Runoff - Gauging

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Content

Objectives

Understand Runoff Generation

- Runoff production
- Runoff concentration
- Flood routing
- Runoff measurement
- Runoff data analysis

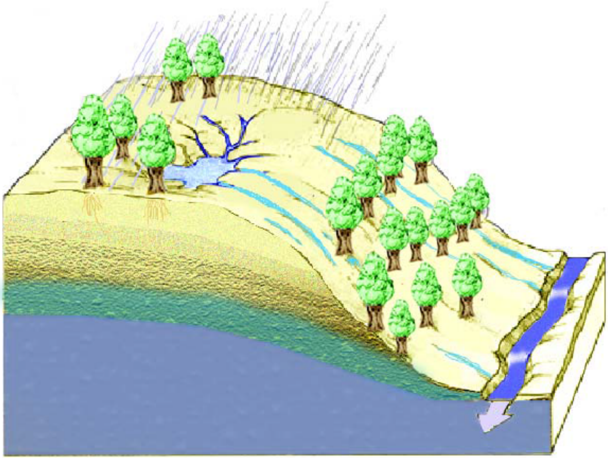
Runoff
Overflow, Cascading

Runoff generation is the key topic and concern of hydrology [**?**]: We need to know it as a generic resource and to control flood risks.

$$Q_s = P - I\,[\mathrm{mm}]$$

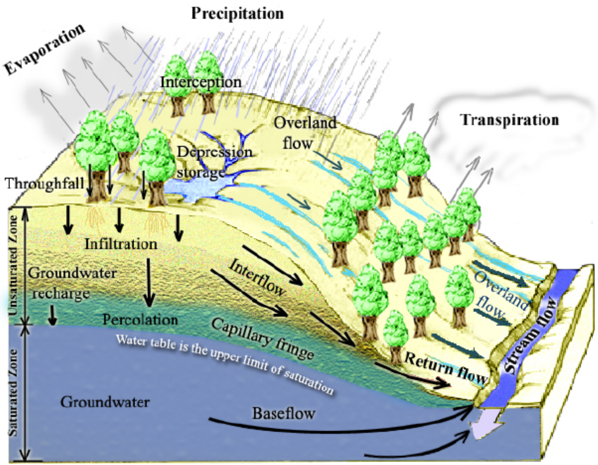
mit Q_s = surface runoff in mm, P Precipitation, I Infiltration in mm.

Runoff



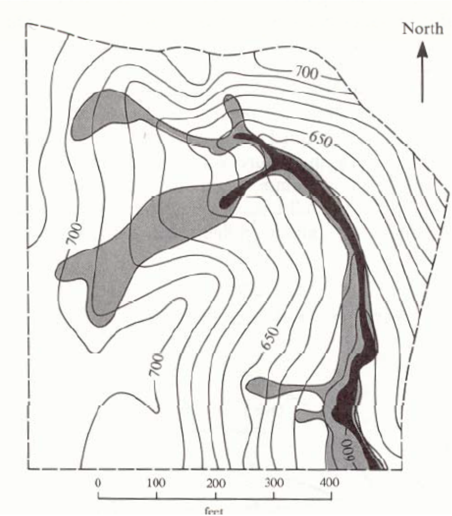
Tarboton, 2003

Runoff



Tarboton, 2003

Runoff



Dunne & Leopold, 1997

- Saturated area near rivers
- Runoff producing areas
- High correlation of moisture with runoff coefficient

Gauging Methods

Gauging Station

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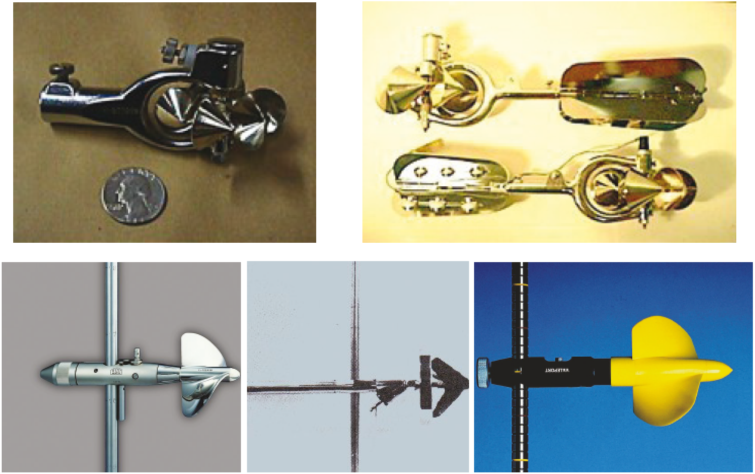
Current Meters



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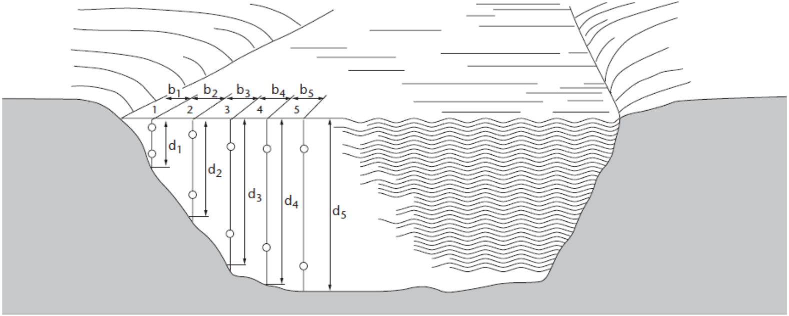
Methods



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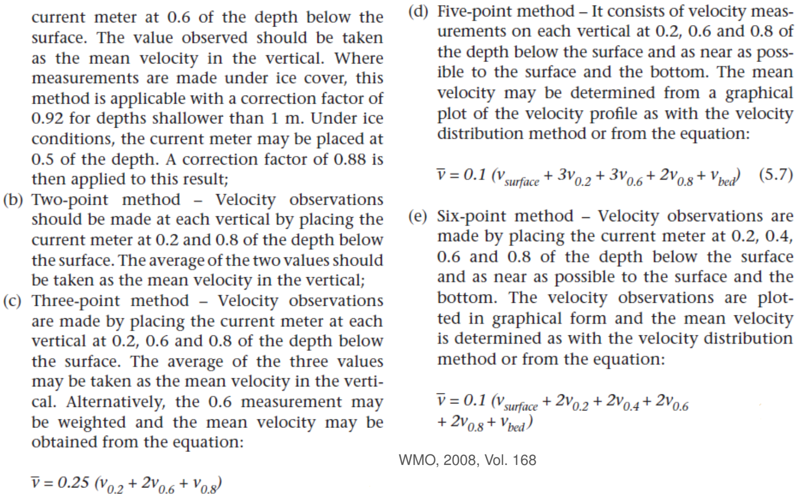
Methods



current meter at 0.6 of the depth below the surface. The value observed should be taken as the mean velocity in the vertical. Where measurements are made under ice cover, this method is applicable with a correction factor of 0.92 for depths shallower than 1 m. Under ice conditions, the current meter may be placed at 0.5 of the depth. A correction factor of 0.88 is then applied to this result;

(b) Two-point method – Velocity observations should be made at each vertical by placing the current meter at 0.2 and 0.8 of the depth below the surface. The average of the two values should be taken as the mean velocity in the vertical;

(c) Three-point method – Velocity observations are made by placing the current meter at each vertical at 0.2, 0.6 and 0.8 of the depth below the surface. The average of the three values may be taken as the mean velocity in the vertical. Alternatively, the 0.6 measurement may be weighted and the mean velocity may be obtained from the equation:

$$\bar{v} = 0.25\ (v_{0.2} + 2v_{0.6} + v_{0.8})$$

(d) Five-point method – It consists of velocity measurements on each vertical at 0.2, 0.6 and 0.8 of the depth below the surface and as near as possible to the surface and the bottom. The mean velocity may be determined from a graphical plot of the velocity profile as with the velocity distribution method or from the equation:

$$\bar{v} = 0.1\ (v_{surface} + 3v_{0.2} + 3v_{0.6} + 2v_{0.8} + v_{bed}) \qquad (5.7)$$

