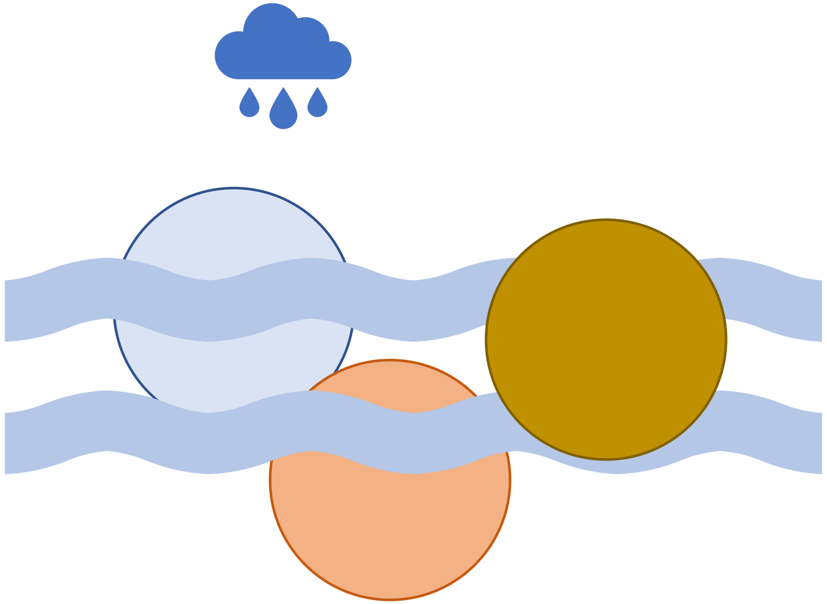
Surface Water Quality Modeling

CEE-EGIN 577



C. D. Guzman, PhD

Week 3

Monday, Feb 10, 2020

Water-Quality Environments

Rivers and Streams

River Types

We are primarily concerned with the hydrogeometric properties of rivers for modeling, that is the hydraulic (flow, velocity, dispersion) and the geometric (depth, width, slope).

River Types

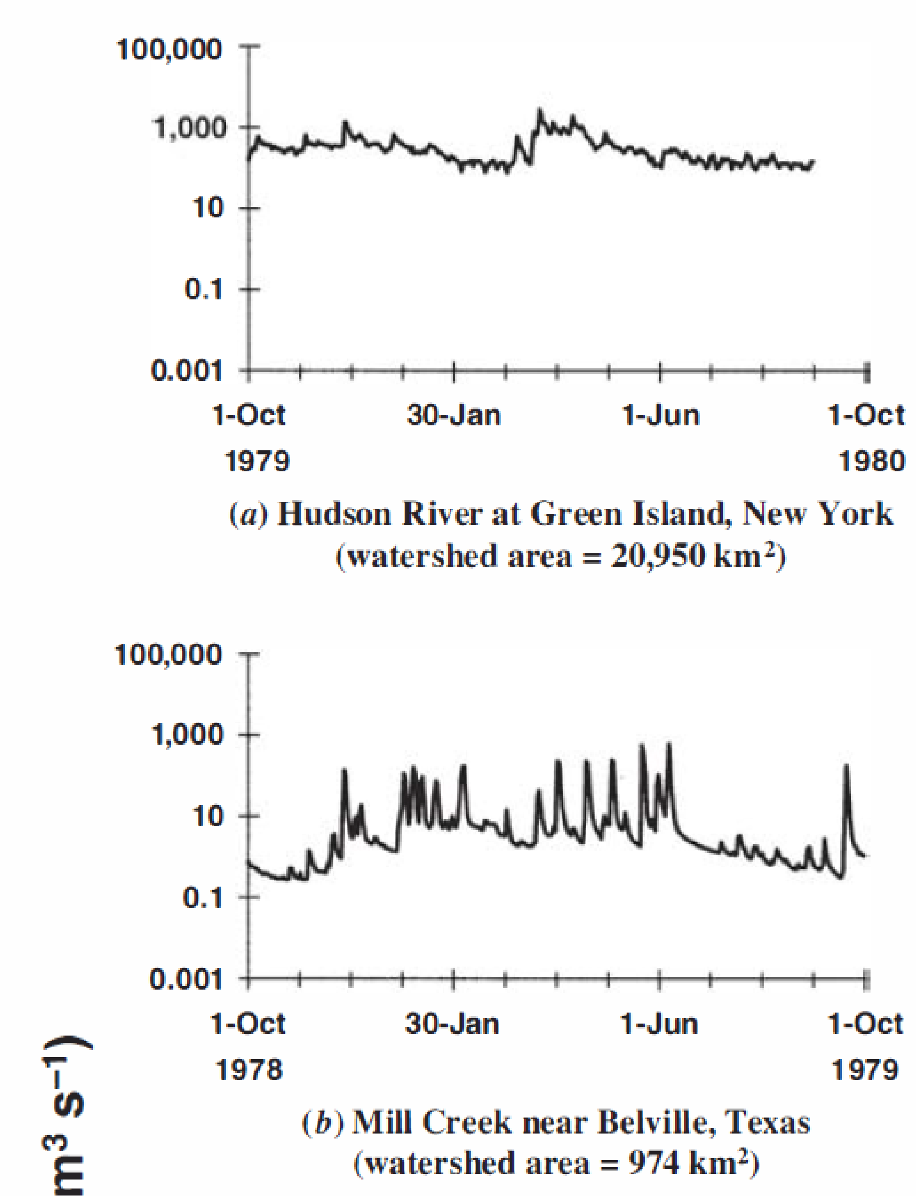
TABLE 14.1
Hydrogeometric parameters for a range of rivers ordered by flow (Fischer et al. 1979)

River	Mean depth (m)	Width (m)	Slope	Velocity (mps)	Flow ($m^3\ s^{-1}$)	Dispersion ($10^5\ cm^2\ s^{-1}$)
Missouri	2.70	200	0.00021	1.55	837.0	150.00
Sabine	3.40	116	0.00013	0.61	254.6	49.30
Windy/Big Horn	1.63	64	0.00135	1.22	144.1	10.10
Yadkin	3.10	71	0.00044	0.60	140.1	18.50
Clinch, Tennessee	1.68	53	0.00054	0.70	74.5	3.83
John Day	1.53	30	0.00239	0.92	41.8	3.95
Nooksack	0.76	64	0.00979	0.67	32.6	3.50
Coachella Canal, California	1.56	24	—	0.71	26.6	0.96
Bayou Anacoco	0.93	32	0.00050	0.37	10.9	3.60
Cinch, Virginia	0.58	36	—	0.21	4.4	0.81
Powell, Tennessee	0.85	34	—	0.15	4.3	0.95
Copper, Virginia	0.56	17	0.00130	0.32	3.6	1.51
Comite	0.43	16	0.00059	0.37	2.5	1.40

River Types

Temperate climates produce nearly constant hydrographs with a peak for snowmelt.

