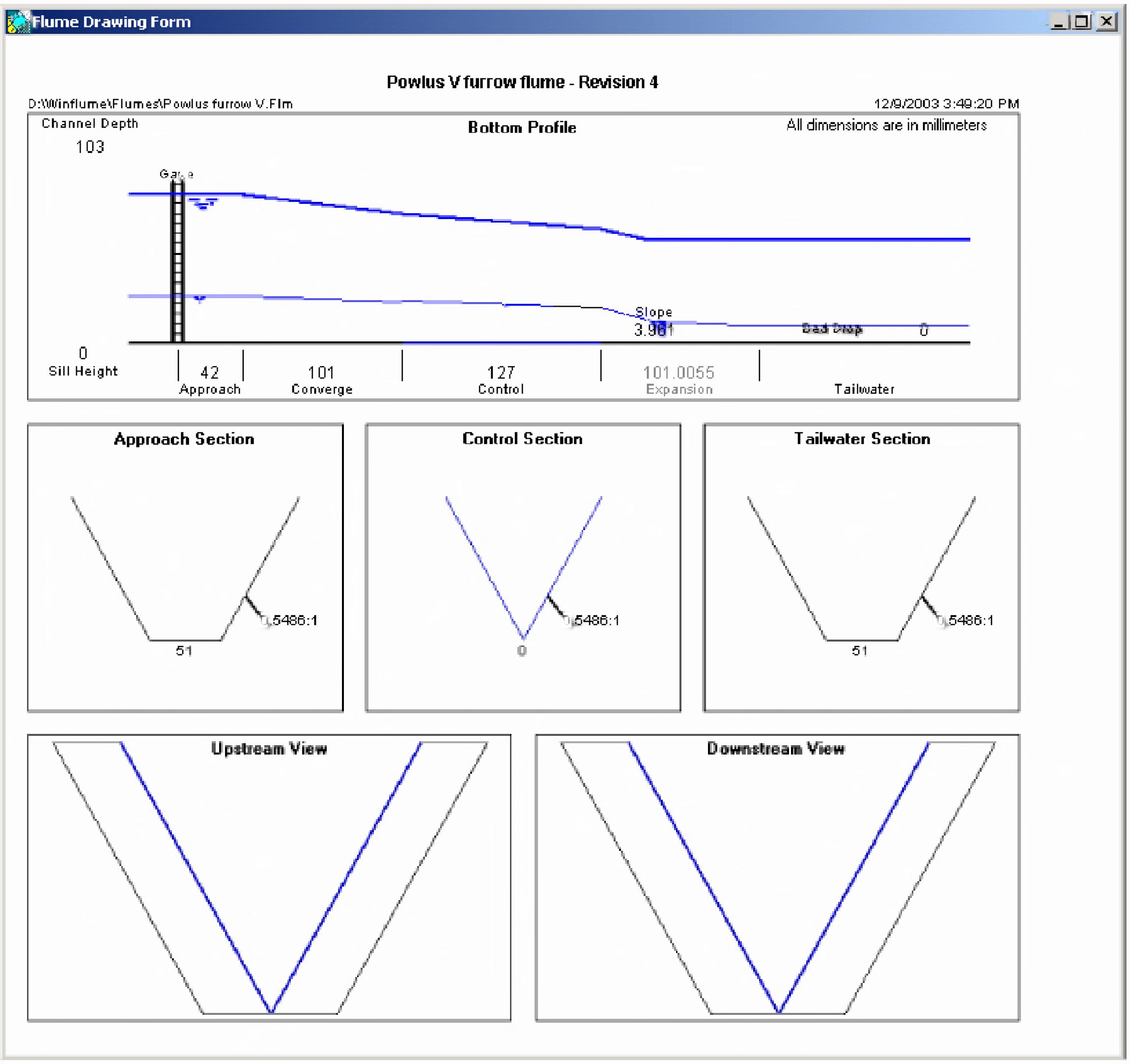

Figure 1. Dimensions (in mm) of Powlus–V furrow flume. Water surface profiles shown at minimum and maximum flow.

side of equation 3 is a function only of depth, provided that the cross–section shape is fixed. This form of equation is useful because, in many settings, the Manning *n* is only approximately known and the local slope may differ from the average field slope. The WinFlume software uses equation 3 to extrapolate the conditions in the channel over a range of flow rates if data for only one set of conditions (depth, flow–rate pair) is known.

