CENTRUM VOOR AGROBIOLOGISCH ONDERZOEK (CABO)
Centre for Agrobiological Research
Wageningen

CALIBRATION OF SLIT ORIFICES FOR FLOW MEASUREMENT

F.W. Zwietering

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Preface

During the period 1983-1986, field experiments were made, as a part of an investigation on interrelationships between vegetation, flow resistance and maintenance of ditches. This investigation was a joint initiative of the Centre for Agrobiological Research and the Dutch Union of Waterboards.

The necessary discharge measurements were made, i.a., with special orifices placed on a bucket. The orifices were calibrated at the Hydraulics Laboratory of the Agricultural University Wageningen. The present report gives a description of the method and results of the calibration.

The actual calibration tests were made by ing. F.J.A. Modde. The author wishes to thank ing. W. Boiten of the Delft Hydraulics Laboratory and dr.ir. W.H. van der Molen of the Wageningen Agricultural University for their review of the manuscript.

Contents

Notation

B	width of the weir crest, perpendicular to the flow direction	m
b	width of the slit orifice	m
C	correction factor for a slit orifice, equation (2)	-
D	reading of the electromagnetic flow meter	m^3s^{-1}
D_o	zero reading of the e.m. flow meter	m^3s^{-1}
E	calibration factor of the e.m. flow meter	-
h	upstream head above the weir crest, figure 10	m
Q	total volume flow rate	m^3s^{-1}
Q_e	flow rate as measured by the e.m. flow meter	m^3s^{-1}
$\bar{Q}_e$	average value of Q_e from a number of replications	m^3s^{-1}
Q_s	flow rate measured with a slit orifice flow meter without application of the correction factor	m^3s^{-1}
$\bar{Q}_s$	average value of Q_s from a number of replications	m^3s^{-1}
q	flow rate per unit crest width, Q/B	m^2s^{-1}
V	volume of water, caught by the slit orifice	m^3
s	standard deviation, equation (5)	-
t	measuring time interval	s
x	correction term on the slit width	m

1. INTRODUCTION

The amount of water flowing through a ditch is usually measured at a weir. A possible method consists of catching a part of the overflowing water during a known length of time and measuring its volume. When this part of the total flow is known, the total flow can easily be calculated.

Under most conditions the water flowing over a weir forms a free jet in the shape of a more or less thin sheet just beyond its downstream edge. It is practicable to intercept a fraction of this jet with the aid of a slit orifice mounted on a receptacle, holding the slit perpendicular to the plane of the jet (figures 1 and 2). This method was first used by J. Bon of the Institute for Land and Water Management Research in Wageningen. The orifices described here were made at the CABO.

For a known width of the crest of the weir and a known width of the slit orifice it is still not accurately known which fraction of the total flow is caught. Should this fraction be in proportion to the mentioned widths the total flow rate would be:

$$Q_s = \frac{B}{b} * \frac{V}{t} \tag{1}$$

where Q_s = total flow rate, uncorrected ($m^3 s^{-1}$)
B = width of weir crest (m)
b = width of slit orifice (m)
V = volume of water, caught by the slit orifice (m^3)
t = time measuring interval (s)

However this simple formula is not satisfactory for accurate measurements. The systematic errors arising from its use are mostly a few per cent, but can amount to more than 10 per cent (section 3.2). Therefore a correction factor is defined by:

$$C = \frac{Q}{Q_s} \tag{2}$$

where C = correction factor for the orifice (-)
Q = true value of the total flow rate ($m^3 s^{-1}$)

The correction factor has been established for each of a set of orifices and for different values of the flow rate in a calibration procedure. For this purpose the slit orifice was used simultaneously with an electromagnetic flow meter which is used here as reference. The e.m. flow meter and the whole flow system was put at our disposal by the Hydraulics Laboratory of the Agricultural University Wageningen.

Attention will be given in this report to several questions arising when slit orifices are used in field situations.