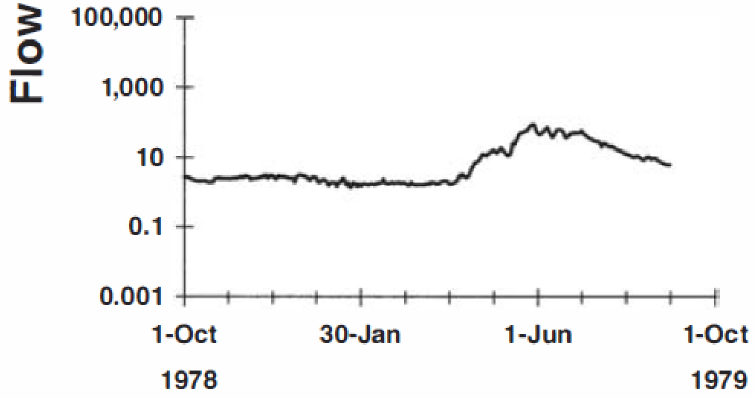
Humid climates show a more varied hydrograph, with spikes due to thunderstorms. The difference between spring and summer is not as pronounced due to even distribution of precipitation.



(a) Hudson River at Green Island, New York (watershed area = 20,950 km²)

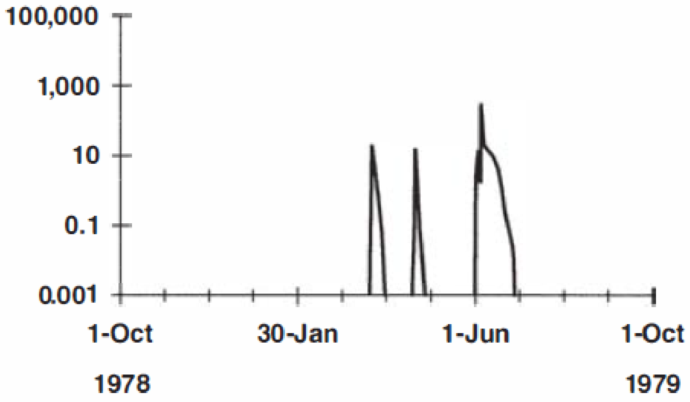
(b) Mill Creek near Belville, Texas (watershed area = 974 km²)

River Types



(*c*) East River at Altmont, Colorado
(watershed area = 748 km^2)

In colder climates there are drastically different periods of peakflow due to a significant portion of snowmelt.

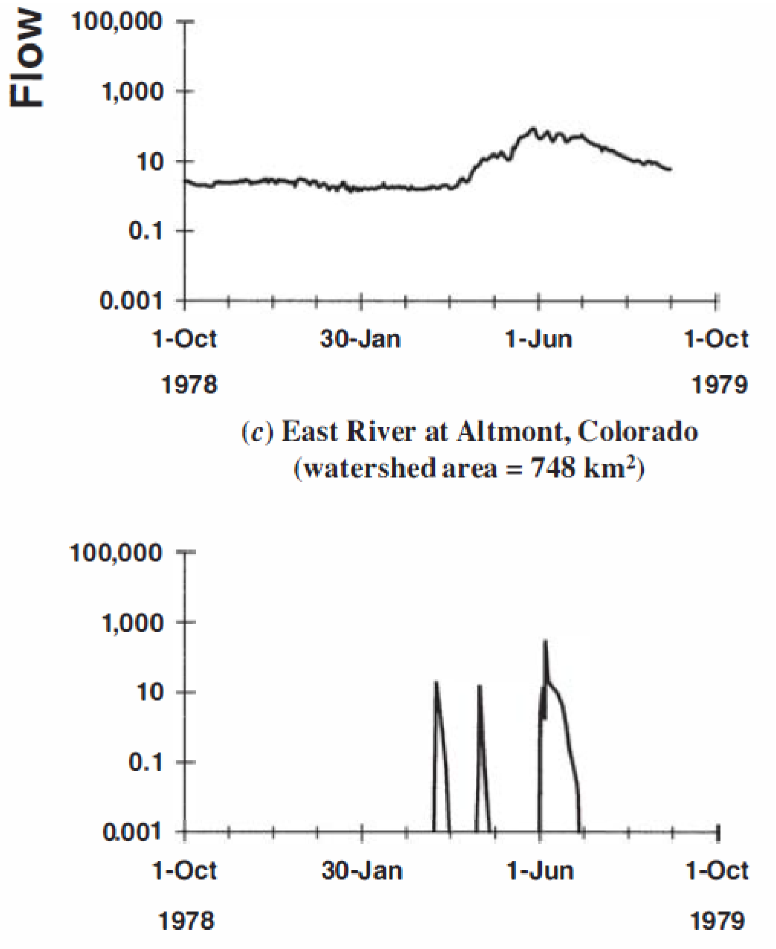


(*d*) Frio River near Uvalde, Texas
(watershed area = 1712 km^2)

Ephemeral streams in an arid climate show significant periods where the river is dry and then flow when there are large storms

FIGURE 14.1
Annual streamflow hydrographs for (*a*) perennial temperate river, (*b*) perennial humid river, (*c*) snowfed river, and (*d*) ephemeral river.

River Types



(*c*) East River at Altmont, Colorado (watershed area = 748 km^2)

(*d*) Frio River near Uvalde, Texas (watershed area = 1712 km^2)

Human influence can substantial hydrographs:

Impoundments: Moderate streams by reducing seasonal variability, shifting timing of minima and maxima

Urbanization and channelization: Creates more pronounced and concentrated runoff, leading to higher spikes

Human water use: irrigation, hydropower, alter the spatial and temporal variability (withdrawals and discharges)

Stream Hydrogeometry

A stream's hydrogeometry consists of its hydrologic characteristics (velocity, flow, dispersion) and its geometry (depth, width, cross-sectional area, slope).

Two approaches are available for determining these parameters:

at a point

at a reach

Point Estimates (Transect)