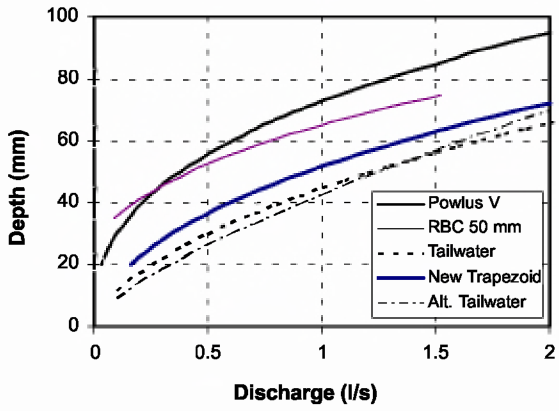

Figure 2. Water depth versus flow rate for furrow and various flumes.

Data were collected on 9 furrows with 3 inflow rates (three replicates each) on a 180–m long field in Kimberly, Idaho, on 21 September 2000. Powlus–V furrow flumes were placed at the head and tail of each furrow, and at the quarter points of field length, for a total of five flumes per furrow. Flow rates were measured at each flume periodically during the irrigation. Inflow rates averaged 0.37, 0.47, and 0.57 L/s, for the three furrows at each inflow rate. Near the end of the irrigation event after the flows, water depths, and furrow cross sections had stabilized, water depths and top widths were measured at six locations in the middle 35 m between flumes. Representative locations were chosen for each measurement that were not immediately upstream or downstream from a head cut or other abnormality. Water depths and top widths were measured with a metal scale, being careful not to push the scale into the sediment of the bed.

Prior to irrigation, furrow cross sections were roughly parabolic or triangular. By the end of the irrigation event, they were almost rectangular, with a relatively wide bottom and steep sides. The flow tended to under cut the sides of the

Table 1. Head–discharge relationships for Powlus–V and Powlus–T flumes.

Head at Gage, h_1 Mm (vertical)	Discharge (L/s)	
	Powlus–V	Powlus–T
10		0.046
12		0.064
14		0.084
16		0.106
18		0.132
20	0.034	0.160
22	0.043	0.190
24	0.055	0.223
26	0.068	0.259
28	0.083	0.298
30	0.099	0.340
32	0.118	0.385
34	0.138	0.432
36	0.160	0.483
38	0.184	0.537
40	0.211	0.594
42	0.240	0.654
44	0.271	0.717
46	0.304	0.784
48	0.339	0.854
50	0.377	0.928
52	0.418	1.005
54	0.461	1.086
56	0.507	1.170
58	0.555	1.258
60	0.606	1.350
62	0.660	1.446
64	0.717	1.545
66	0.777	1.648
68	0.839	1.756
70	0.905	1.867
72	0.973	1.983
74	1.045	2.102
76	1.120	2.226
78	1.198	2.354
80	1.280	2.486
82	1.364	2.623
84	1.453	2.763
86	1.544	2.908
88	1.639	3.058
90	1.737	3.213

furrow causing material to slough into the flow. Head cuts occurred occasionally over the length. These head cuts propagated slowly in the upstream direction. Flume design in this setting should minimize the difference in water level caused by addition of the flume to the furrow. In order to evaluate this, we need information on the existing flow conditions in the furrow over the range of flows to be encountered.

The values of $S^{1/2}/n$ computed from the measured top widths and depths assuming that the furrow shape was trapezoidal with a side–slope $z = 0.5$ (0.5 horizontal to 1.0 vertical) (i.e., roughly the furrow shape prior to irrigation) are given in figure 3. In theory, the value should not be a function of flow rate, and a single measured value can be used to determine the head–discharge relationship of the furrow. Values of $S^{1/2}/n$ for given values of S and n are given in table 2. The average field slope was 0.012 m/m. The upper quarter of the field has much higher (effective) values of $S^{1/2}/n$, suggesting either a higher slope or smaller roughness, or both. In these fields where erosion occurs, more erosion occurs at the head end, with deposition at the tail end, often resulting in a steeper slope at the head end. A smaller value of $S^{1/2}/n$ results in a greater depth for a given discharge and cross–section shape. The value used in the initial WinFlume design (3.73) is also shown in figure 3 for reference, while the average value was 3.62. The initial design value was based on assuming a flow rate of 0.5 L/s, a depth of 30 mm, and with the cross section defined by the flume approach section. The resulting head–discharge relationship is shown in figure 2, labeled “Tailwater,” since the water depth in the furrow will be the tailwater level that the flume experiences. (This represents a bottom width of 51 mm).