(e) Six-point method – Velocity observations are made by placing the current meter at 0.2, 0.4, 0.6 and 0.8 of the depth below the surface and as near as possible to the surface and the bottom. The velocity observations are plotted in graphical form and the mean velocity is determined as with the velocity distribution method or from the equation:

$$\bar{v} = 0.1\ (v_{surface} + 2v_{0.2} + 2v_{0.4} + 2v_{0.6} + 2v_{0.8} + v_{bed})$$

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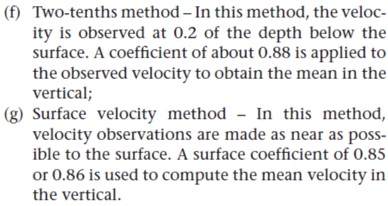
Methods

- 1-point: $v_{0.6}$
- 2-point: $(v_{0.2} + v_{0.8})/2$
- 3-point: $(v_{0.2} + v_{0.6} + v_{0.8})/3$ or $(v_{0.2} + 2 * v_{0.6} + v_{0.8})/4$
- 5-point: $(v_{surf.} + 3 * v_{0.2} + 3 * v_{0.6} + 2 * v_{0.8} + v_{bed})/10$
- 6-point:
  $(v_{surf.} + 2 * v_{0.2} + 2 * v_{0.4} + 2 * v_{0.6} + 2 * v_{0.8} + v_{bed})/10$

Methods



(f) Two-tenths method – In this method, the velocity is observed at 0.2 of the depth below the surface. A coefficient of about 0.88 is applied to the observed velocity to obtain the mean in the vertical;

(g) Surface velocity method – In this method, velocity observations are made as near as possible to the surface. A surface coefficient of 0.85 or 0.86 is used to compute the mean velocity in the vertical.

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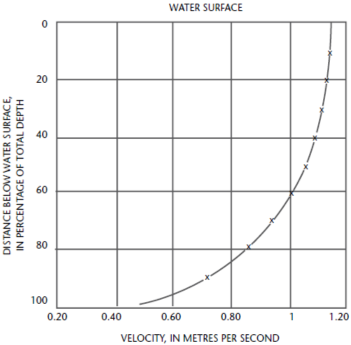
Logarithmic Profile



Ratio of observation depth to depth of water	*Ratio of point velocity to mean velocity in the vertical*
0.05	1.160
0.1	1.160
0.2	1.149
0.3	1.130
0.4	1.108
0.5	1.067
0.6	1.020
0.7	0.953
0.8	0.871
0.9	0.746
0.95	0.648

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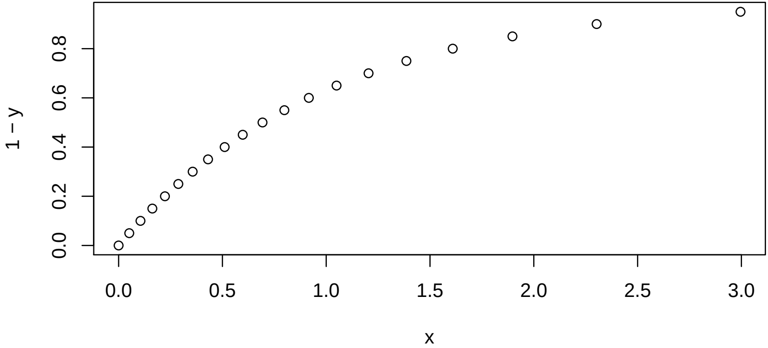
- Average at 0.6
- Surface velocity is 1/1.160=0.85
- At 0.2*depth 1/1.49 or 0.87 to 0.88 of velocity

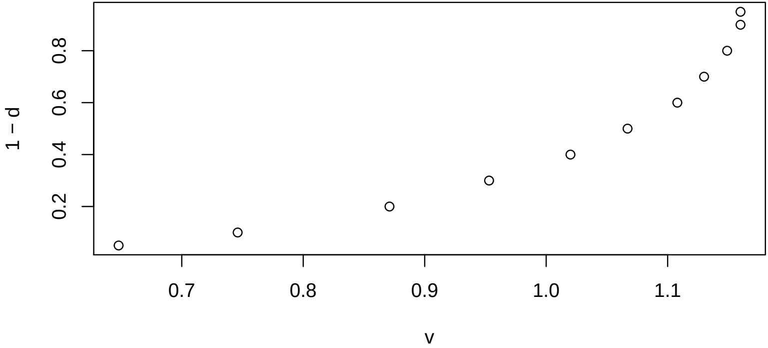
Velocity profile

Velocity as a function of depth, here 1-d:

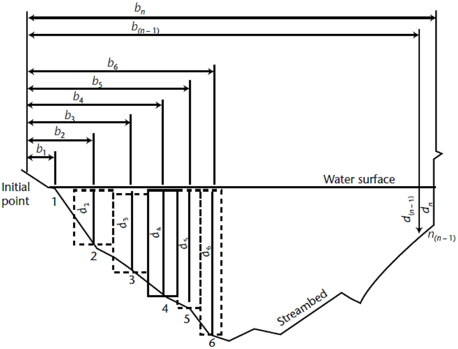


Ratio of real to mean velocity

Ratio of real to mean velocity as a function of depth, here 1-d:



Averaging of velocities



Notes:

1,2, 3,.................. n: Observation verticals

b_1, b_2, b_3,............ b_n: Distance, in metres, from the initial point to the observation vertical

d_1, d_2, d_3,............ d_n: Depth of water, in metres, at the observaion vertical

Dashed lines: Boundaries of subsections: the one heavily outlined is discussed in text.

- *b* is total distance from benchmark
- *d* is depth from water table to river-bed
- *v* is average velocity of depth profile

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Mid-section method

The mid-section method is used to average the mean velocity of a profile with its distances from the benchmark *b* and the measured depth (at the profile) *d*:

$$Q = v_1 * d_1 * \left(\frac{b_1 + b_2}{2}\right) + \ldots + v_n * d_n * \left(\frac{b_{n-1} + b_n}{2}\right)$$

with			
	Q	discharge	$[L^3/T]$
	v_i	velocity	$[L/T]$
	d	depth	$[L]$
	b_i	width	$[T]$

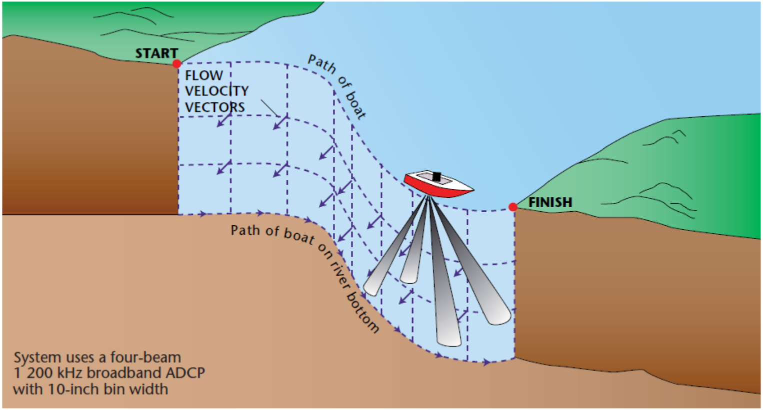
Mean-section method

The mean-section method is used to average the velocities and depths of two profiles with a width of that section *b*:

$$Q = \frac{v_1 + v_2}{2} * \frac{d_1 + d_2}{2} * b$$

with	Q	discharge	$[L^3/T]$
	v_i	velocity	$[L/T]$
	d_i	depth	$[L]$
	b	width	$[T]$

ADCP measurement



The layout of a typical acoustic Doppler measurement
(Source: United States Geological Survey, http://www.usgs.gov)

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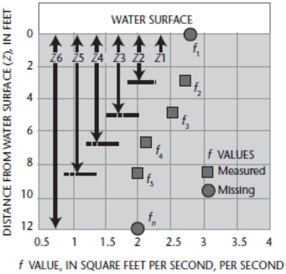
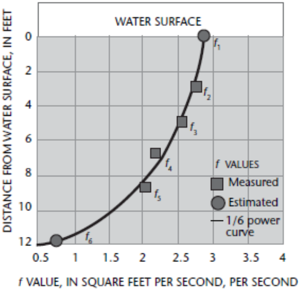
ADCP Profiler