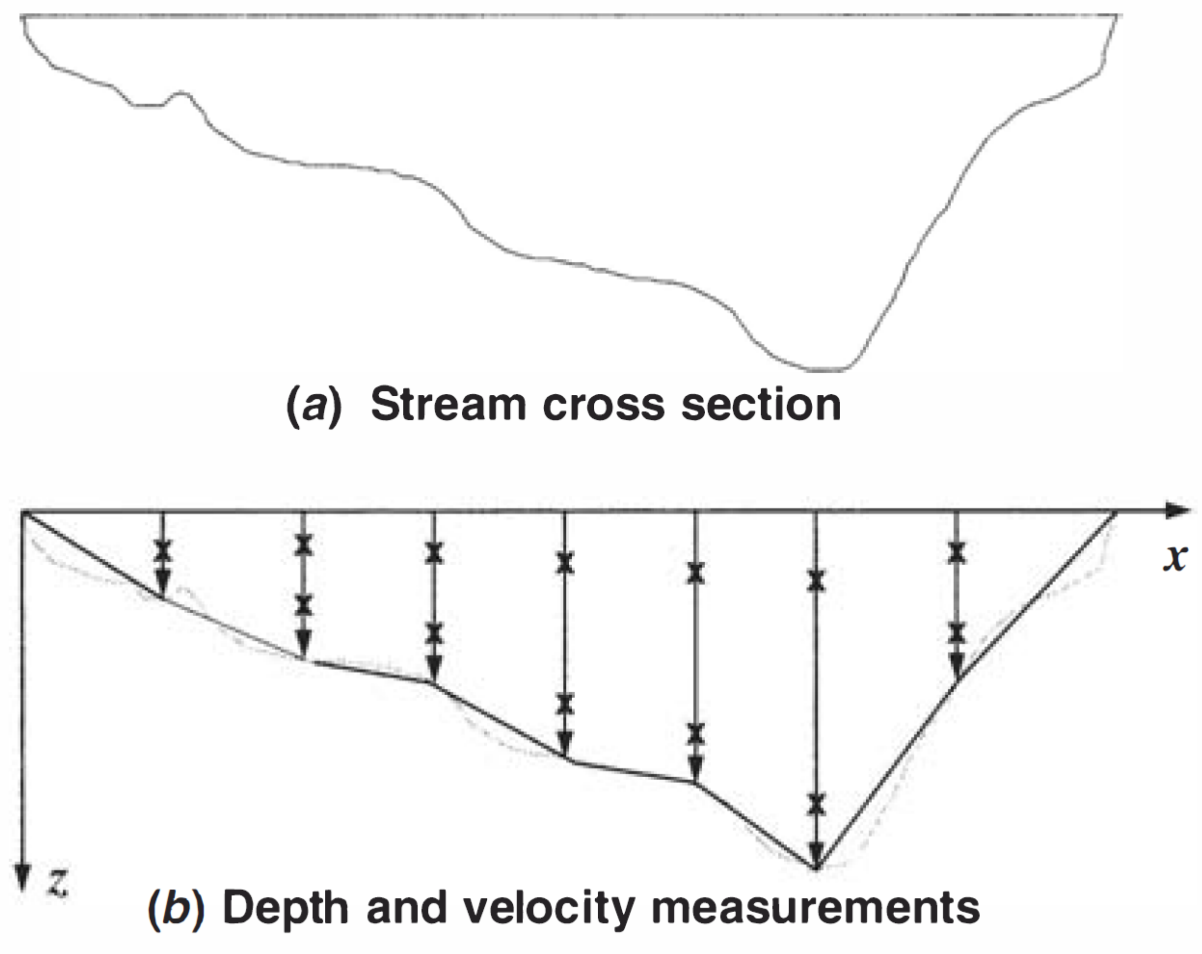
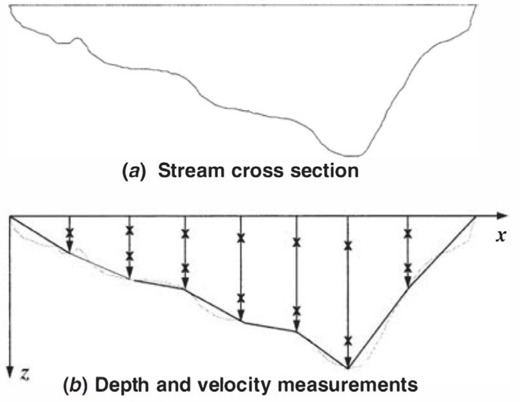


FIGURE 14.2
(*a*) A stream cross section along with (*b*) a transect showing depth and velocity measurements needed to calculate mean depth, flow, and other hydrogeometric parameters. Note that the velocity measurements (x) are taken at 60% depth for shallow water and at 20% and 80% for deep points.

Point Estimates (Transect)



Depth and **water velocity** measurements are evaluated, then used to estimate mean depth and cross-sectional area via integration.

$$A_c = \int_0^B z(x)\,dx$$

$$H = \frac{A_c}{B}$$

where A_c = cross-sectional area (m^2)

x = distance measured across the stream (m)

$z(x)$ = depth measured at location x (m)

H = mean depth (m)

B= stream width

Point Estimates (Transect)

Once the average velocity for each point on the transect is derived, $\overline{U}(x)$, the values can be integrated to arrive at the mean flow

$$Q = \int_0^B \overline{U}(x) z(x)\, dx$$

And mean velocity:

$$U = \frac{Q}{A_c}$$

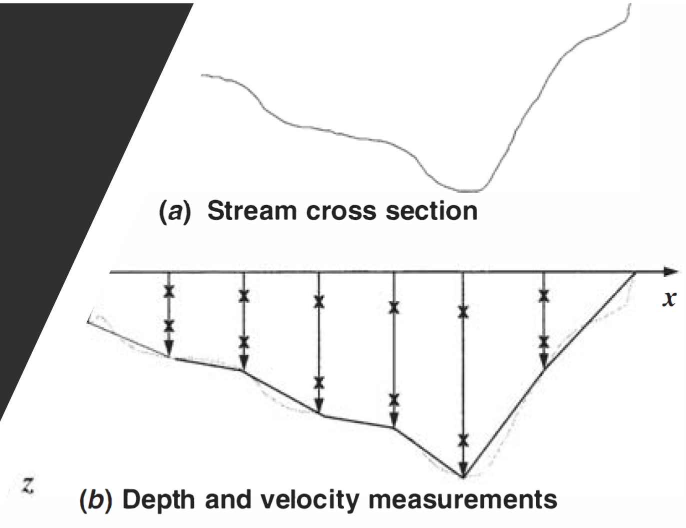


FIGURE 14.2
(a) A stream cross section along with (b) a transect showing depth and velocity measurements needed to calculate mean depth, flow, and other hydrogeometric parameters. Note that the velocity measurements (x) are taken at 60% depth for shallow water and at 20% and 80% for deep points.

EXAMPLE 14.1. POINT ESTIMATION. The following data were collected for a stream cross section:

x (m)	0	4	8	12	16	20
z (m)	0	0.4	1	1.5	0.2	0
$U(x)_{0.2}$ (mps)	0		0.2	0.3		0
$U(x)_{0.6}$ (mps)	0	0.05			0.07	0
$U(x)_{0.8}$ (mps)	0		0.12	0.2		0
$\overline{U}(x)$ (mps)	0	0.05	0.16	0.25	0.07	0
$\overline{U}(x)z$ ($m^2\ s^{-1}$)	0	0.02	0.16	0.375	0.014	0

Use this data to determine the (*a*) area, (*b*) mean depth, (*c*) flow, and (*d*) velocity.

Reach Estimates

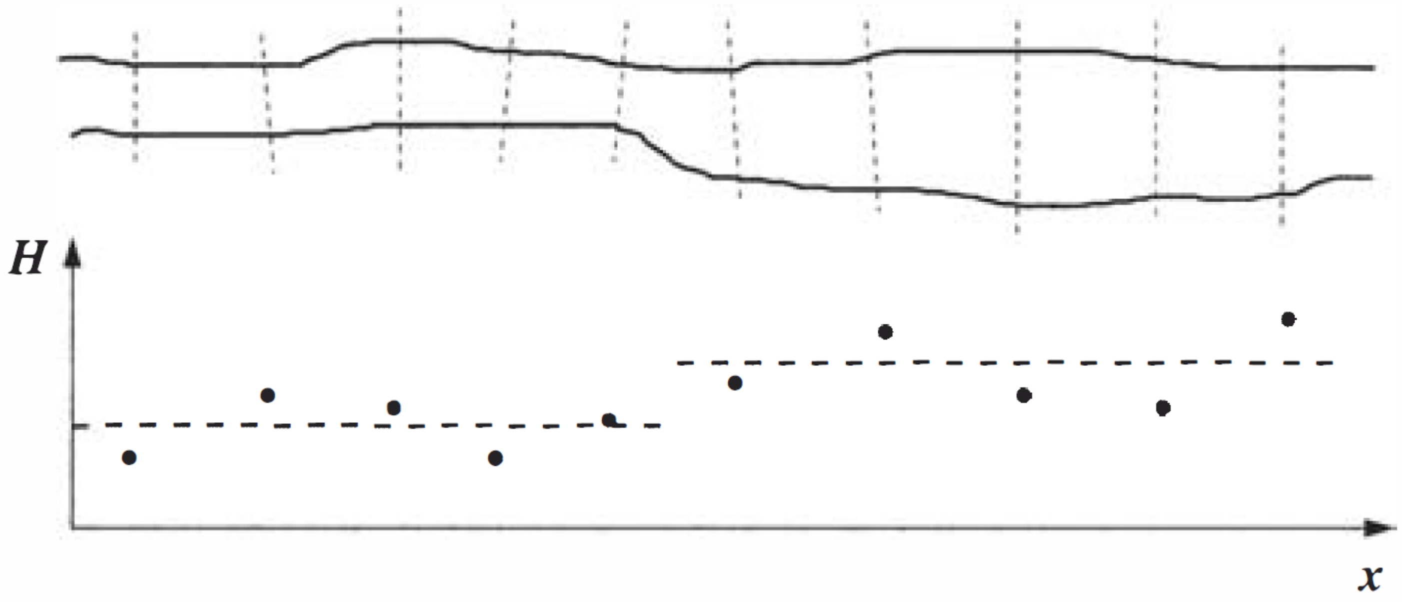


FIGURE 14.3
Data from individual transects can be plotted versus distance to develop average values of parameters for reaches.