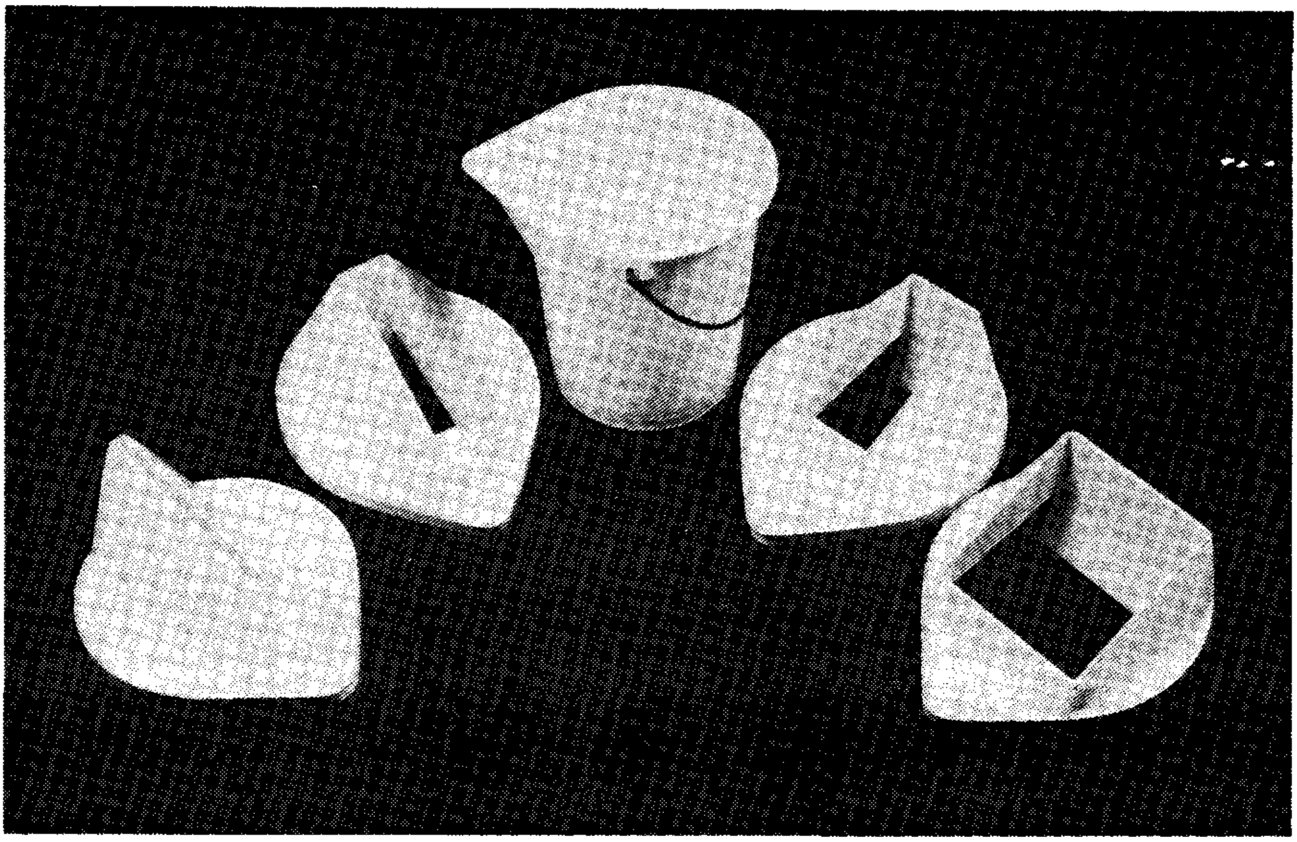

Figure 1. The slit orifices.

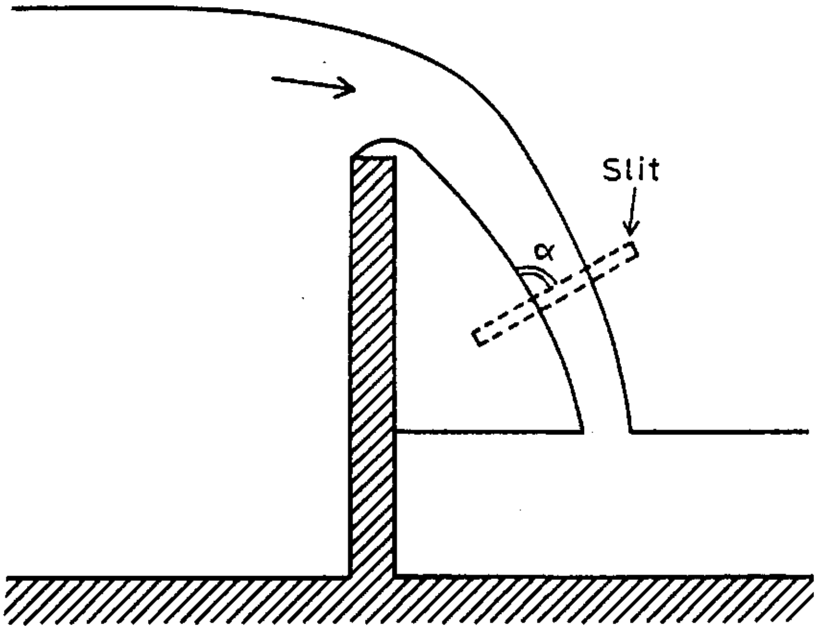

Figure 2. The orifice is placed is the jet flowing over the weir.

2. MATERIALS AND METHODS

2.1. Orifices

The orifices in use had slit widths of 1, 5, 10 and 20 cm successively. For each of the widths 1 and 5 cm there were two nearly identical orifices, designated by the numbers 1a, 1b, 5a and 5b.
In section from inside to outside the shape of each of the two long edges at the top of the slit was symmetrical.

The bucket used for collecting the water taken in by the orifices had a volume of 0.015 m^3. For one measurement it was filled to about 12 litres.

2.2. Weir

The measurements were all made on a laboratory weir which had a crest width of 0.801 m. This weir was of the sharp-crested type (Bos, 1976; ISO 1438/1, 1980) which induces a flow pattern commonly encountered at weirs in field situations and which can be easily measured with orifices.

The supply ditch upstream of the weir had everywhere the same width of 0.801 m so that no lateral contraction effects occurred.

With regard to the position of the orifice it was placed near the middle of the width of the water sheet, about 10 cm below the crest, and with an angle α of 90° (figure 2).

A few measurements were repeated with a different position of the slit orifice.

2.3. Flow rates

The flow through the supply ditch could be regulated by a control valve. Some preliminary experiments showed that the best conditions for measurement prevail when the bucket fills up to about 12 litres in 5 to 40 seconds. A fill-up time shorter than 5 s implies inaccuracy in the time measurement whereas a duration longer than 40 s is inconvenient and unnecessary. In field applications the right fill-up time can be achieved by a suitable choice of the slit width.