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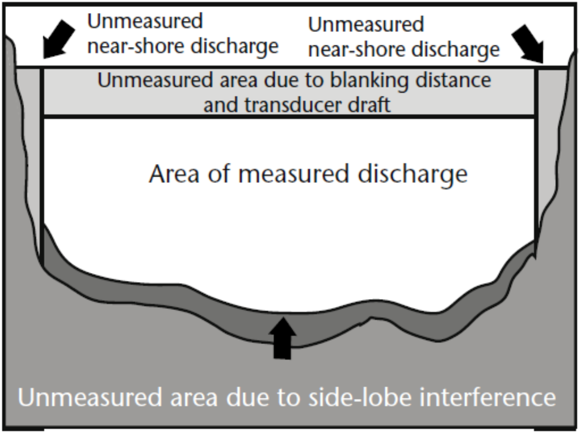
- Upper and lower end not measured
- Extrapolation needed

ADCP problematic zones



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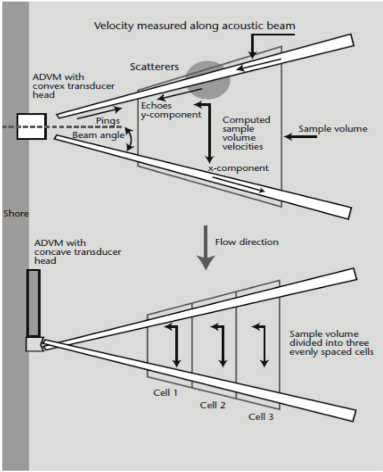
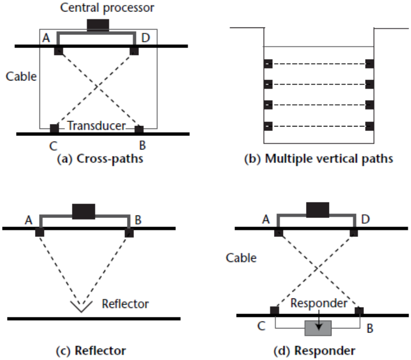
ADCP Fixed Installation





(a) Cross-paths

(b) Multiple vertical paths

(c) Reflector

(d) Responder

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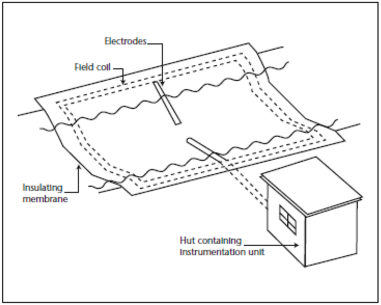
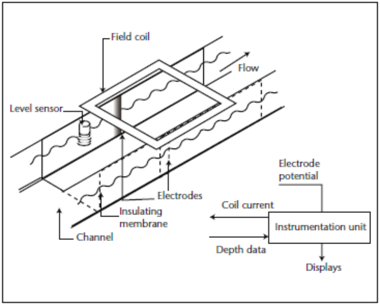
Electro-Magnetic Station





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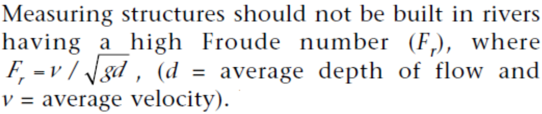
Weirs

When to use weirs?



Measuring structures should not be built in rivers having a high Froude number (F_r), where $F_r = v / \sqrt{gd}$, (d = average depth of flow and v = average velocity).

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- $F < 0.5$
- not to fast
- not to shallow

Weirs for Discharge Measurement

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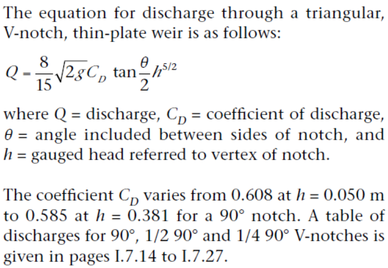
V Notch Triangular Weir

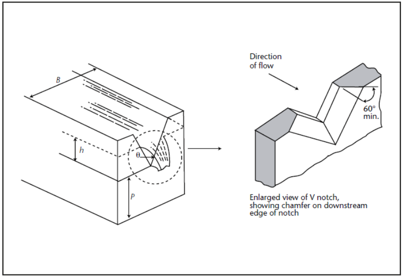


The equation for discharge through a triangular, V-notch, thin-plate weir is as follows:

$$Q = \frac{8}{15}\sqrt{2g}C_D \tan\frac{\theta}{2}h^{5/2}$$

where Q = discharge, C_D = coefficient of discharge, θ = angle included between sides of notch, and h = gauged head referred to vertex of notch.

The coefficient C_D varies from 0.608 at $h = 0.050$ m to 0.585 at $h = 0.381$ for a 90° notch. A table of discharges for 90°, 1/2 90° and 1/4 90° V-notches is given in pages I.7.14 to I.7.27.



Enlarged view of V notch, showing chamfer on downstream edge of notch

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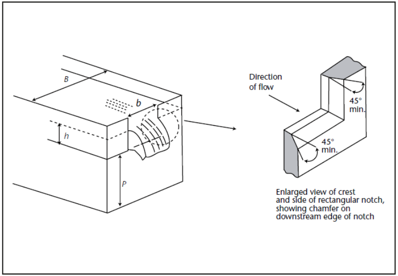
Note:

- for rather small variability (springs)
- precise for small discharges

Rectangular Thin Plate Weir



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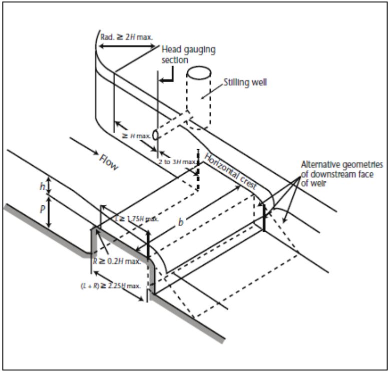
The basic discharge equation for a rectangular thin-plate weir is as follows:

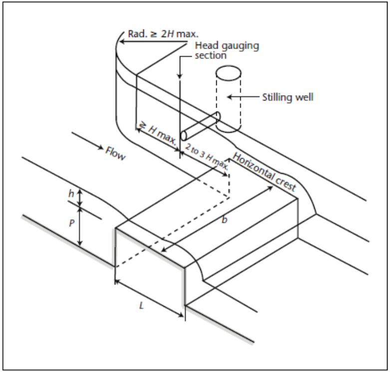
$$Q = C\frac{2}{3}\sqrt{2g}\,bh^{3/2}$$

Note:

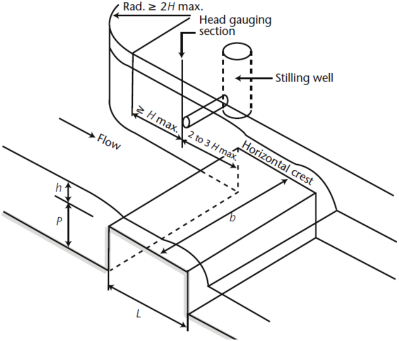
- for higher variability (creeks)
- less precise for small discharges

Large Weirs


Rad. ≥ 2H max.
Head gauging section
Stilling well
≥ H max.
2 to 3H max.
Flow
Horizontal crest
Alternative geometries of downstream face of weir
h
P
L ≥ 1.75H max.
b
R ≥ 0.2H max.
(L + R) ≥ 2.25H max.


Rad. ≥ 2H max.
Head gauging section
Stilling well
≥ H max.
2 to 3 H max.
Flow
Horizontal crest
h
P
b
L

Rectangular Profile Weir



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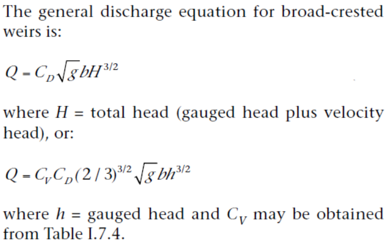
The Rehbock discharge equation for the full width weir is:

$$Q = \frac{2}{3}\sqrt{2g}C_D b h_c^{3/2}$$

where $h_c = h + 0.0012$ m, and $C_D = 0.602 + 0.083\, h/P$.

Broad Crested Weir



The general discharge equation for broad-crested weirs is:

$$Q = C_D \sqrt{g}\, bH^{3/2}$$

where H = total head (gauged head plus velocity head), or:

$$Q = C_V C_D (2/3)^{3/2} \sqrt{g}\, bh^{3/2}$$

where h = gauged head and C_V may be obtained from Table I.7.4.