If we assume that the furrow cross–section shape is nearly rectangular (the shape after irrigation, with z=0.1), the values of $S^{1/2}/n$ are smaller, as shown in figure 4. An alternative furrow head–discharge relationship was developed assuming $S^{1/2}/n = 3.1$, while the average value was 3.27 (a conservative estimate). The head–discharge relationships for these conditions are labeled as the alternative or “Alt. Tailwater” curve (figs. 2 and 4). (This represents a bottom width of 90 mm). The difference in cross section shape causes the general slope of the relationship to change. However the differences may not be significant (<5 mm), or real, considering the errors in these measurement. This alternative tailwater level will be used in analysis of flume placement errors.

INFLUENCE OF FLUME PLACEMENT

Data from several prior erosion studies were used to evaluate the performance of existing Powlus–V furrow flumes and to determine the needs for a new design. During an irrigation event on 21 May 2001, eight furrows were irrigated on the same field described above. The same flow rate was applied to each furrow. In four furrows, a sheet–metal form with roughly the furrow shape was placed in the bottom of the furrow. The form provided essentially no contraction in the flow. In the other four furrows, Powlus–V flumes were installed with the invert of the flume essentially at the bottom of the furrow. Sediment was collected from these furrows as described in Trout (1996). The concentration of sediment collected in the eight furrows is shown in figure 5. The inflow rate for these tests was 0.4 L/s. It was recognized during installation that flumes placed in this position would back water up and trap sediment upstream from the flume. The data show a 43% reduction in average measured sediment moving through the flume. Even with the scatter of data, these differences were statistically significant. This is not surprising, considering the difference between the V–flume upstream water level and the (alternative) tailwater level in figure 2. At 0.4 L/s, the difference is nearly 30 mm (23 mm for the channel vs. 51 mm for the V–flume). The velocity in the upstream channel is 0.19 m/s, while the velocity in the approach to the V–flume is only 0.10 m/s. This reduction in velocity will cause sediment to deposit upstream from the flume.

Our observations suggest that the sediment will build in the approach section of the flume until the velocity is restored to the value in the upstream channel. At 0.4 L/s, this would result in sediment deposition of 29 mm in the approach section to the flume. This deposition occurs gradually, depending on the sediment load. With the sediment deposition, the velocity head changes from 0.5 to 1.9 mm. At this

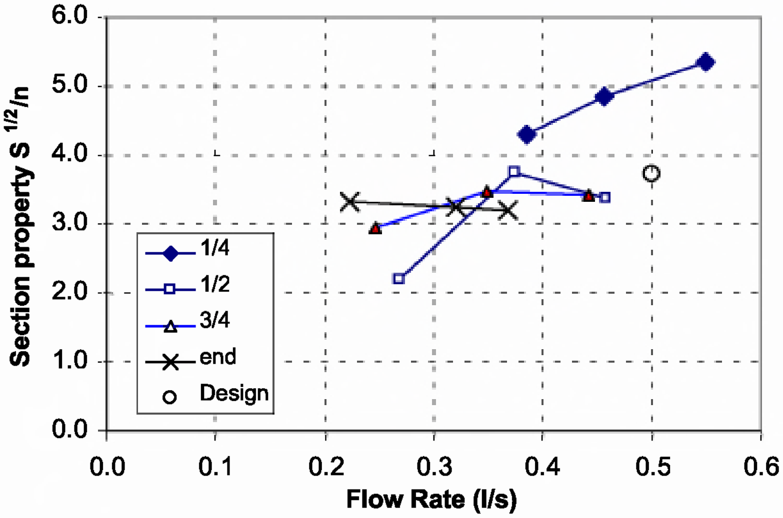

Figure 3. Channel properties based on measured depth, top–width and flow rate, assuming furrow side slope $z = 0.5$. Measurements taken at furrow–length quarter points (1/4, 1/2, 3/4, end).

flow, the systematic error caused by the change in velocity head is 7%. The same analysis at 1.0 L/s flow gives a 2–mm error caused by velocity head, which translates to a 7% error, as shown in table 3. In addition to the error caused by the change in velocity head, with this much sediment deposition, the assumption of parallel flow in the throat may no longer be valid, adding additional sources of error. (Note, if we had used the design tailwater curve, errors would have been 10% because of the higher flow velocities resulting from a narrower bottom width).