Reach Estimates

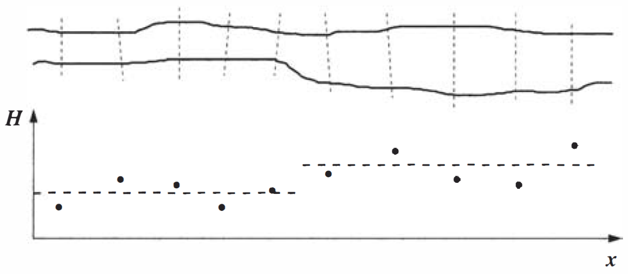


FIGURE 14.3
Data from individual transects can be plotted versus distance to develop average values of parameters for reaches.

The **reach** approach is predicted on the assumption that stream width is less variable than its depth. Given this, a ***stream reach*** is identified that has a relatively constant width, once measured, the flow at the end of this reach is determined by **point estimate**.

A travel time is determined by injecting a tracer such as dye at the head end and timing how long it takes to traverse the reach. The mean velocity:

$$U = \frac{x}{t}$$

where x = reach length and t =travel time.

Reach Estimates

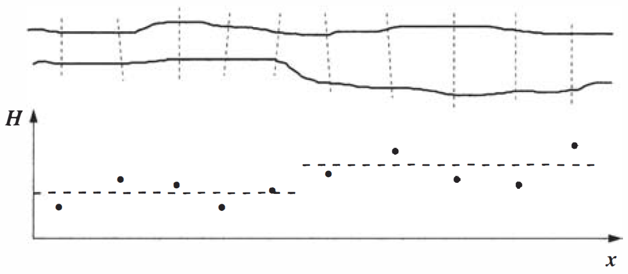


FIGURE 14.3
Data from individual transects can be plotted versus distance to develop average values of parameters for reaches.

The velocity and flow rate can then be used to estimate the average cross-sectional area:

$$A_c = \frac{Q}{U}$$

and then used to determine the mean depth:

$$H = \frac{A_c}{B}$$

EXAMPLE 14.2. REACH ESTIMATION OF VELOCITY AND MEAN DEPTH. Suppose that the point estimate calculated in Example 14.1 is at the downstream end of a 2-km reach with a mean width of 22 m. Recall that the point estimate of flow was 2.3105 $m^3\ s^{-1}$. You perform a dye study and determine that it takes 3.2 hr for the dye to traverse the 2 km. Use the reach approach to determine the velocity, cross-sectional area, and mean depth for the reach.

Low-Flow Analysis

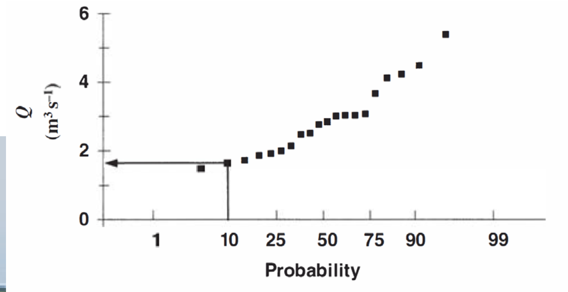


FIGURE 14.4
Frequency curve corresponding to the 7-d minimum flow for the river from Example 14.3.

https://www.fws.gov/r5crc/habitat.html

Traditional water-quality modeling has used the steady, low-flow summer period as its design condition,…..

How do you establish low-flow conditions?

Low-Flow Analysis

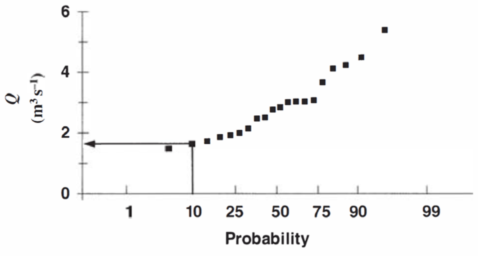


FIGURE 14.4
Frequency curve corresponding to the 7-d minimum flow for the river from Example 14.3.

7Q10: The minimum 7-day flow that would be expected to occur every 10 years is generally expected as the standard design flow. This can be established for the **entire year**, by **month**, or for a **season** (e.g. a summer: July to September).

First: Long-term flow record is required for the specific location

Next: Examine data to determine smallest flow that occurs for seven consecutive days.

Then: tabulate *n* flows in ascending order and assign them a rank *m*.

Low-Flow Analysis

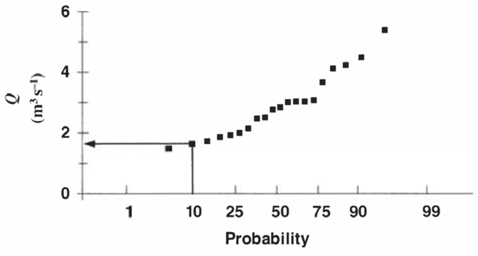


FIGURE 14.4
Frequency curve corresponding to the 7-d minimum flow for the river from Example 14.3.

Then: tabulate *n* flows in ascending order and assign them a rank *m*.

The cumulative probability of occurrence is given by:

$$p = \frac{m}{N+1}$$

The recurrence interval is :

$$T = \frac{1}{p}$$

EXAMPLE 14.3. CALCULATION OF 7Q10. The following 7-d low flows were compiled for a river:

1971	1.72	1976	4.23	1981	4.48	1986	5.39
1972	3.03	1977	4.11	1982	3.03	1987	3.00
1973	2.76	1978	1.92	1983	2.84	1988	2.50
1974	1.65	1979	2.14	1984	3.66	1989	2.47
1975	2.00	1980	1.48	1985	1.87	1990	3.07

Use this data to determine the 7Q10.