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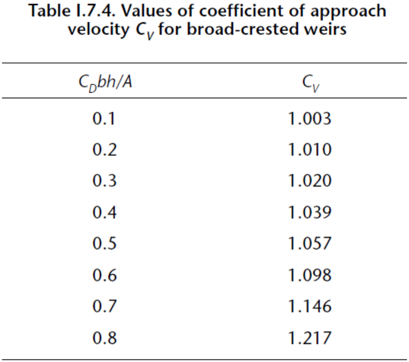
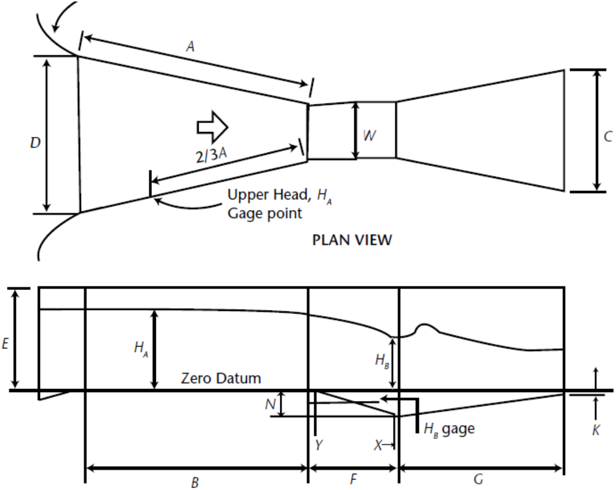


Table I.7.4. Values of coefficient of approach velocity C_V for broad-crested weirs

$C_D bh/A$	C_V
0.1	1.003
0.2	1.010
0.3	1.020
0.4	1.039
0.5	1.057
0.6	1.098
0.7	1.146
0.8	1.217

Parshall Flume



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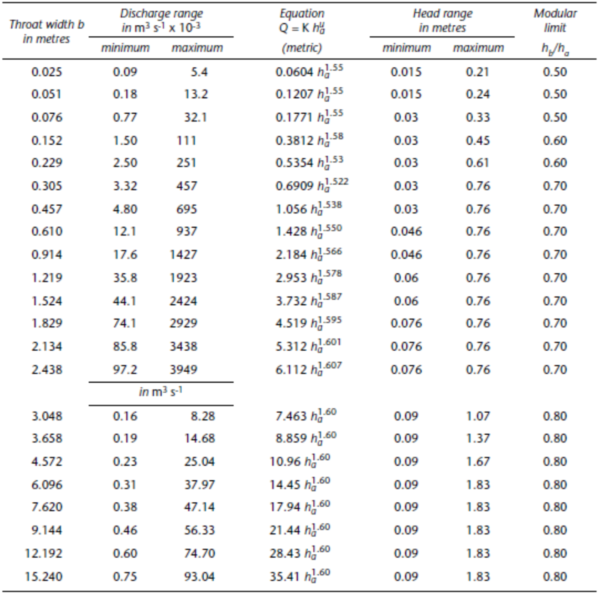
Hydrometric Weirs



Throat width b in metres	Discharge range in $m^3\ s^{-1} \times 10^{-3}$ minimum	maximum	Equation $Q = K\ h_a^u$ (metric)	Head range in metres minimum	maximum	Modular limit h_b/h_a
0.025	0.09	5.4	$0.0604\ h_a^{1.55}$	0.015	0.21	0.50
0.051	0.18	13.2	$0.1207\ h_a^{1.55}$	0.015	0.24	0.50
0.076	0.77	32.1	$0.1771\ h_a^{1.55}$	0.03	0.33	0.50
0.152	1.50	111	$0.3812\ h_a^{1.58}$	0.03	0.45	0.60
0.229	2.50	251	$0.5354\ h_a^{1.53}$	0.03	0.61	0.60
0.305	3.32	457	$0.6909\ h_a^{1.522}$	0.03	0.76	0.70
0.457	4.80	695	$1.056\ h_a^{1.538}$	0.03	0.76	0.70
0.610	12.1	937	$1.428\ h_a^{1.550}$	0.046	0.76	0.70
0.914	17.6	1427	$2.184\ h_a^{1.566}$	0.046	0.76	0.70
1.219	35.8	1923	$2.953\ h_a^{1.578}$	0.06	0.76	0.70
1.524	44.1	2424	$3.732\ h_a^{1.587}$	0.06	0.76	0.70
1.829	74.1	2929	$4.519\ h_a^{1.595}$	0.076	0.76	0.70
2.134	85.8	3438	$5.312\ h_a^{1.601}$	0.076	0.76	0.70
2.438	97.2	3949	$6.112\ h_a^{1.607}$	0.076	0.76	0.70
	in $m^3\ s^{-1}$					
3.048	0.16	8.28	$7.463\ h_a^{1.60}$	0.09	1.07	0.80
3.658	0.19	14.68	$8.859\ h_a^{1.60}$	0.09	1.37	0.80
4.572	0.23	25.04	$10.96\ h_a^{1.60}$	0.09	1.67	0.80
6.096	0.31	37.97	$14.45\ h_a^{1.60}$	0.09	1.83	0.80
7.620	0.38	47.14	$17.94\ h_a^{1.60}$	0.09	1.83	0.80
9.144	0.46	56.33	$21.44\ h_a^{1.60}$	0.09	1.83	0.80
12.192	0.60	74.70	$28.43\ h_a^{1.60}$	0.09	1.83	0.80
15.240	0.75	93.04	$35.41\ h_a^{1.60}$	0.09	1.83	0.80

Portable Parshall Flume
Mobile Installation in the Field

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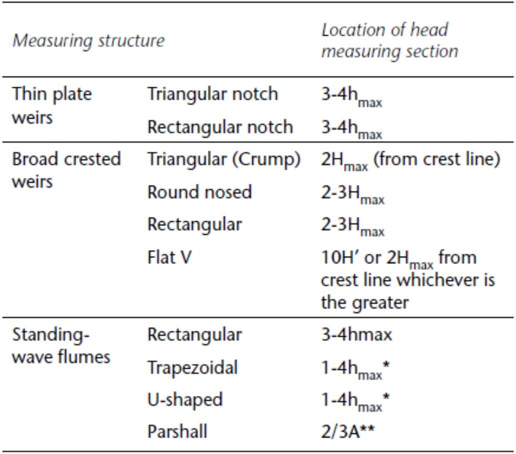
Where to measure stage?



Measuring structure		*Location of head measuring section*
Thin plate weirs	Triangular notch	3-4h_{max}
	Rectangular notch	3-4h_{max}
Broad crested weirs	Triangular (Crump)	2H_{max} (from crest line)
	Round nosed	2-3H_{max}
	Rectangular	2-3H_{max}
	Flat V	10H′ or 2H_{max} from crest line whichever is the greater
Standing-wave flumes	Rectangular	3-4hmax
	Trapezoidal	1-4h_{max}*
	U-shaped	1-4h_{max}*
	Parshall	2/3A**

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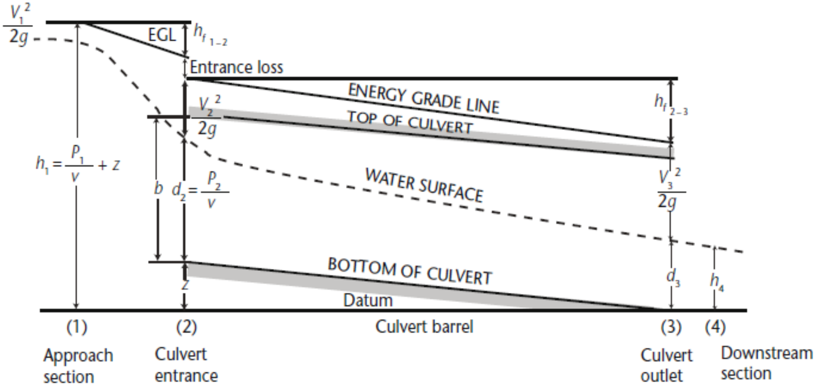
- $3 - 4 * h_{max}$ for thin plate
- $2 - 3 * H_{max}$ for broad crested
- $2/3 * A$ for Parshall

Stage-Discharge

Energy - Bernoulli



Note: The loss of energy near the entrance is related to the sudden contraction and subsequent expansion of the live stream within the culvert barrel.