On the basis of a fill-up time of 5 tot 40 seconds for 12 litres a series of test flow rates was calculated, using a provisional value C=1 for the correction factor.

As an example, for a crest width of 0.801 m, a slit width of 0.05 m, the desired volume of 0.012 m^3 will be caught in 20 s when the flow rate is

$$Q \simeq \frac{0.801}{0.05} * \frac{0.012}{20} \simeq 0.01 \ m^3 s^{-1}$$

In this way a measuring program was established, see table 1.

Table 1. Numbers pertaining to the measurements.
Each number corresponds to one of the slits and to one preselected flow rate.

slit orifice (nr.) / nominal flow rate (m^3s^{-1})	1a	1b	5a	5b	10	20
0.002					1	2
0.005			3	4	5	6
0.010			7	8	9	10
0.025	11	12	13	14	15	
0.050	16	17	18	19		
0.100	20	21				
0.200	22	23				

Each one of the values of the flow rate was measured eight times with each of the matching orifices. These eight replications differed slightly with respect to the position of the orifice so that small irregularities in the flow profile were accounted for.

The flow was measured by two persons: one serving the orifice, the other measuring the time. The whole procedure for one measurement is explained in appendix 1.

2.4. Electromagnetic flow meter

The flow according to the electromagnetic flow meter (Brooks, type 7208) was calculated from

$$Q_e = E\,(D-D_o) \qquad (3)$$

where Q_e = flow according to the e.m. flow meter (m^3s^{-1})
D = reading of the e.m. flow meter (m^3s^{-1})
D_o = zero reading i.e. without flow (m^3s^{-1})
E = calibration factor (-)

This flow meter was calibrated earlier by the Hydraulics Laboratory. Its standard deviation was about 0.5 or 1 percent. The calibration factor E differed for its three measuring ranges, being 1.057 at "high range", 0.264 at "middle range" and 0.0656 at "low range".

The electromagnetic flow meter was used as a reference in the calibration of the slit orifices, so

$$Q = Q_e \qquad (4)$$

The zero reading D_o was taken at the start of the measurements after the whole water system had run for some time and temperatures had equalized. A second reading of D_o was taken at the end of the measurements. The actual reading D was taken more than once during each of the measurements.

The values of the zero reading D_o, before and after the measurements, for each of the three ranges of the e.m. flow meter are shown in table 2.

Table 2. Zero readings D_o (m^3s^{-1}) of the electromagnetic flow meter.

time range	before	after
high	-0.0016	-0.0013
middle	-0.0025	-0.0023
low	-0.0045	-0.0044

The first measurements were made with the e.m. flow meter at its "low" range setting, after this the "middle" range was used and for the last measurements the "high" range. The calculations were made with the values of D_o successively: $D_o = -0.0045$ (low), $D_o = -0.0024$ (middle) and $D_o = -0.0013$ (high). The remaining values of D_o served as a check on the drift of the apparatus.

3. RESULTS AND DISCUSSION

3.1. Correction factor

Table 3 contains the values of Q_e and $\bar{Q}_s$ and the correction factor C derived from these by formula (2). One value of $\bar{Q}_s$ in table 3 is derived from the replications in one measurement. The standard deviation is calculated from

$$s = \sqrt{\frac{\sum (Q_s-\bar{Q}_s)^2}{n-1}} \qquad (5)$$

where s = standard deviation of Q_s (m^3s^{-1})

n = number of replications (-)

Figures 3 through 8 show the resulting correction factors C for the six different slit orifices.

Tabel 3. Experimental correction factor C for the slit orifice flow meters.

Q_e flow rate as measured by the e.m. flow meter

Q_s flow rate measured with a slit orifice flow meter without application of the correction factor

$\bar{Q}_s$ average value of Q_s from a number of replications

V volume of water, caught by the slit orifice
s standard deviation, equation (5)
t measuring time interval
Explanation: first measurement: $Q_e = 0.003497\ m^3s^{-1}$

measurement number	slit number	10^3Q_e (m^3s^{-1})	$10^3V\ t^{-1}$ (m^3s^{-1})	$10^3\ \bar{Q}_s$ (m^3s^{-1})	10^3s (m^3s^{-1})	C (-)
1	10	3.497	0.443	3.549	0.032	0.985
2	20	3.410	0.860	3.443	0.024	0.990
3	5a	3.940	0.328	5.249	0.039	0.941
4	5b	4.914	0.327	5.246	0.032	0.937
5	10	4.897	0.625	5.004	0.025	0.978
6	20	4.861	1.229	4.924	0.025	0.987
7	5a	10.04	0.664	10.63	0.04	0.944
8	5b	10.02	0.670	10.74	0.03	0.933
9	10	10.00	1.261	10.10	0.07	0.990
10	20	10.00	2.514	10.08	0.13	0.993
11	1a	25.24	0.482	38.48	1.04	0.654
12	1b	25.19	0.432	34.62	0.27	0.728
13	5a	25.19	1.730	27.72	0.11	0.909
14	5b	25.19	1.704	27.30	0.17	0.923
15	10	25.15	3.245	25.99	0.57	0.968
16	1a	50.21	0.917	73.44	0.60	0.684
17	1b	50.17	0.842	67.45	1.08	0.744
18	5a	50.17	3.626	58.09	1.50	0.864
19	5b	50.19	3.533	56.60	1.38	0.887
20	1a	99.78	1.782	142.73	4.51	0.699
21	1b	99.73	1.587	126.20	3.74	0.785
22	1a	200.35	3.080	241.34	18.74$^{1)}$	0.812
23	1b	200.09	2.792	223.64	9.66	0.895

$^{1)}$In this case the slit length was less than the thickness of the water sheet.