Rank	Flow	Probability	Recurrence interval	Rank	Flow	Probability	Recurrence interval
1	1.48	4.76	21.00	11	2.84	52.38	1.91
2	1.65	9.52	10.50	12	3.00	57.14	1.75
3	1.72	14.29	7.00	13	3.03	61.90	1.62
4	1.87	19.05	5.25	14	3.03	66.67	1.50
5	1.92	23.81	4.20	15	3.07	71.43	1.40
6	2.00	28.57	3.50	16	3.66	76.19	1.31
7	2.14	33.33	3.00	17	4.11	80.95	1.24
8	2.47	38.10	2.63	18	4.23	85.71	1.17
9	2.50	42.86	2.33	19	4.48	90.48	1.11
10	2.76	47.62	2.10	20	5.39	95.24	1.05

Low-Flow Analysis

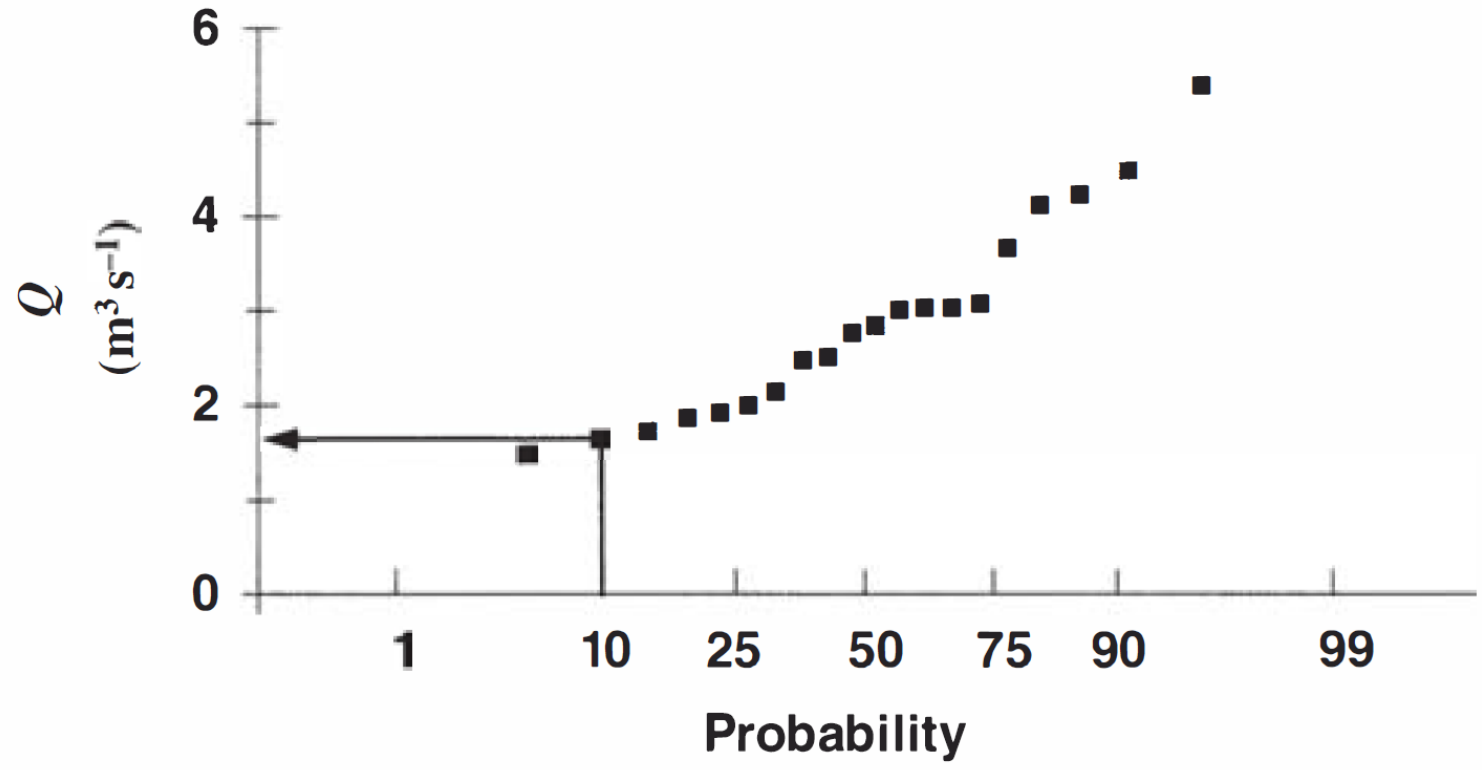


FIGURE 14.4
Frequency curve corresponding to the 7-d minimum flow for the river from Example 14.3.

Dispersion and Mixing

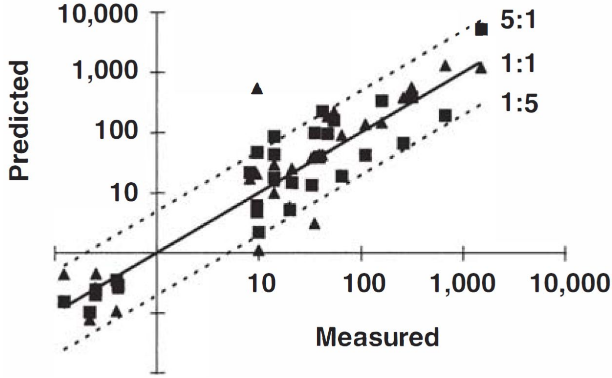
In rivers, we examine two mixing regimes:

First: with one-dimensional models, we are concerned with mixing in the direction of flow (***longitudinal mixing***), parametrized by the dispersion coefficient.

In addition: we are interested in the mixing across the stream (***lateral mixing***).

We assess our assumption that the point sources are instantaneously mixed, quantifying the longitudinal flow length required to attain lateral mixing.

Longitudinal Dispersion



To estimate the longitudinal dispersion coefficient for streams and rivers, Fischer et al (1979) developed the following:

$$E = 0.011 \frac{U^2 B^2}{H U^*}$$

where E has units ($m^2\ s^{-1}$)

U= velocity ($m\ s^{-1}$)

B= width (m)

H= mean depth (m)

U^*= shear velocity ($m\ s^{-1}$), which is defined by:

$$U^* = \sqrt{gHS}$$

Longitudinal Dispersion

$$U^* = \sqrt{gHS}$$

where g = acceleration due to gravity (m s^{-2}) and S = channel slope (dimensionless).

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Hydrogeometric parameters for a range of rivers ordered by flow (Fischer et al. 1979)

River	Mean depth (m)	Width (m)	Slope	Velocity (mps)	Flow ($m^3\ s^{-1}$)	Dispersion ($10^5\ cm^2\ s^{-1}$)
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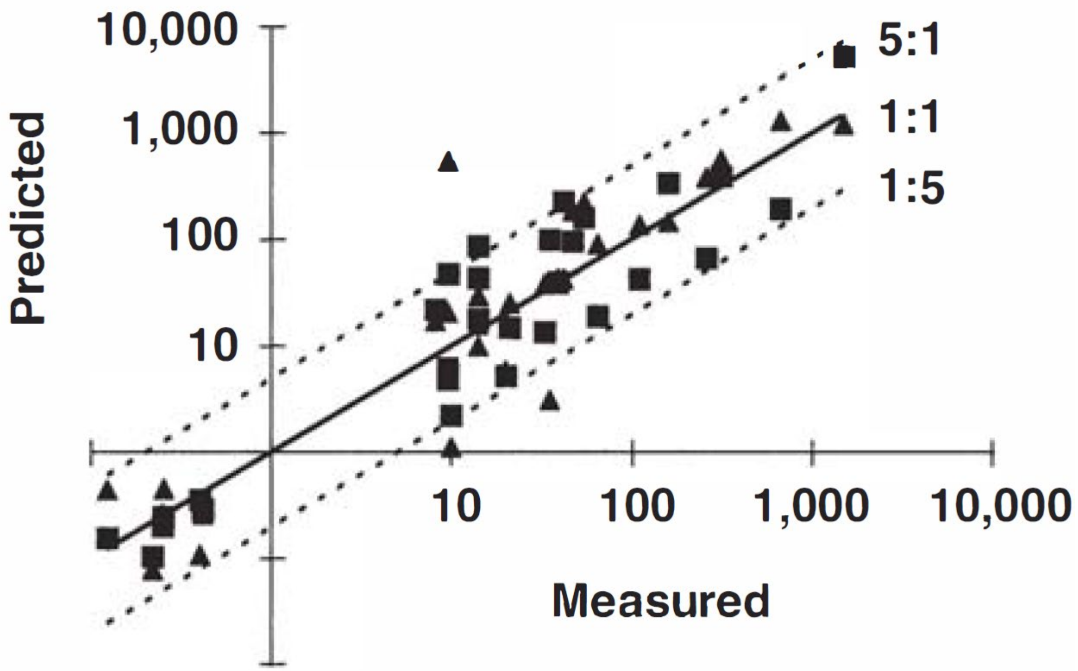