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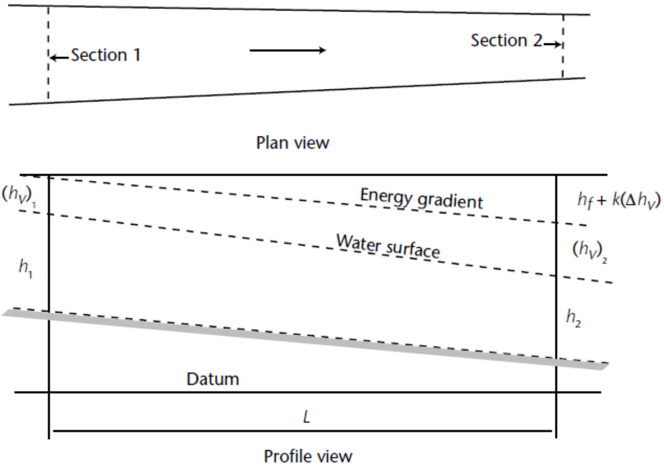
General Stage-Discharge: Manning



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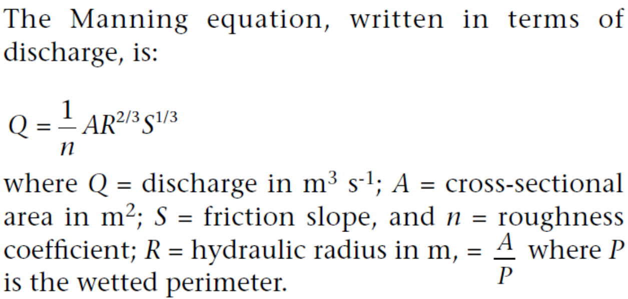
General Stage-Discharge: Manning



The Manning equation, written in terms of discharge, is:

$$Q = \frac{1}{n} A R^{2/3} S^{1/3}$$

where Q = discharge in $\mathrm{m}^3\ \mathrm{s}^{-1}$; A = cross-sectional area in m^2; S = friction slope, and n = roughness coefficient; R = hydraulic radius in m, = $\frac{A}{P}$ where P is the wetted perimeter.

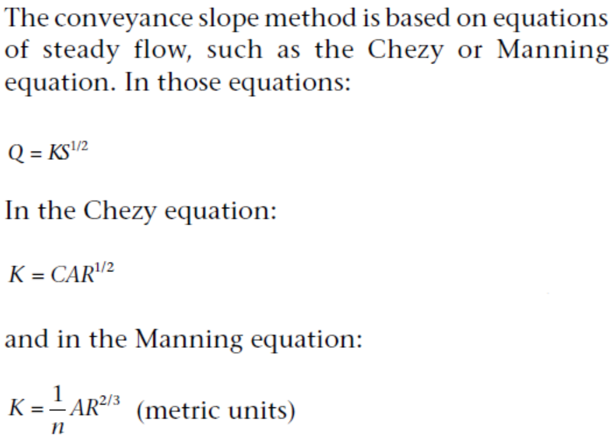
General Stage-Discharge: de Chezy

The Chezy equation is:

$$Q = CAR^{1/2}S^{1/2}$$

where C is the Chezy form of channel roughness.

Stage-Discharge: Conveyance Method



The conveyance slope method is based on equations of steady flow, such as the Chezy or Manning equation. In those equations:

$$Q = KS^{1/2}$$

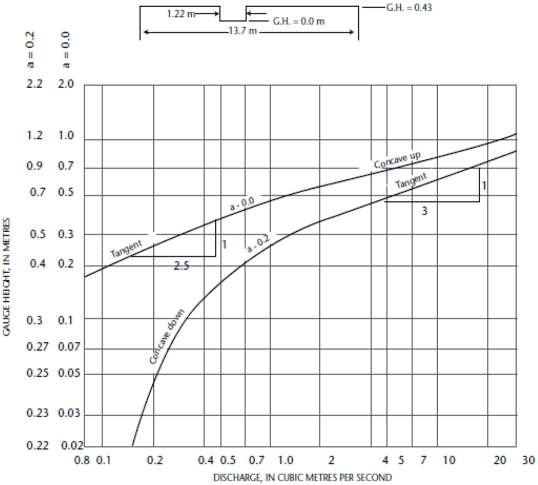
In the Chezy equation:

$$K = CAR^{1/2}$$

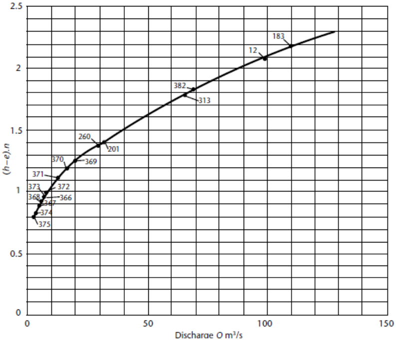
and in the Manning equation:

$$K = \frac{1}{n} AR^{2/3} \quad \text{(metric units)}$$

Stage-Discharge: Weirs



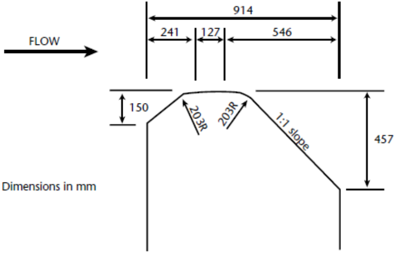
Stage-Discharge: Weirs



$$Q = C_D B H^{\beta}$$

where Q is discharge, in cubic metres per second ($m^3\ s^{-1}$); C_D is a coefficient of discharge and may include several factors; B is cross-section width, in metres (m); H is hydraulic head, in metres, and β is an exponent depending on the shape of the control (for example for V-shaped, $\beta = 2.5$ and for rectangular, $\beta = 1.5$).

Stage-Discharge: Trenton Weir

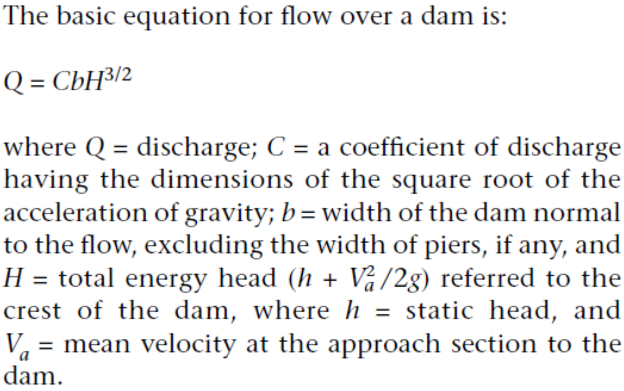


The so-called Trenton-type control is a concrete weir that is popular in the United States. The dimensions of the cross-section of the crest are shown in Figure II.1.7. The crest may be constructed so as to be horizontal for its entire length across the stream or for increased low flow sensitivity the crest may be given the shape of an extremely flat V. For a horizontal crest, the equation of the stage discharge relation, as obtained from a logarithmic plot of the discharge measurements, is commonly of the order of:

$$Q = 2.31bh^{1.65}$$

where b = top width of water surface, in metres.

Stage-Discharge for Flow over Dam



The basic equation for flow over a dam is:

$$Q = CbH^{3/2}$$

where Q = discharge; C = a coefficient of discharge having the dimensions of the square root of the acceleration of gravity; b = width of the dam normal to the flow, excluding the width of piers, if any, and H = total energy head ($h + V_a^2/2g$) referred to the crest of the dam, where h = static head, and V_a = mean velocity at the approach section to the dam.