It is the decreased flow velocity in the flume approach section that causes sediment deposition. Under typical furrow irrigation conditions, any sediment that passes through the flume approach section will also pass through the throat. The only exception we have observed is massive bed–load dunes during flood flows in channels that can bury the entire structure. As shown in figure 2, the 50–mm RBC flume has a similar head at 0.4 L/s as the V–flume (49 vs. 51 mm). Thus we would expect similar performance. Calculated values for the sediment accumulation and systematic error are shown in table 3. Note that the estimated sediment accumulation caused by changes in the approach velocity exceeds the crest height of 25 mm. Unfortunately, since these flumes do not contain a side contraction, they would no longer function as a critical measuring device under these conditions. Thus we conclude that these RBC flumes are not appropriate for measuring discharges in furrows where erosion occurs.

One solution to this problem is to place the invert of the flume below the furrow bottom. In essence, this lowers the Powlus–V flume depth–discharge curve in figure 2. Tests were run with the flume invert placed slightly below the furrow bottom on 27 June 2001, with six furrows; three with the Powlus–V flumes and three with the metal forms (three replicates each). The inflow rate for this test was 0.4 L/s per

Table 2. Values of $S^{1/2}/n$ as a function of S and n.

	Slope S			
Manning n	0.008	0.010	0.012	0.014
0.025	3.58	4.00	4.38	4.73
0.030	2.98	3.33	3.65	3.94
0.035	2.56	2.86	3.13	3.38
0.040	2.24	2.50	2.74	2.96
0.045	1.99	2.22	2.43	2.63

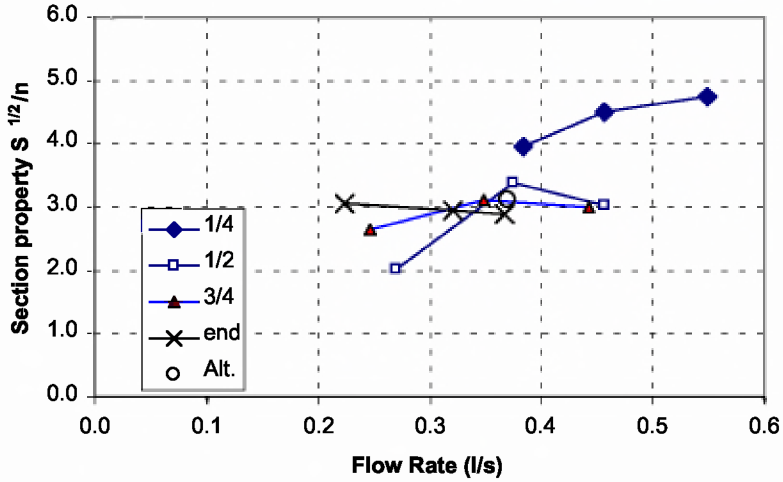

Figure 4. Channel properties based on measured depth, top–width and flow rate, assuming furrow side slope $z = 0.1$. Measurements taken at furrow–length quarter points (1/4, 1/2, 3/4, end).