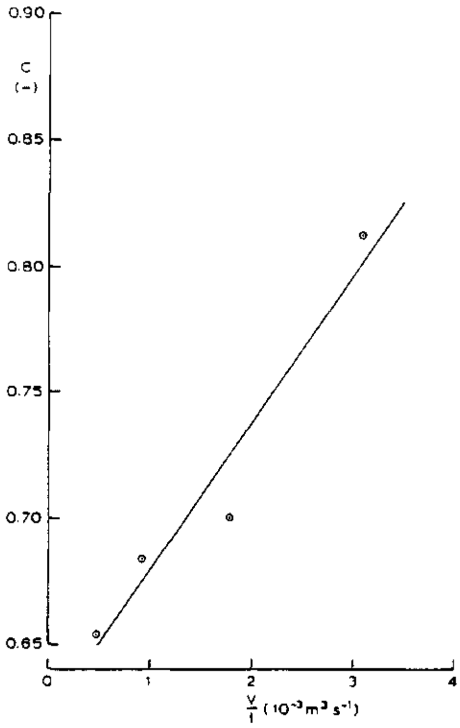

Figure 3. Correction factor C for slit orifice nr. 1a.

The correction factor always has a value less than 1.00.
Slit orifices with a little width need more correction to produce correct flow rates than orifices with more width.
The slope in the figures 3-8 is fluctuating positive and negative.

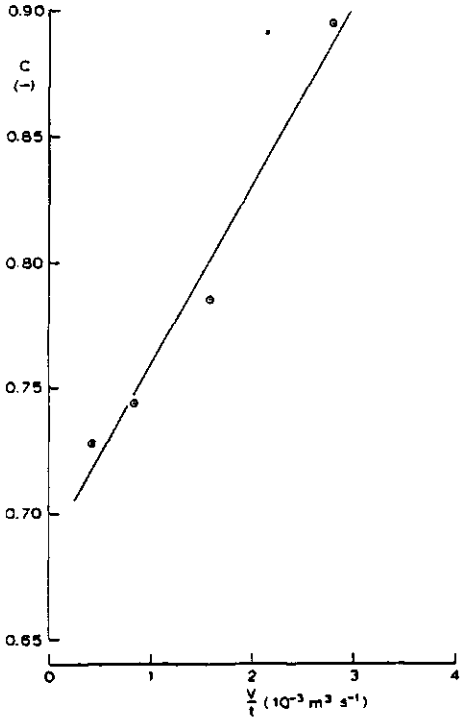

Figure 4. Correction factor C for slit orifice nr. 1b.

The correction factor for slit orifice number 1a is not the same as for number 1b, so for number 5a and 5b respectivily.

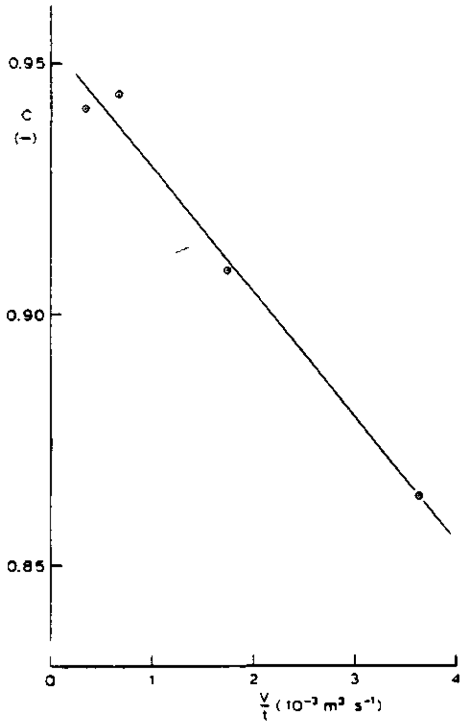

Figure 5. Correction factor C for slit orifice nr. 5a.

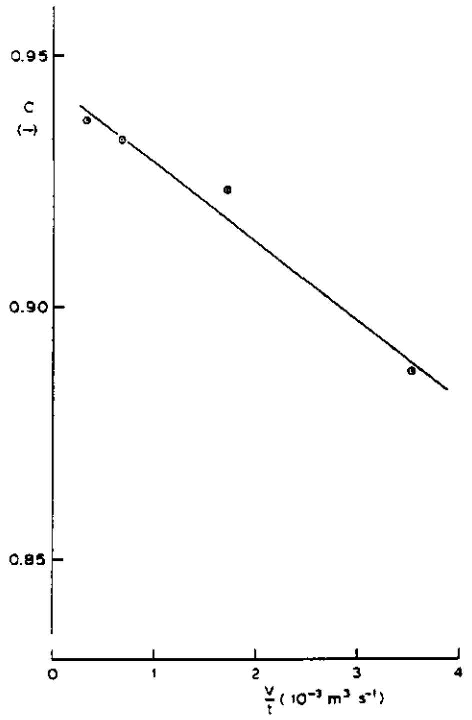

Figure 6. Correction factor C for slit orifice nr. 5b.