Longitudinal Dispersion

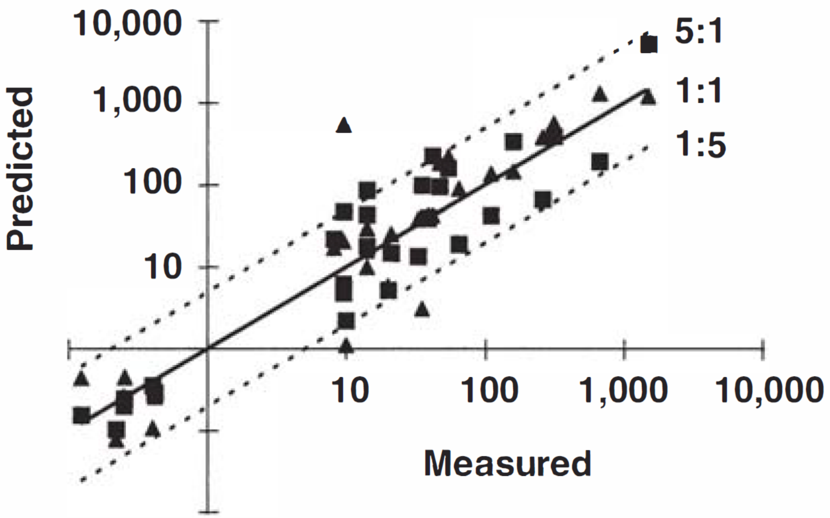

FIGURE 14.5
Comparison of measurements (Table 14.1) with predictions using Eqs. 14.15 (■) and 14.17 (▲). The solid line represents a perfect correlation between the predictions and the measurements, whereas the dashed lines correspond to a factor of 5 above and below the 1:1 correlation. Note that some additional data beyond Table 14.1, from some laboratory flumes and canals (Fischer et al. 1979), have been included on this plot.

An alternative formula is (McQuivey and Keefer, 1974):

$$E = 0.058 \frac{Q}{SB}$$

where Q = mean flow (m^3 s^{-1}). M&K74 studied rivers from 35 to 33,000cfs, limiting it to Froude No. ($F = U/\sqrt{gH}$) less than 0.5.

Lateral Mixing

Lateral mixing of point sources is the second facet of mixing relevant to one-dimensional stream water-quality modeling.

$$E_{lat} = 0.6HU^*$$

where *H* = mean depth (m) and *U** = shear velocity (mps). This can be used to compute the length to attain complete lateral mixing. For side discharge:

$$L_m = 0.4U\frac{B^2}{E_{lat}}$$

For discharge in the center of the channel:

$$L_m = 0.1U\frac{B^2}{E_{lat}}$$

Lateral Mixing

Yotsukura (1968) has proposed the following alternative formula for a side discharge:

$$L_m = 8.52U\frac{B^2}{H}$$

where L_m= mixing length (m)

U = velocity (mps)

B = width (m)

H = depth (m)

EXAMPLE 14.4. LONGITUDINAL DISPERSION AND LATERAL MIXING. The following data applies to Boulder Creek, Colorado, immediately below the Boulder wastewater treatment plant discharge:

$$U = 0.3 \text{ mps}$$
$$B = 15 \text{ m}$$
$$H = 0.4 \text{ m}$$
$$S = 0.004$$
$$Q = 1.8 \text{ cms}$$

Use this data to determine the longitudinal dispersion coefficient and the length required to attain complete lateral mixing.

Flow, Depth, and Velocity

If a steady flow rate Q enters the upstream end for a sufficiently long period of time, then the continuity equation will describe these conditions for steady, uniform flow conditions:

$$Q = UA_c$$

where A_c = cross-sectional area and U = mean velocity. Since these factors (velocity, depth, width) are components, we can use them to relate these characteristics to flow.

Discharge Coefficients

Power equations (Leopold and Maddock, 1953) can be used to relate mean velocity, depth, and width to flow:

$$U = aQ^b$$

$$H = \alpha Q^\beta$$

$$B = cQ^f$$

Average values and ranges of exponents in hydrogeometric correlations

Correlation	Exponent	Value	Range
Velocity-flow	b	0.45	0.3–0.7
Depth-flow	β	0.4	0.1–0.6
Width-flow	f	0.15	0.05–0.25

where mean depth, and a, b, α, β, c, f are empirical constants that are determined from stage-discharge rating curves (log-log plots)

The Manning Equation

The Manning equation which is derived from a momentum balance for the channel, provides a means to relate velocity to channel characteristics

$$U = \frac{C_o}{n} R^{2/3} S_e^{1/2}$$

where C_o = a constant (= 1.0 metric, 1.486 for English)

n = Manning's roughness coefficient

R = channel's hydraulic radius (m or ft) = A_c/P

P = wetted perimeter (m or ft)

S_e = slope of the channel's energy grade line

The Manning Equation

The Manning equation can also be substituted into the continuity equation ($Q = UA_c$) to calculate the flow:

$$Q = \frac{C_o}{n} A_c R^{2/3} S_e^{1/2}$$

If we had a flow and area and hydraulic radius, can be expressed as depth, there is one unknown- depth. This can be solved for then used with flow to calc. velocity.

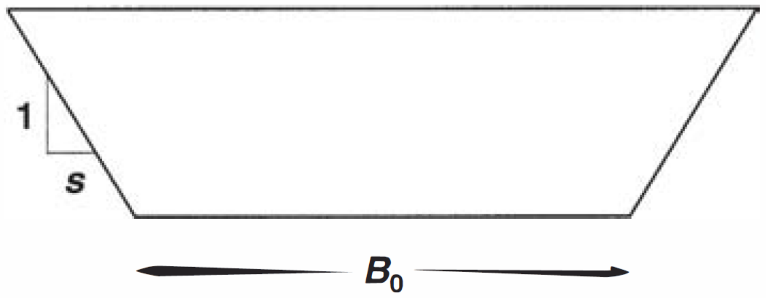

FIGURE 14.6
A cross section of a trapezoidal channel showing the parameters needed to uniquely define the geometry: B_0 = bottom width, s = side slope.

TABLE 14.3
The Manning roughness coefficient for various open channel surfaces (Chow 1959)

Material	*n*
Artificial channels:	
Concrete	0.012
Gravel bottom with sides:	
Concrete	0.020
Mortared stone	0.023
Riprap	0.033
Natural stream channels:	
Clean, straight	0.030
Clean, winding	0.040
Weeds and pools, winding	0.050
Heavy brush, timber	0.100

The Manning Equation

If we had a flow and area and hydraulic radius, can be expressed as depth, there is one unknown- depth. This can be solved for then used with flow to calc. velocity.