Stage-Discharge: River Bend

The discharge equation given by Apmann (1973) is:

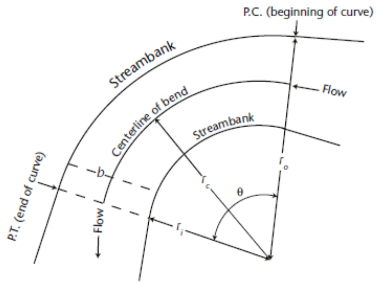
$$Q = A\sqrt{\frac{gh}{K}}$$

The value of *K* is determined from the equation:

$$K = \frac{5}{4}tgh\left(\left(\frac{r_c\theta}{b}\right)\right)log_e\left(\left(\frac{r_o}{r_i}\right)\right)$$

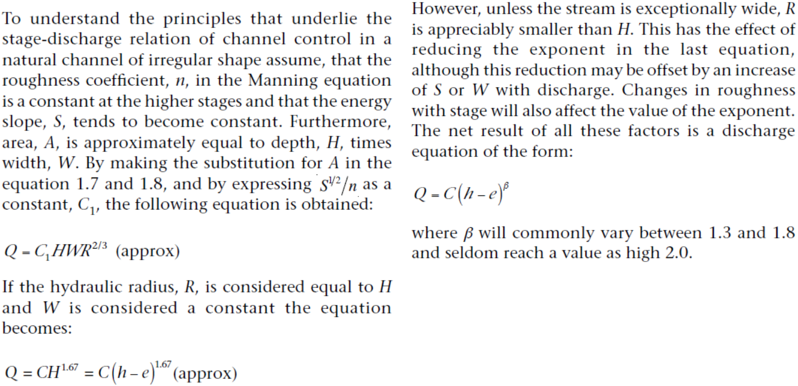
Note: *tgh* is the hyperbolic tangent.

The symbols in equation 9.8 are shown in the sketch in Figure I.9.5.



The angle θ is measured in radians.

Stage-Discharge: Natural Channel



To understand the principles that underlie the stage-discharge relation of channel control in a natural channel of irregular shape assume, that the roughness coefficient, n, in the Manning equation is a constant at the higher stages and that the energy slope, S, tends to become constant. Furthermore, area, A, is approximately equal to depth, H, times width, W. By making the substitution for A in the equation 1.7 and 1.8, and by expressing $S^{1/2}/n$ as a constant, C_1, the following equation is obtained:

$$Q = C_1 H W R^{2/3} \text{ (approx)}$$

If the hydraulic radius, R, is considered equal to H and W is considered a constant the equation becomes:

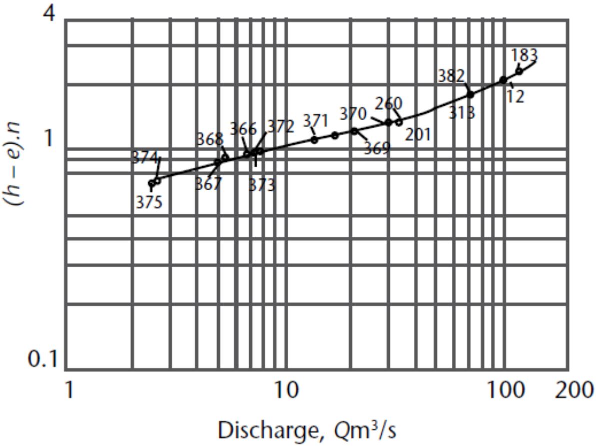
$$Q = CH^{1.67} = C(h-e)^{1.67} \text{(approx)}$$

However, unless the stream is exceptionally wide, R is appreciably smaller than H. This has the effect of reducing the exponent in the last equation, although this reduction may be offset by an increase of S or W with discharge. Changes in roughness with stage will also affect the value of the exponent. The net result of all these factors is a discharge equation of the form:

$$Q = C(h-e)^{\beta}$$

where β will commonly vary between 1.3 and 1.8 and seldom reach a value as high 2.0.

Stage-Discharge: Example



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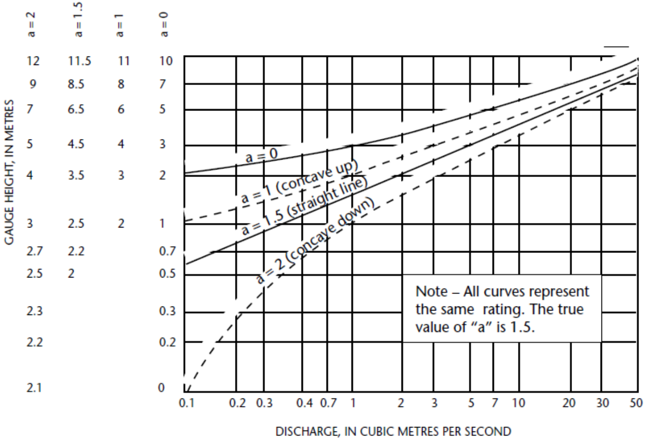
Stage-Discharge: Logarithmic



Note – All curves represent the same rating. The true value of "a" is 1.5.

Rating curve shapes resulting from the use of differing values of effective zero-flow

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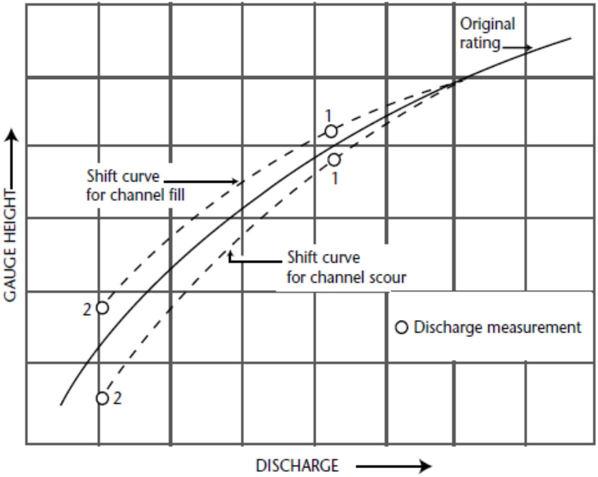
Stage-Discharge: Changes



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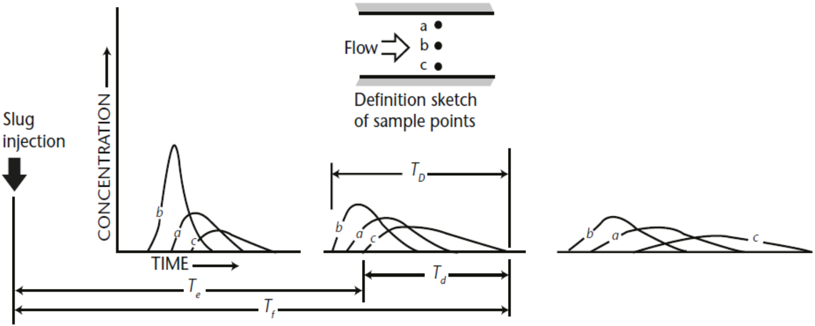
Tracer Methods

Tracer Slug Injection



Short Distance
Curve areas not the same,
lateral mixing incomplete.

Optimum Distance
Curve areas about the same,
mixing nearly complete.

Long Distance
Curve areas identical,
perfect mixing.

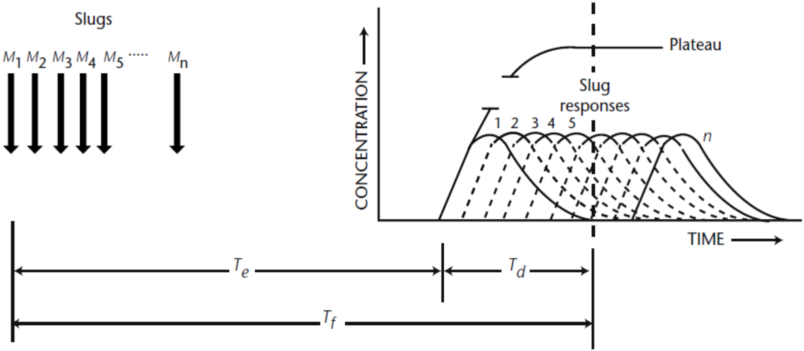
WMO, 2008, Vol. 168

Tracer Slug Injection Equation

$$Q_r = \frac{M}{\int_0^t c(t) * dt}$$

with			
	Q_r	discharge or river	$[L/T]$
	M	mass of injection	$[g]$
	$c(t)$	concentration of tracer	$[g/L]$
	dt	time step	$[T]$

Tracer Continuous Injection



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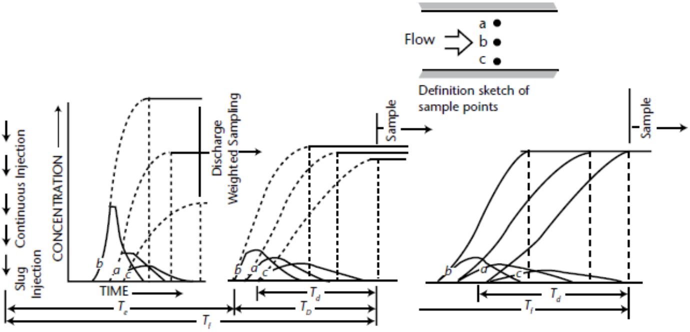
Tracer Continuous Injection Equation

$$\begin{aligned} m_t &= m_r \\ q_t * c_t &= (Q_r + q_t) * c_r \\ Q_r &\approx Q_r + q_t \\ q_t * c_t &\approx Q_r * c_r \\ Q_r &= q_t * \frac{c_t}{c_r} \end{aligned}$$

with	Q_r	discharge or river	$[L/T]$
	q_t	flow of injection	$[L/T]$
	c_t	concentration of injection	$[g/L]$
	c_r	concentration in river	$[g/L]$

Tracer Methods for Discharge Measurement



Short distance

1. Curve areas not the same, lateral mixing incomplete.
2. Rapid buildup to plateaus of different levels.
3. Dilution-discharge measurement can be obtained by using discharge proportional sampling or by discharge weighting the concentration data.