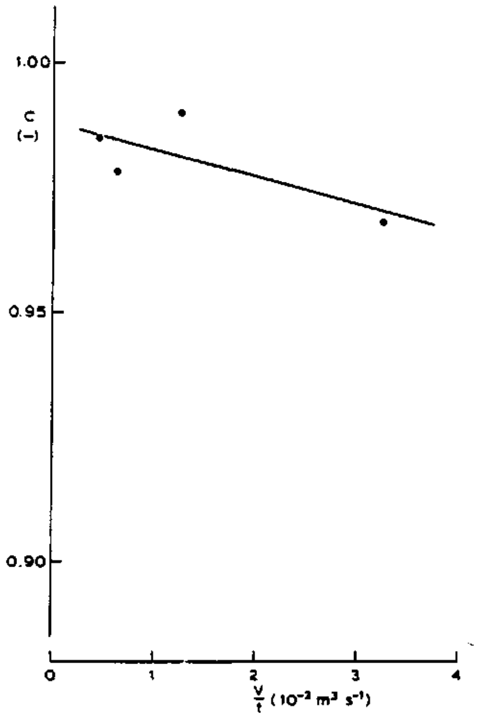

Figure 7. Correction factor C for slit orifice nr. 10.

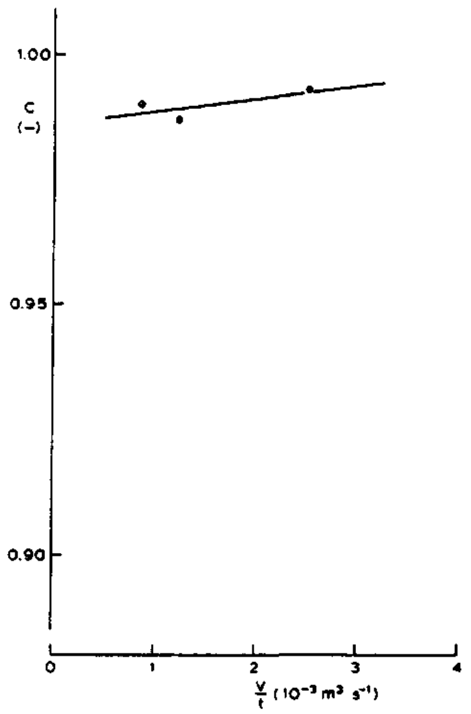

Figure 8. Correction factor C for slit orifice nr. 20.

3.2. Choice of the slit width

Since the time to fill the bucket with 12 litres of water must be between 5 and 40 seconds a suitable range of flow rates can be indicated for each slit width at a given width of the weir crest.

As an example, take a crest width equal to 1 m, and an orifice with a slit width equal to 5 cm. The lowest flow rate which may be measured by this orifice is determined using a slight modification of equation (1):

$$\frac{Q_{s,min}}{B} = \frac{1}{b} \frac{V}{t_{max}} \qquad (1a)$$

The right hand side amounts to 0.012/(0.05 x 40) = $6.0 * 10^{-3}\ m^3 m^{-1} s^{-1}$. For this value of the flow rate per unit width we read from figure 5 a correction factor C = 0.95, whence

$$Q = 0.95\ Q_s$$

Therefore

$$\frac{Q_{min}}{B} = 5.7 * 10^{-3}\ m^3 m^{-1} s^{-1}$$

For a weir with a width of 1 m this corresponds to a flow rate equal to $Q_{min} = 5.7*10^{-3}\ m^3 s^{-1}$.

In this way the minimum and maximum flow rates are calculated for all orifices. The calculations are given in appendix 2, and the results are shown in figure 9.

There is some overlap in the range of application of the different orifices. The data in table 3 show a lower accuracy for high values of $V t^{-1}$, corresponding to short measuring times. So when a choice can be made between two orifices, the one with the narrowest slit should be taken in order to get the most accurate results.

3.3. Flow measurement by water head

Often the flow is determined by measuring the upstream head h of the water above the weir crest (see figure 10). The range of application of this method will be discussed presently.

The accuracy of this method decreases badly for small flow rates because of an increase in the relative error of the measurement of the head. A minimum flow rate may be given for which this method can be used.

For a sharp-crested weir the following equation holds (Bos, 1976)

$$Q \approx 1.9\ B\ h^{1.5} \qquad (6)$$

where h = upstream head above the weir crest, see figure 10 (m)