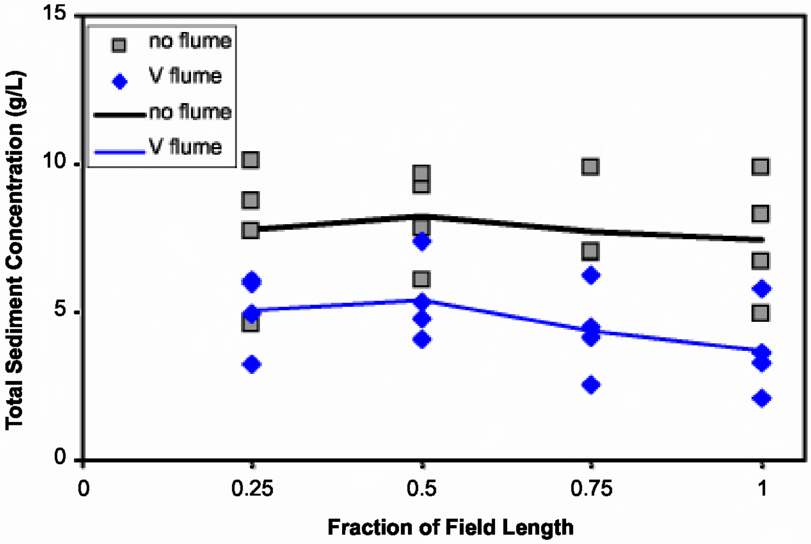

Figure 5. Sediment concentrations in water collected in furrow erosion studies on 21 May 2001. Flume invert at furrow invert. Lines shown connect averages values.

furrow. A comparison between a simple metal form and the flume showed that the flume passed 87% of the sediment that the form passed, as shown in figure 6. These differences are not statistically significant, although more differences are seen as the sediment load becomes larger toward the end of the field in this example. There are three problems with this approach to setting these V–flumes in the furrow. First, the furrow has to be dug out somewhat to install the flume. This causes a disturbance in the normal furrow cross section. Second, placing the flume bottom below the furrow bottom causes difficulty with collecting water and sediment samples on the downstream side of the flume. This can compromise our ability to collect good, representative samples. Third, sediment tends to accumulate in the approach section of the flume, as discussed above, resulting in an error in the flow rate reading for the flume. The flow rate readings will be low and thus the estimates of sediment discharge will also be low. This is less of a problem when flow and sediment are only measured at the end of a field because the flumes can be dug in without disturbing downstream conditions.

NEW FLUME DESIGN

To overcome the limitations of the Powlus–V flume, the WinFlume program was run with the tailwater level shown in figure 2. This tailwater level represents a depth of 30 mm at a flow rate of 0.5 l/s. For sediment studies, it was felt desirable to keep the invert of the throat and approach the same (i.e., no contraction from the bottom). It was also desirable to keep the approach and tailwater cross–section shape and dimensions the same as in the Powlus–V flume, since the existing water–sediment collection scoops would still work with the new design. The design choice, then, was to alter the throat width to more closely match the channel conditions. Too narrow a throat would cause the upstream water level to be too great, while too wide a throat would cause the flume to exceed its modular limit. The Winflume software was run to evaluate the performance of flumes with various throat widths. The range of flows chosen was 0.2 to 2.0 L/s. Required freeboard was 5% of the sill–referenced upstream depth. Head measurement accuracy was assumed to be ±1 mm. Discharge accuracy at high and low flows were set to 5% and 10% respectively. Results are shown in table 4.

The design criteria were satisfied with throat bottom widths varying from 0 to 28.4 mm. The upper limit on width was determined from the tailwater curve at low flows. However, we couldn't go much wider without violating the constraint on Froude number. Above a Froude number of 0.5, standing waves can exist within the approach section. These standing waves make measuring a representative upstream head extremely difficult and unreliable. For portable devices, we generally limit the Froude number to 0.45 since the entrance to the portable flume can cause additional standing waves, even at lower Froude numbers. A gradual transition to the portable flume (e.g., wing walls) can reduce this

Table 3. Analysis of the influence of sediment deposition on flume accuracy.

	Depth (mm)	Velocity (m/s)	Velocity Head (mm)	Sediment Accumulation (mm)	Flow–Rate Error from Sed. Accum. (%)	Sensitivity to 1 mm Head–Reading Error (%)
at 0.4 L/s						
Alt. tailwater channel	23	0.19	1.9	n.a.	n.a.	n.a.
Powlus V–flume	51	0.10	0.5	29	7	5
50–mm RBC flume	49	0.11	0.6	30	10	8
Powlus T–flume	33	0.18	1.6	3	2	6
at 1.0 L/s						
Alt. tailwater channel	43	0.25	3.2	n.a.	n.a.	n.a.
Powlus V–flume	73	0.15	1.2	37	7	4
50–mm RBC flume	65	0.19	1.8	26	7	5
Powlus T–flume	52	0.24	3.0	2	1	4