E.g a trapezoid:

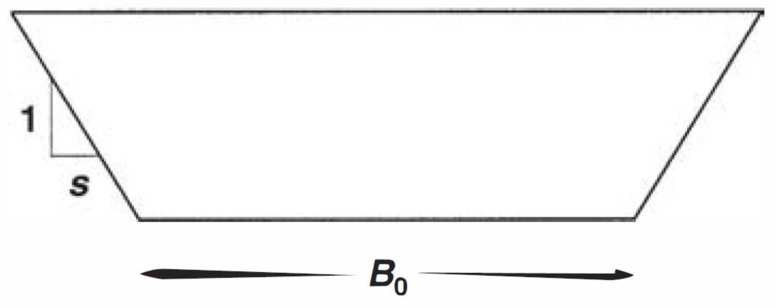

FIGURE 14.6
A cross section of a trapezoidal channel showing the parameters needed to uniquely define the geometry: B_0 = bottom width, s = side slope.

$$A_c = (B_0 + sy)y$$

$$P = B_0 + 2y\sqrt{s^2 + 1}$$

$$R = \frac{A_c}{P} = \frac{(B_0 + sy)y}{B_0 + 2y\sqrt{s^2 + 1}}$$

The Manning Equation

These equations ($A_c = (B_0 + sy)y$; $R = \frac{A_c}{P} = \frac{(B_0+sy)y}{B_0+2y\sqrt{s^2+1}}$) can be substituted into the Manning Equation ($Q = \frac{C_o}{n} A_c R^{2/3} S_e^{1/2}$).

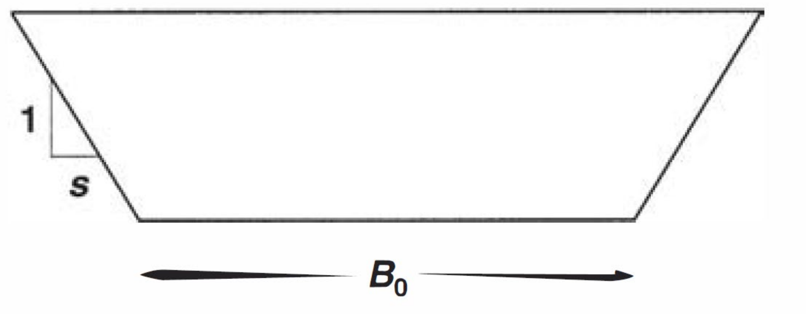

FIGURE 14.6
A cross section of a trapezoidal channel showing the parameters needed to uniquely define the geometry: B_0 = bottom width, s = side slope.

$$Q = \frac{1}{n} \frac{[(B_0+sy)y]^{5/3}}{(B_0+2y\sqrt{s^2+1})^{2/3}} S_e^{1/2}$$

$$f(y) = \frac{1}{n} \frac{[(B_0+sy)y]^{5/3}}{(B_0+2y\sqrt{s^2+1})^{2/3}} S_e^{1/2}$$

EXAMPLE 14.5. THE MANNING EQUATION. A channel has the following characteristics:

Flow = 6.25 cms
Channel slope = 0.0002
Bottom width = 10 m
Side slope = 2
Roughness = 0.035

Determine the depth, cross-sectional area, and velocity for the channel.

Routing and Water Quality (Advanced Topic)

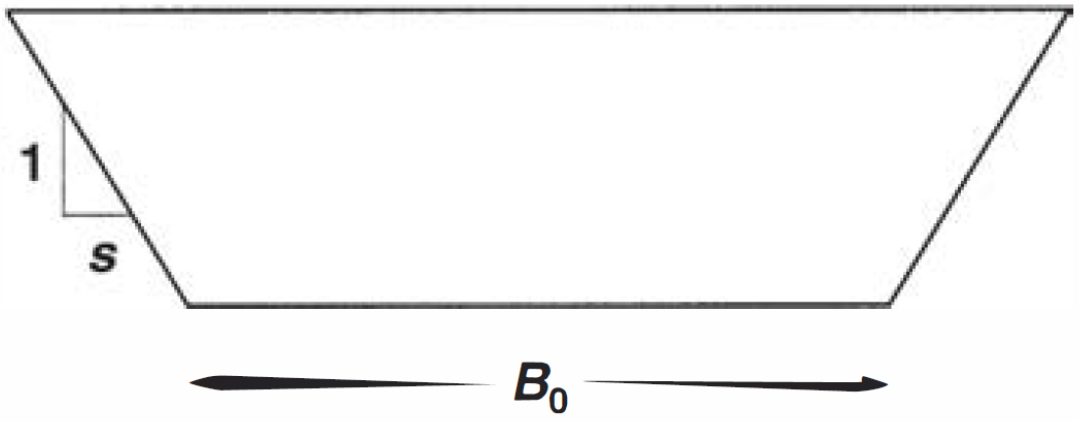

FIGURE 14.6
A cross section of a trapezoidal channel showing the parameters needed to uniquely define the geometry: B_0 = bottom width, s = side slope.

Routing Water

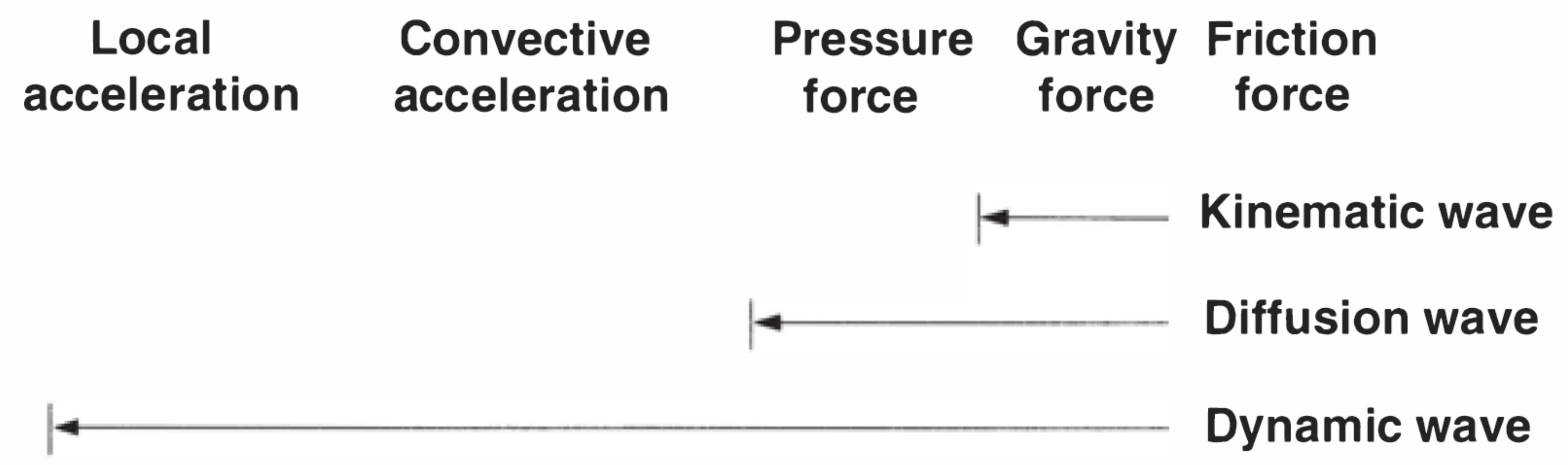

FIGURE 14.7
The St. Venant equation for momentum can be simplified by dropping terms as shown (redrawn from Chow et al. 1988).