For an assessment of the accuracy of the method, (6) is differentiated

$$\Delta Q = 1.9\ B * 1.5\ h^{0.5}\ \Delta h \qquad (6a)$$

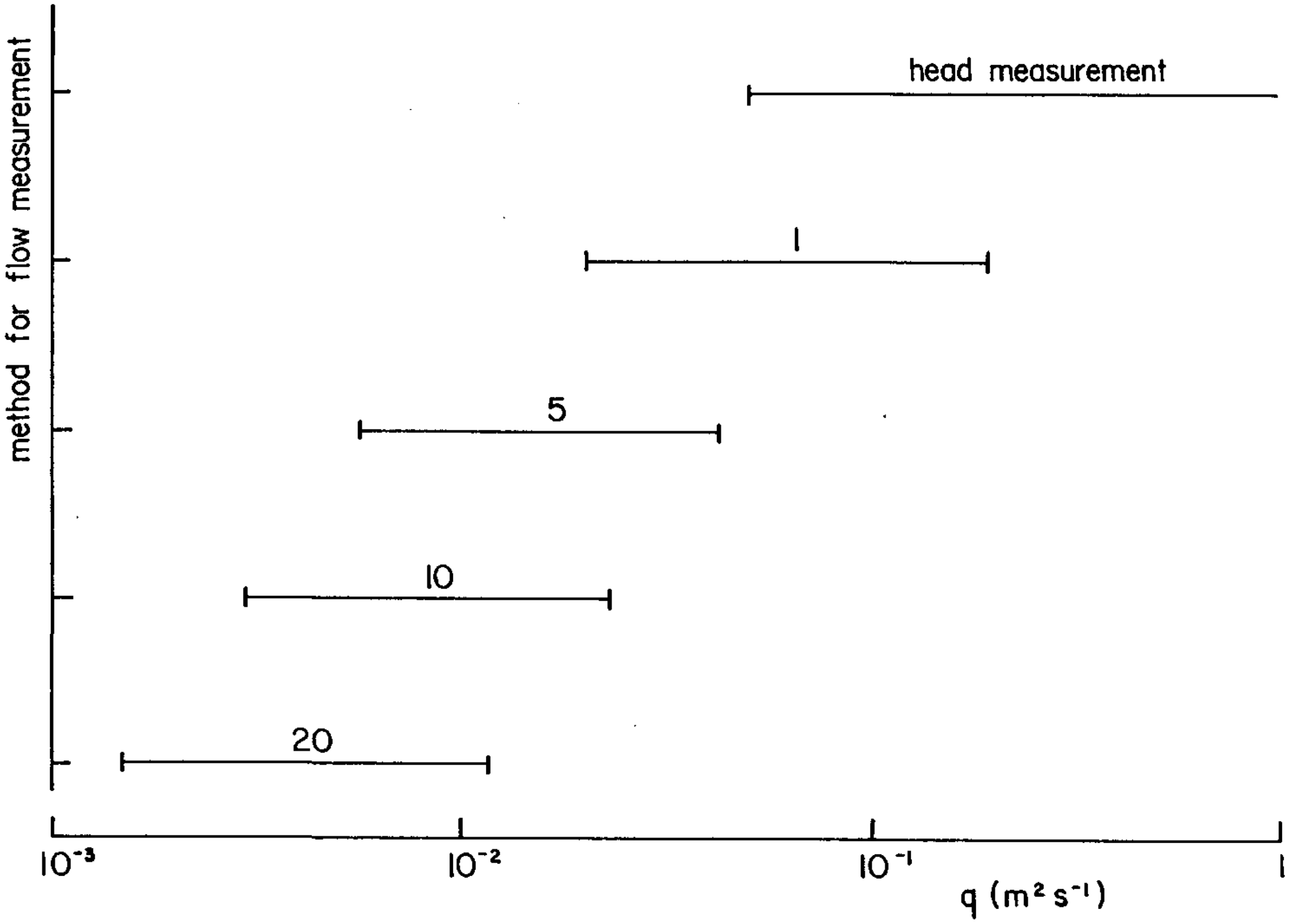

Figure 9. Range of application of the slit orifices, and the range for an alternative method, in which the water head h is measured, for the same accuracy as the orifices.
20: width of the slit (cm).

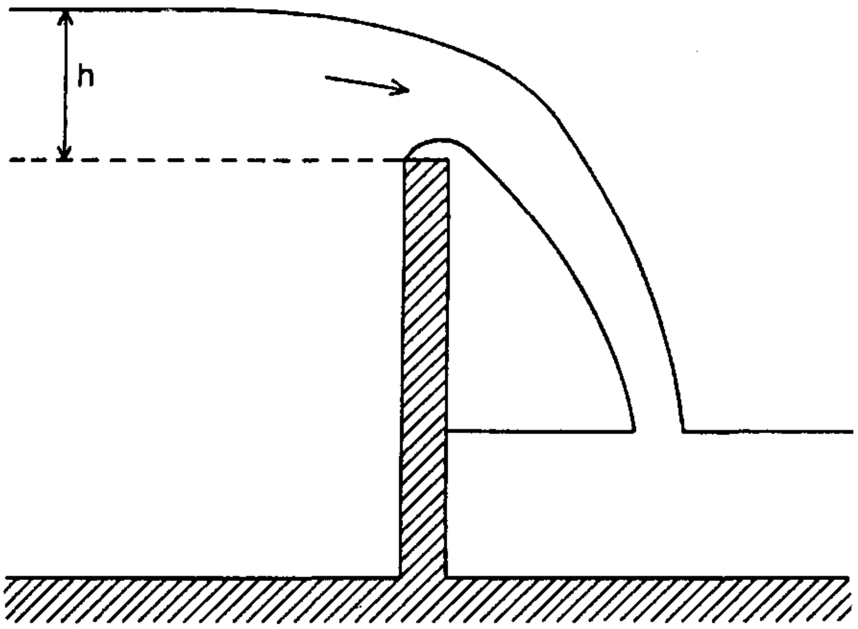

Figure 10. Upstream head h above the weir crest.