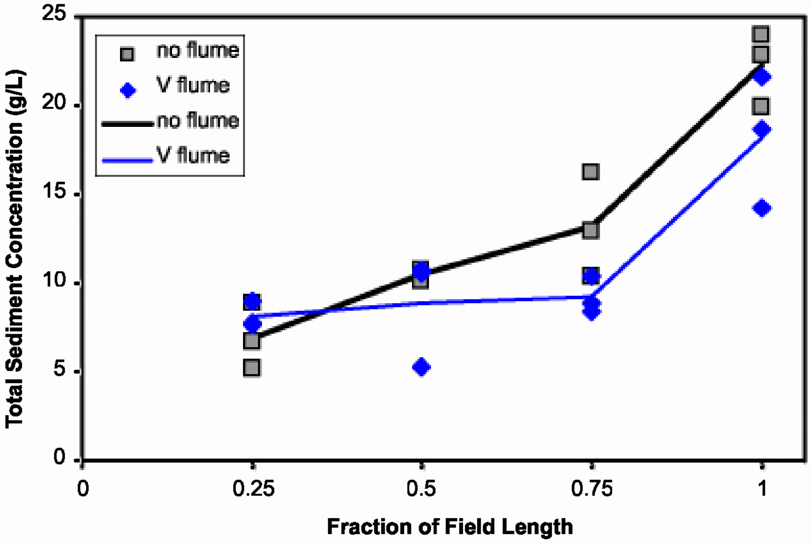

Figure 6. Sediment concentrations in water collected in furrow erosion studies on 27 June 2001. Flume invert below furrow invert to reduce flume–induced backwater effects. Lines shown connect average values.

Table 4. Design alternatives for Powlus–T flume.

Throat Width (mm)	Actual Head Loss (mm)	Actual Froude No. at Q_{max}	Extra Freeboard at Q_{max} (mm)	Submergence Protection (mm)	Error at Q_{max} (%)	Error at Q_{min} (%)
28.4	4	0.46	28	0	3.5	8.3
28	5	0.46	28	0	3.5	8.3
27	5	0.45	27	1	3.4	8.2
26	6	0.44	26	2	3.4	8.1
25	7	0.43	25	2	3.4	8.0
24	8	0.42	25	3	3.4	7.9
23	9	0.41	24	4	3.4	7.8
22	9	0.40	23	4	3.4	7.7
21	10	0.40	22	4	3.4	7.6
20	11	0.39	21	5	3.4	7.6
19	12	0.38	20	5	3.4	7.5
18	13	0.37	19	6	3.4	7.4
17	14	0.37	18	6	3.3	7.3
16	14	0.36	18	7	3.3	7.3
15	15	0.35	17	7	3.3	7.2
14	16	0.34	16	8	3.3	7.1
13	17	0.34	15	8	3.3	7.1
12	18	0.33	14	9	3.3	7.0
11	19	0.32	13	9	3.3	7.0
10	20	0.32	12	10	3.3	6.9
9	21	0.31	11	11	3.3	6.9
8	22	0.31	10	11	3.3	6.8
7	22	0.30	9	12	3.3	6.8
6	23	0.29	8	13	3.3	6.8
5	24	0.29	7	13	3.3	6.7
4	25	0.28	6	14	3.3	6.7
3	26	0.28	5	15	3.3	6.7
2	27	0.27	4	16	3.3	6.7
1	28	0.27	3	16	3.3	6.7
0	29	0.26	2	17	3.3	6.7

problem. With a general flume design, we usually recommend a situation where the submergence protection about equals the extra freeboard. This gives some protection in both directions for inaccurate estimation of conditions. For this design, this intermediate value occurs at a width of 9 mm. However, in this case, we want to minimize the influence of sediment deposition by keeping the Froude number as high as practical. With the 0.45 Froude number limit, we might have chosen a width of 27 mm. For construction simplicity, we chose one inch (25.4 mm). Regarding the sensitivity of measurements, we see from table 4 that at maximum flow, the wider flume throat has little influence on accuracy. At the lower flows, the addition of the throat width adds about 1% to the random uncertainty caused by gage–reading errors.

The longitudinal dimensions were altered in accordance with the established WinFlume design criteria and also to maintain the same overall flume length as the Powlus–V flume. These dimensions are shown in Figure 7. Because this flume is manufactured by the same person (Powlus) as the prior flume, we have named this the Powlus–T flume, T for trapezoid. The head–discharge relationships for these two flumes are shown in table 1 (called New Trapezoid).