Optimum distance

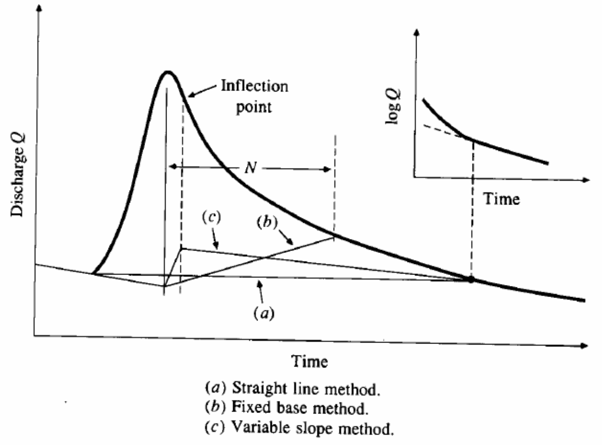
1. Curve areas about the same, mixing nearly complete.
2. Fast buildup to plateaus nearly the same in concentration mixing adequate.
3. Good dilution discharge measurement can be made with moderate length injection, T_D.

Long distance

1. Curve areas identical, perfect mixing.
2. Slow buildup to plateau concentrations exactly the same but only after long period of injection.
3. Excellent dilution discharge measurement can be made if injection is long enough to allow sampling after slowest point in section had reached an equilibrium plateau.

Direct and Baseflow

Graphical Separation



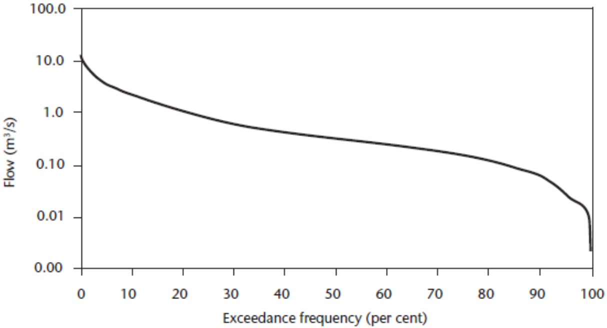
(a) Straight line method.
(b) Fixed base method.
(c) Variable slope method.

Baseflow Separation Techniques (from Chow et al, 1988).

Linsley et al. (1982) suggest as a rule of thumb N=0.2A, for A in square miles and N in days for the fixed base method (b).

Wundt Kille Method

Baseflow is separated using a flow duration curve (sort in descending order, determine median, reject Q10 and Q90 or Q95)



Source: Manual on Low-flow Estimation and Prediction (Operational Hydrology Report No. 50, WMO-No. 1029), page 50

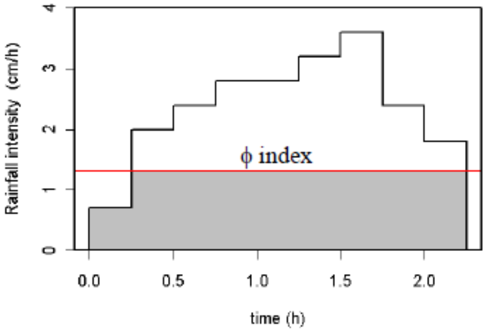
Isotopic and Chemical Separation

$$
\begin{aligned}
Q_t * c_t &= Q_d * c_d + Q_b * c_b \\
Q_t &= Q_d + Q_b \\
Q_d &= Q_t - Q_b \\
Q_t * c_t &= (Q_t - Q_b) * c_d + Q_b * c_b \\
Q_t * c_t &= Q_t * c_d + Q_b * c_b - Q_b * c_d \\
Q_t * c_t &= Q_t * c_d + Q_b * (c_b - c_d) \\
Q_b * (c_b - c_d) &= Q_t * (c_t - c_d) \\
\frac{Q_b}{Q_t} &= \frac{(c_t - c_d)}{(c_b - c_d)}
\end{aligned}
$$

with	Q_t	discharge or river	$[L/T]$
	Q_d, Q_b	direct flow, baseflow	$[L/T]$
	$c_d,\, c_r$	concentration of direct and base flow	$[g/L]$

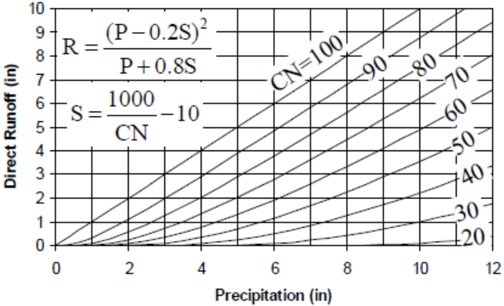
Runoff Models

Φ – *IndexMethod*



- Φ is a constant infiltration rate
- $R > \Phi: \ \ Q = R - \Phi$ runoff
- $R < \Phi: \ \ Q = 0$ no runoff
- coarse material, long time steps, large basins

SCS Method
Rural Basins

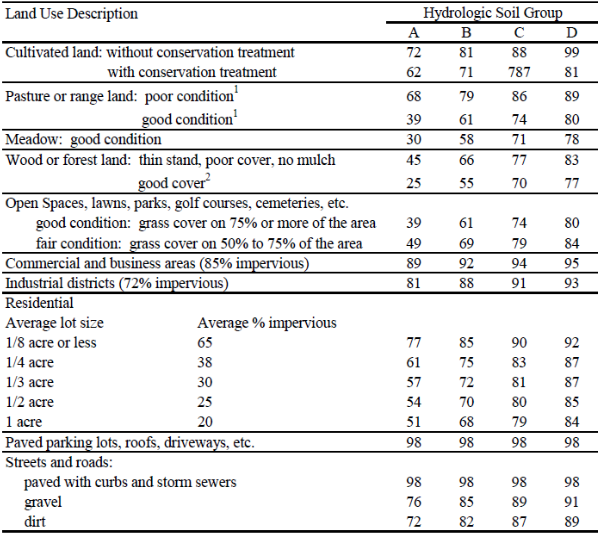


$$R = \frac{(P - 0.2S)^2}{P + 0.8S}$$

$$S = \frac{1000}{CN} - 10$$

- yields total runoff in [mm]
- regional model (!), conversion to SI [mm]: CN*25.4

SCS Method



Land Use Description		Hydrologic Soil Group			
		A	B	C	D
Cultivated land: without conservation treatment		72	81	88	99
with conservation treatment		62	71	787	81
Pasture or range land: poor condition[1]		68	79	86	89
good condition[1]		39	61	74	80
Meadow: good condition		30	58	71	78
Wood or forest land: thin stand, poor cover, no mulch		45	66	77	83
good cover[2]		25	55	70	77
Open Spaces, lawns, parks, golf courses, cemeteries, etc.					
good condition: grass cover on 75% or more of the area		39	61	74	80
fair condition: grass cover on 50% to 75% of the area		49	69	79	84
Commercial and business areas (85% impervious)		89	92	94	95
Industrial districts (72% impervious)		81	88	91	93
Residential					
Average lot size	Average % impervious				
1/8 acre or less	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	87
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
Paved parking lots, roofs, driveways, etc.		98	98	98	98
Streets and roads:					
paved with curbs and storm sewers		98	98	98	98
gravel		76	85	89	91
dirt		72	82	87	89

- soil groups A,B,C,D
- vegetation type
- yield Curve Numbers (CN-values)