Dividing 6a into 6:

$$\frac{\Delta Q}{Q} = 1.5 \frac{\Delta h}{h} \qquad (6b)$$

Allowing a maximum error of 5% in the value of Q (the same accuracy as for the orifices, paragraph 3.5) and estimating the error in h at 3 mm, it follows

$$0.05 = 1.5 \frac{0.003}{h} \approx \text{or } h = 0.09$$

Thus the minimum difference h is 0.09 m, corresponding to a minimum flow rate per unit width:

$$q_{min} \simeq 0.051 \ m^2 s^{-1}$$

This minimum flow rate for the method of head measurement is indicated in figure 9.

3.4. Slit width and weir width

In the deriviation of formula 1 defining the uncorrected flow Q_s, it is postulated that the fraction, caught by the orifice, equals the ratio of slit width and weir crest width.
Now these last two quantities will be considered.

The total weir width may be used only when the flow rate is uniform at all points of the weir. Therefore is is necessary that the weir crest is straight and horizontal. Moreover, the perturbation at the left and right ends of the weir must be small.

In the calibration experiments the broader slit orifices showed a correction factor very close to the theoretical value 1.00, which is an indication that indeed no appreciable deviation occurred at the ends of the weir.

Repetition of some experiments with the slit orifice at the left or right end of the weir produced no other value of C. See appendix 3.

In field situations in the Netherlands the weir is mostly built between two upright walls, standing parallel to the flow. In these cases the lateral contraction above the weir is practically non-existent, and the width B of the weir needs no correction.

As we find a systematic difference between the uncorrected flow rate Q_s and the real flow rate Q leading to a correction factor C deviating from the value 1.00 we are led to the supposition that the flow conditions in the immediate neighbourhood of the slit are causing the deviation.
The part of the flow which enters the measuring device may have, in the undisturbed region above the slit, not exactly the same width as the aperture of the slit.

Consequently the correction factor C on the flow can be replaced by a correction term x on the slit width.

In that case formula (1) becomes

$$Q = \frac{B}{b + x} \quad \frac{V}{t} \qquad (7)$$

where x = correction term on the slit width (m)

As it is found that C depends on the flow rate q, also the value of x depends on q.
In figure 11 the value of x has been plotted vs. the true value of q. The values for the narrowest slit (1 cm) are not given, as they show large deviations. Although the evidence from these measurements is not conclusive it may be supposed that this correction term is a function of q only, independent of b, and given by a correlation formula (lineair regression)

$$x = 0.0017 + 0.084\ q$$

which applies for all slit widths (except 1 cm).

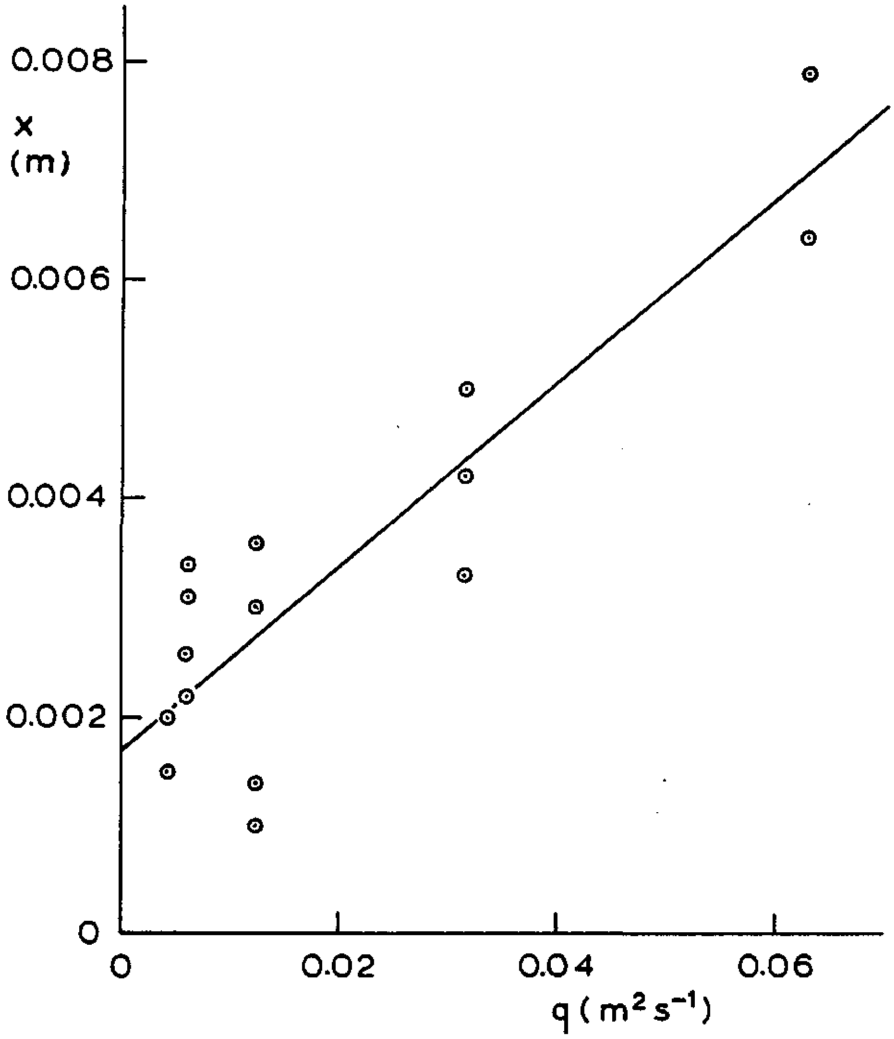

Figure 11. Slit width correction term x as a function of flow rate q per unit crest width.