We evaluated the expected deposition in the approach section of the flume based on maintaining the upstream velocity for the "Alternative" tailwater conditions, as was done for the other flumes. From table 3, we see that sediment deposition is on the order of 2 to 3 mm, which might cause 1 to 2% systematic error in the flume reading. Selecting a narrower throat width would have increased these systematic errors.

Field studies were conducted on 15 August 2002, to test the performance of this new flume. As in the previous study, six furrows were run, each with 0.33 l/s. The Powlus–V and Powlus–T flumes were each placed in five locations in three furrows each. The first flume in each furrow recorded inflow, the other four were used to measure flow and sediment concentration. The Powlus–V flumes were set below the bottom of the furrow so that the flume would do a reasonable job of passing sediment, even though this made water and sediment sample collection difficult. As shown in figure 8, the new Powlus–T flume still passed 9% more sediment than the Powlus–V flume, although differences were not statistically significant. No comparison was made with the simple sheet–metal form. Thus the Powlus–T flume more accurately measures the sediment loads, while avoiding difficulties in installation and avoiding the need to trade off between accurate flow measurement and accurate sediment sampling.

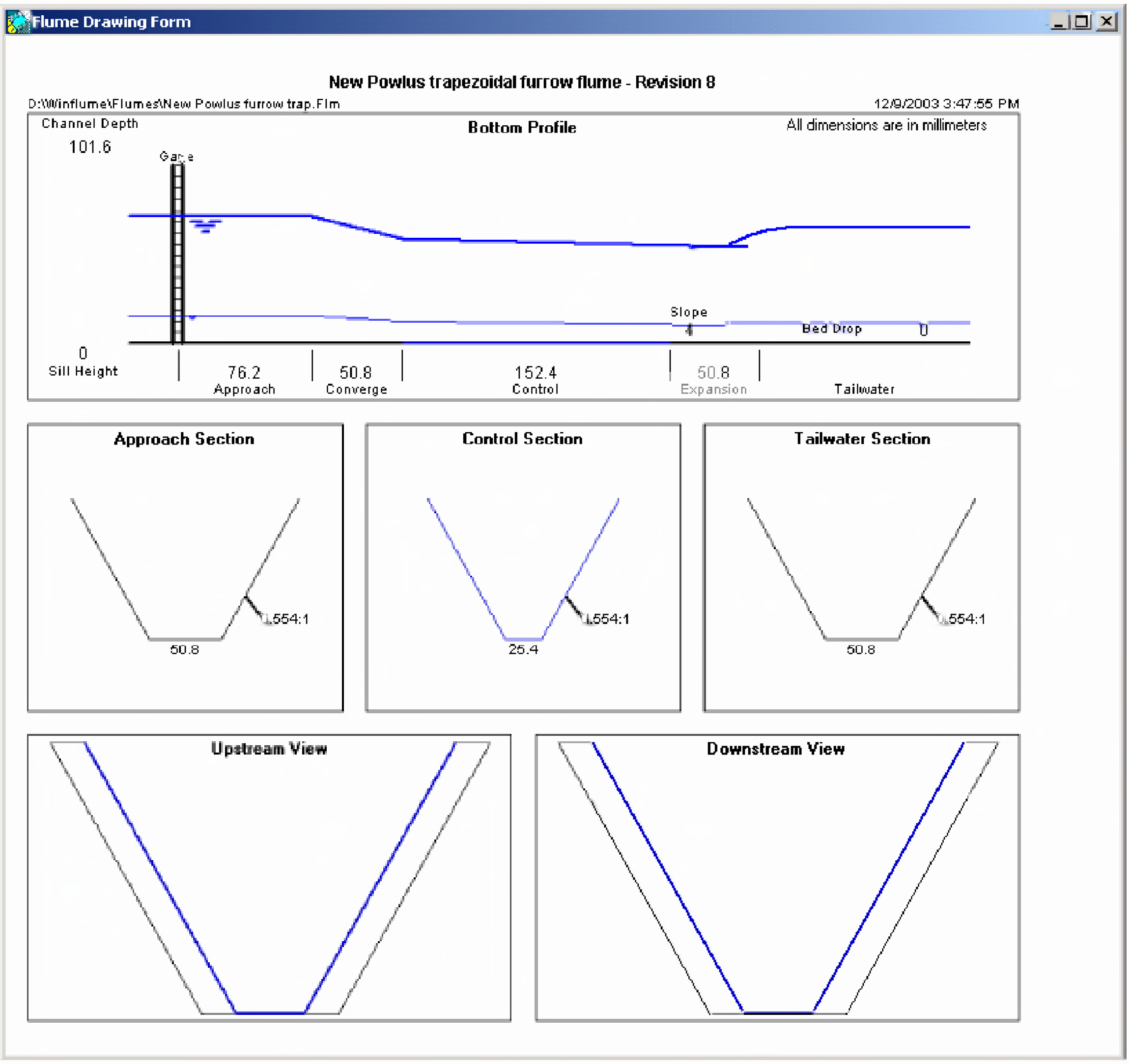

Figure 7. Dimensions (in mm) of new Powlus–T furrow flume.

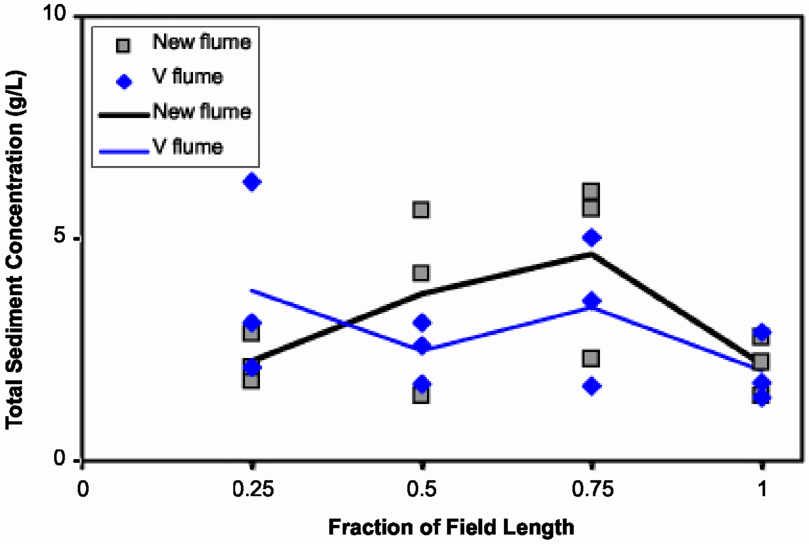

Figure 8. Sediment concentrations in water collected in furrow erosion studies on 15 August 2002. V–flume invert below furrow invert. New flume invert at furrow invert. Lines shown connect average values.

In practice, these flumes are installed level so that the water level measured with a wall gauge on the side wall of the approach section is properly referenced to the invert of the flume throat. If the field is on a slope of 0.01 m/m, the change in bottom elevation of the furrow over the 0.5–m overall length of the flume is roughly 5 