Routing Water

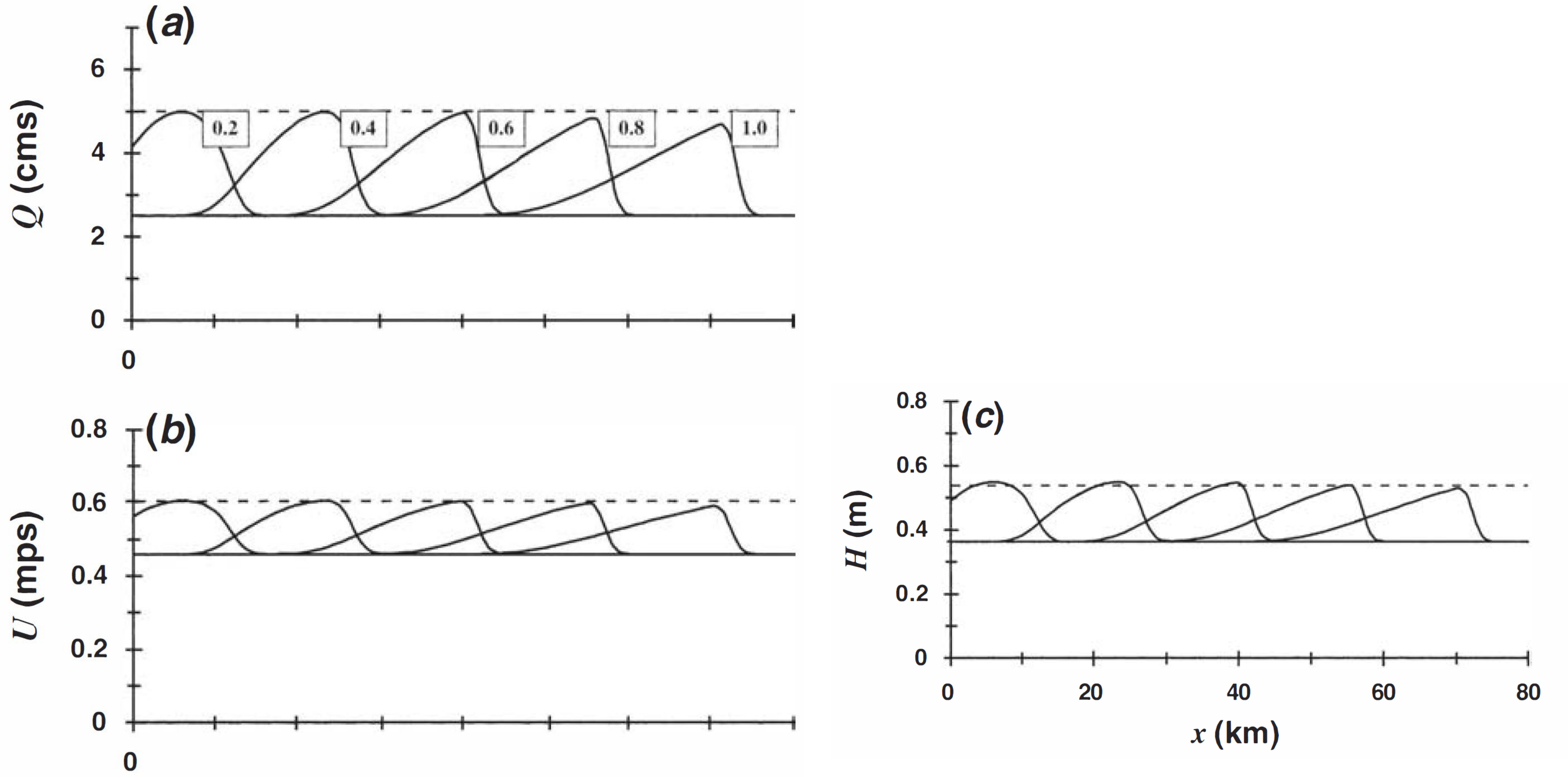

FIGURE 14.8 Simulation of a wave moving through a channel. The boxed numbers represent the amount of time (d) following the onset of the wave. Also the dashed lines indicate the peak values.

Routing Pollutants

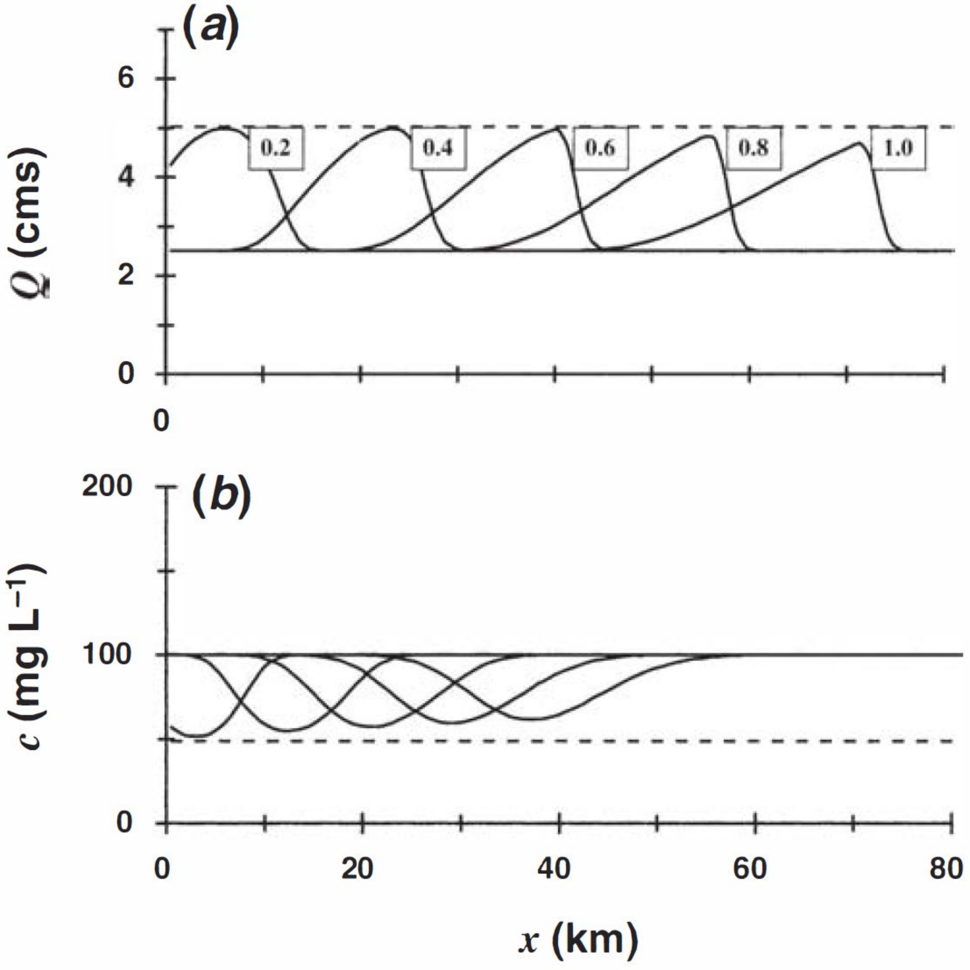

FIGURE 14.9
Simulation of (*a*) a hydrograph and (*b*) a dilution wave or "dilutograph" moving through a channel.