3.5. Accuracy and limits of application

From the standard deviations in tabel 3 it can be deduced that the over-all accuracy of slit orifice measurements varies from 1 to 5%. The best results are achieved for broader slits at small flow rates.

The result of a measurement with a slit orifice is hardly influenced by small changes in the position of the orifice with respect to the weir crest. See appendix 3.

With a combination of slit specimens of 1, 5 and 20 cm respectively a wide range of flows can be measured.

Instead of the limit of 5 seconds mentioned earlier it is preferable to use measuring times longer than 10 seconds.

For the use of the slit there are several limitations.

The upper edge of the bucket must be kept above the water level downstream from the weir, in order to fill it only with water passing through the slit. The height of the slit orifice on the bucket is 10-15 cm. Therefore the slit orifices can be used only when the head loss over the weir exceeds 15 cm.

Moreover the use of the slit orifice is limited by the slit length, that is 20 to 30 cm, depending on the slit specimen. So the maximum thickness of the sheet caught is about 20 cm (figure 2), corresponding to (equation 6) $q \simeq 0.2\ m^2 s^{-1}$. In most cases the weir crest width is 1 to 4 m, so the maximum flow rate is 0.3 to 1.2 $m^3 s^{-1}$ respectively. For the slits 1a and 1b, at this flow rate, $V\ t^{-1} = 2*10^{-3} m^3 s^{-1}$ with accuracy of about 5%.

Summarizing there are limitations to the head h above the weir crest, to be measured with slit orifices.
Field weirs in the Netherlands are almost always built for level control and have therefore, unlike measuring weirs, a crest width as large as possible. The resulting head is moderate or small in most cases, especially in summer when flow rates are low.
Therefore in practice the use of the slit orifices will seldom be restricted by the head.

The measurement of flow rates can well be done with slit orifices when an accuracy of 5% is acceptable. It is a method that needs less time and preparation than a method in which the head is measured to calculate the flow rate. Slit orifices are recommended when flow rates over a great number of different weirs have to be measured incidentally.

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Appendix I

Procedure for flow rate measurement with a slit orifice.

One measurement consists of eight replications, of which only the first one is different.

first replication

person 1 operates the bucket with orifice	time	person 2 time measurement
"ready ?"		
		"yes"
brings the orifice into the jet with a rapid but controlled and predictable movement.		operates the stopwatch at the moment when the orifice catches the jet.
"nearly"		
"yes"		
removes the orifice from the yet with a rapid, controlled, predictable movement.		operates the stopwatch at the moment when the orifice leaves the yet.
		reads the volume in the bucket.

After this first trial it is roughly known how long it takes to catch 12 liter water in the bucket.

following replications

time

person 1 operates the bucket with orifice	person 2 time measurement
"ready ?"	
	"yes"
brings the orifice in the jet with a rapid but controlled and predictable movement.	operates the stopwatch at the moment when the orifice catches the jet.
	"nearly"
	"yes"
removes the orifice from the jet with a rapid, controlled, predictable movement.	operates the stopwatch at the moment when the orifice leaves the jet.
	reads the volume in the bucket.

Appendix 2

Limits for the flow rates per unit crest width, q, which may be measured with different slits.

These limits are determined by the condition that an amount of 0.012 m^3 water is caught between 5 and 40 seconds.
The minimum acceptable flow rate for all slits is:

$$\frac{V}{t} = \frac{0.012}{40} = 0.0003\ m^3s^{-1}$$

The maximum is

$$\frac{V}{t} = \frac{0.012}{5} = 0.0024\ m^3s^{-1}$$

In the following table the q_{min} and q_{max} for each orifice is calculated from

$$q = C\,\frac{1}{b}\,\frac{V}{t}$$

Table. Minimum and maximum values of q to be measured by slit orifices.

orifice (nr.)	b (m) 1)	minimum		maximum	
		C (-) 2)	q (m^2s^{-1})	C (-) 3)	q (m^2s^{-1})
1a	0.01	0.64	0.0192	0.76	0.1824
1b	0.01	0.71	0.0213	0.86	0.2064
5a	0.05	0.95	0.0057	0.89	0.0427
5b	0.05	0.94	0.0056	0.91	0.0437
10	0.10	0.99	0.0030	0.97	0.0233
20	0.20	0.99	0.0015	0.99	0.0119

1) b = nominal slit width
2) the value of C for a certain orifice, for the minimum flow rate
3) the value of C for a certain orifice, for the maximum flow rate

The values of q_{min} and q_{max} are shown in figure 9.

Appendix 3

Changes in the correction factor C by a changed position of the orifice with respect to the water sheet, flowing over the weir.

Table 1. The correction factor C found from three measurements and found from repetitions with the slit orifice changed in a horizontal direction parallel to the weir.

measurement number	C position with respect to the water sheet[1)] middle	one side	other side
2	0.990	0.974	0.994
12	0.728	0.723	0.712
23	0.895	0.867	0.906

[1)] and consequently left, middle or right side of the weir.

Table 2. The correction factor C found from measurement 11 at a varying angle α (see figure 2).

α	defining the position of the slit	C
> 90°	horizontal	0.645
90°	normal use of the slit	0.654
< 90°	as vertical as possible, just to intercept the jet	0.661