mm, or about the amount of head loss required. Thus the design is somewhat conservative and will likely function properly at slightly smaller slopes and at higher values of furrow roughness. If flume submergence becomes a problem, the flume can be placed slightly higher than the furrow bottom, however this might cause sedimentation upstream and reduce the amount of sediment measured through the flume.

Overall, the new flume has worked extremely well in field tests. Technicians report that it is easier to install with less guesswork on setting the correct elevation, and less variation from installation to installation.

This flume is useful for flow rates up to 2 L/s and should function well for bottom slopes above 0.01 m/m. For flatter slopes, the flume invert may need to be raised above the furrow invert to obtain modular flow, particularly at the higher flow rates. Alternatively, a different flume shape can be developed that provides more flow–area constriction for application under these milder slopes. For example, the Powlus–V flume, when set at the furrow invert, provides modular flow at slopes above 0.005 m/m. At lower slopes, soil erosion and sediment transport are typically much less of an issue and the RBC flumes of various sizes can be used.

CONCLUSIONS

A new furrow flume was designed to measure both water and sediment flow in irrigation furrows. This new Powlus–T flume is easier to install (typically with invert on furrow bottom), passes sediments with less disruption in either the furrow cross section or upstream water levels, and when set to accurately measure sediment, provides better flow measurement accuracy than the existing Powlus–V flume. The addition of a wider throat makes the accuracy more sensitive to head reading errors, but only by about 1%. The new flume avoids systematic errors caused by sediment deposition upstream that can be as high as 7% for the V–shaped flume. This new trapezoidal flume, commercially available in fiberglass, is now recommended for studies of furrow erosion.

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