SCS Method

	Total 5-day antecedent rainfall (in)	
AMC group	Dormant Season	Growing Season
I	Less than 0.5	Less than 1.4
II	0.5 to 1.1	1.4 to 2.1
III	Over 1.1	Over 2.1

$$\mathrm{CN(I)} = \frac{4.2\mathrm{CN(II)}}{10 - 0.058\mathrm{CN(II)}}$$

and

$$\mathrm{CN(III)} = \frac{23\mathrm{CN(II)}}{10 + 0.13\mathrm{CN(II)}}$$

- normal II
- if dry I
- if wet III

SCS Equation
Basic Assumptions

The SCS equation is based on the assumption that:

$$\frac{F}{S} = \frac{Q}{(P - I_a)}$$

with	F	infiltration amount	$[mm]$
	S	maximum storage	$[mm]$
	Q	runoff	$[mm]$
	P	precipitation	$[mm]$
	I_a	initial loss	$[mm]$

We also assume that the water balance holds:

$$F = (P - I_a) - Q$$

SCS Equation
Solution

The SCS equation is derived by combining both assumptions and solving for Q:

$$\begin{aligned}
F &= (S * Q)/(P - I_a) \\
F &= (P - I_a) - Q \\
(P - I_a) - Q &= (S * Q)/(P - I_a) \\
(P - I_a)^2 - Q * (P - I_a) &= (S * Q) \\
(P - I_a)^2 &= (Q * S) + Q * (P - I_a) \\
(P - I_a)^2 &= Q * (P + S - I_a) \\
Q &= \frac{(P - I_a)^2}{(P + (S - I_a))}
\end{aligned}$$

SCS Equation
Initial loss

The equation is simplified by expressing I_a as a function of S:

$$\begin{aligned} I_a &= f * S \\ f &= 0.1 \\ Q &= \frac{(P - f * S)^2}{(P + (S - f * S))} \\ Q &= \frac{(P - f * S)^2}{(P + ((1 - f) * S))} \\ Q &= \frac{(P - 0.1 * S)^2}{(P + (0.9 * S))} \end{aligned}$$

For U.S. f=0.2 for Europe usually f=0.05-0.1.

SCS Equation

Runoff Q in [mm] can be calculated using the equation:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S)}$$

with			
	F	infiltration amount	$[mm]$
	S	maximum storage	$[mm]$
	Q	runoff	$[mm]$
	P	precipitation	$[mm]$
	I_a	initial loss	$[mm]$

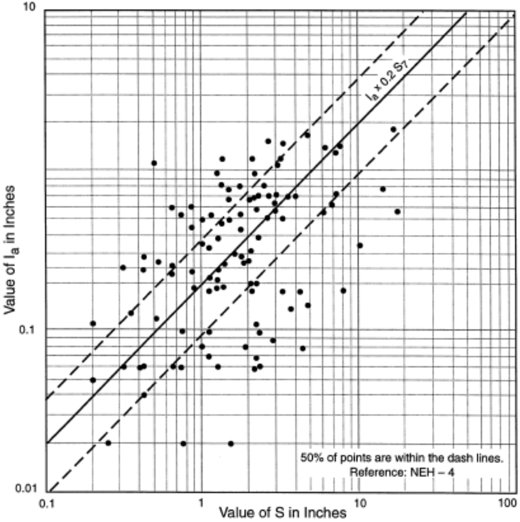
Curve Numbers

The storage can be translated into curve numbers or CN into storage using:

$$
\begin{aligned}
S &= \frac{1000}{(S+10)} \\
S &= f_c * \left[\frac{1000}{(S+10)}\right] \\
S &= \frac{25,400}{(S+254)}
\end{aligned}
$$

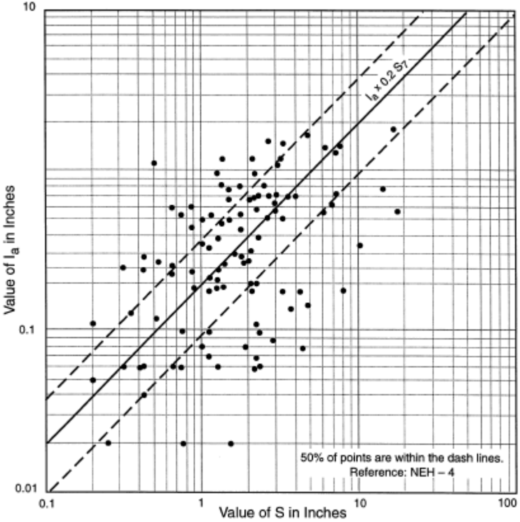
S	maximum storage	$[mm]$
CN	curve number	$[-]$
f_c	conversion inches $\rightarrow$ mm	$[-]$ = 25.4

Estimation of initial loss and total storage



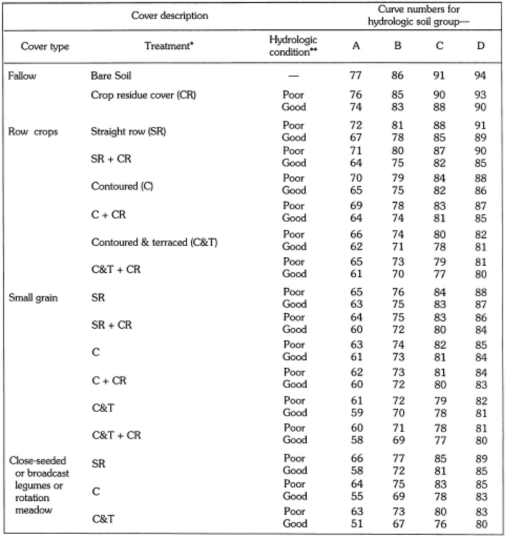
- Regional experiments I_a versus S
- S estimated from water balance
- Requires measurement of P, Q, F

Estimation of initial loss and total storage



- Regional experiments I_a versus S
- S estimated from water balance
- Requires measurement of P, Q, F

Curve Numbers

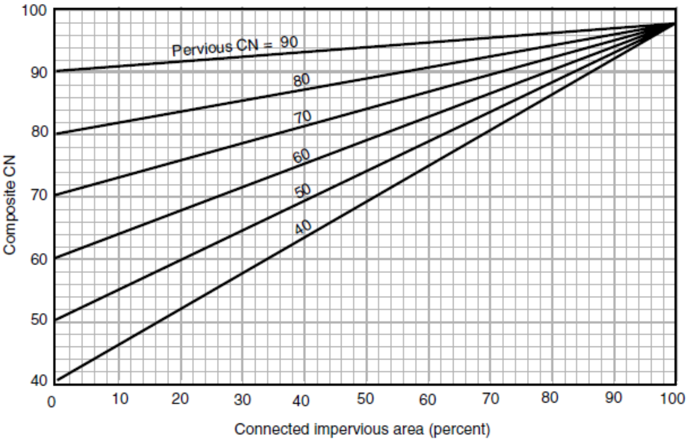


Cover description			Curve numbers for hydrologic soil group—			
Cover type	Treatment*	Hydrologic condition**	A	B	C	D
Fallow	Bare Soil	—	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T + CR	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T + CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80

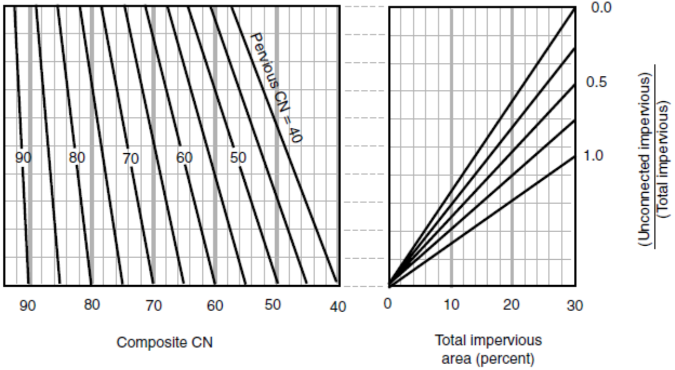
Sample curve numbers. Reference: TR-55

- soil for hydrologic groups
- vegetation specifically for agriculture

Curve Numbers
Impervious Area Correction



Curve Numbers
Impervious Area Correction



Summary

- Measurement methods: Guelph, double ring, single ring and suction plate
- Models: Horton, Philip, Green-Ampt, Haverkamp
- Application: Runoff modeling, recharge, pollutants