United States Department of Agriculture
Natural Resources Conservation Service

Part 634 Hydraulics
National Engineering Handbook

Chapter 1 General Concepts

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Chapter 1 –General Concepts

634.0100 Introduction

This section presents the hydraulic principles that apply to the design and operation of soil and water conservation measures. Contained within this document are explanations of dimensions and units, principles of water at rest (hydrostatics), and principles of water in motion (hydrokinetics). Also discussed is the application of these principles to flow of water in pipes and open channels. Other information presents the more common methods of measuring flow of water in open channels and pipes and hydraulic modeling.

634.0101 Dimensions and Units

A. The word "dimensions" refers to physical quantities involved in describing a physical system. The basic dimensions of length (L), time (T), and mass (M) can be selected. In the analysis of hydraulic problems, many derived quantities are used that combine these basic dimensions. Some of these derived quantities are listed as:

(1) Velocity:	$V = L / T$	(velocity = length/time)
(2) Acceleration:	$a = V / T = L / T^2$	(acceleration = velocity/time)
(3) Force:	$F = M\, a = M\, L / T^2$	(force = mass × acceleration)
(4) Momentum:	$I = M \cdot V = M\, L / T$	(momentum = mass × velocity)
(5) Work or Energy:	$W = F \cdot L = M\, L^2 / T^2$	(work = force × length)
(6) Power:	$P = W / T = M\, L^2 / T^3$	(power = work/time)

B. The definition of force given above, referred to as Newton's second law of motion, indicates that the force (F) required to provide an acceleration (a) to a body of mass (M) is given by $F = M\, a$. In terms of the basic dimensions (L, T, M), a force has dimensions of $M\, L / T^2$, as indicated above. Sometimes, force (F) is used as a basic dimension together with L and T, and mass (M) is considered a derived quantity. In such case, the basic dimensions are (L, T, F) and mass has dimensions of $M = F\, T^2 / L$.

C. Velocity and acceleration have the same basic dimensions (L and T) when either mass or force (F) is considered a basic dimension. Using L, T, and F as basic dimensions, the following derived quantities are written:

(1) Momentum:	$I = M\, V = (F\, T^2 / L)(L / T) = F\, T$
(2) Work or Energy:	$W = F\, L$
(3) Power:	$P = W / T = F\, L / T$

D. The basic dimensions and the derived quantities referred to above are described in terms of units of measurement. There are two commonly used systems of units in modern engineering practice: the International System (referred to as SI, or Systeme Internationale in French) and the English System (referred to as ES, and also known as the Imperial System of units). The SI uses length, time, and mass (L, T, M) as the basic dimensions, while the ES uses length, time, and force (L, T, F) as the basic dimensions. The table of figure 1-1 shows the basic units in both systems.

Figure 1-1: Basic Units of Measurement in the SI and ES Systems

System of units	Length	Time	Mass	Force
International System (SI)	meter (m)	second (s)	kilogram (kg)	--
English System (ES)	foot (ft)	second (s)	--	pound (lb)

E. Besides the foot, the inch (in), yard (yd), and mile (mi) are commonly used units of length in the ES. These units are defined as follows:

(1) 1 in = 1/12 ft; 1 ft = 12 in; 1 yd = 3 ft
(2) 1 mi = 5,280 ft

F. To define the unit of force in the SI or the unit of mass in the ES, it is necessary to use the acceleration of gravity (g), a quantity that is essentially constant on the surface of the Earth and has the value:

$$g = 32.2\ ft/s^2 = 9.806\ m/s^2$$

G. With this acceleration, we can define the weight of a given mass (M) as:

$$Weight\text{: } W = M \cdot g\ (weight = mass \times gravity)$$

H. This relationship allows the definition of a unit of force in the SI, the newton (N), defined as:

$$N = (1\ kg)\left(1\frac{m}{s^2}\right) = 1\ kg \cdot m/s^2$$

I. Similarly, by using the expression for mass in terms of weight:

$$Mass\text{: } M = W/g$$

J. The unit of mass in the ES, the slug, can be defined as:

$$1\ slug = (1\ lb)\ /\ (1\ ft/s^2) = 1\ lb \cdot s^2/ft$$

K. In the United States, the ES is the most commonly used system of units. Therefore, most of the problems presented in this section are worked using ES units. The following are basic ES units for the derived quantities presented earlier:

(1) Velocity: 1 ft / s = 1 fps
(2) Acceleration: 1 ft / s^2
(3) Mass: 1 slug = 1 lb· s^2 / ft.
(4) Momentum: 1 slug·ft / s = 1 slug·fps = (1 lb s^2 / ft)(1 ft / s) = 1 lb s
(5) Work or Energy: 1 lb • ft
(6) Power: 1 lb ft / s

L. The basic SI units for the derived quantities are as follows:

(1) Velocity: 1 m / s
(2) Acceleration: 1 m / s^2
(3) Force: 1 N
(4) Momentum: 1 N·m / s
(5) Work or Energy: 1 J = 1 N·m / s^2 (joule)
(6) Power: 1 W = 1 J / s (watt)

M. The SI of units uses many prefixes to indicate decimal fractions or multiples of a given unit. Some of those prefixes are listed below:

(1) Kilo (k) 10^3 = 1 thousand
(2) Deci (d) 10^{-1} = 0.1 = one tenth
(3) Centi (c) 10^{-2} = 0.01 = one hundredth
(4) Milli (m) 10^{-3} = 0.001 = one thousandth

N. For example, a commonly used unit for measuring travel distance is the kilometer (1 km = 10^3 m = 1,000 m), while small pipe diameters could be measured in centimeters (1 cm =10^{-2} m = 0.01 m).

O. The units of area and volume (e.g., for the measurement of flows) are also of interest in hydraulic applications. The basic units of area and volume (vol) in the ES are the square foot (1 ft^2) and the cubic foot (1 ft^3); however, other units of area and volume are also used:

(1) 1 acre (Ac) = 43,560 ft^2
(2) 1 acre-ft (Ac-ft) = 43,560 ft^3
(3) 1 ft^3 = 7.48 gallons (gal)

P. A derived quantity commonly used in hydraulics is the discharge or flow rate (Q), defined as vol / T, and can be calculated by multiplying velocity (V) times flow area (A) as:

$$Discharge\ or\ flow\ rate, Q = vol/T = V \times A$$

Q. The basic unit of discharge in the ES is 1 ft^3 / s, commonly referred to as 1 cfs (cubic feet per second). As an alternative, the discharge in large rivers is sometimes measured in acre-ft/day.

R. While the basic units of area and volume in the SI are the square meter and cubic meter, other units are also used:

(1) 1 hectare (ha) = 10,000 m^2
(2) 1 m^3 = 1,000 liters (l)

S. Exhibit A in Section 634.0107 provides a list of basic dimensions and units for the ES and SI units.

634.0102 Unit Conversions

A. Unit conversions are straightforward if the conversion factors are known. Some conversion factors were provided in the previous section. For example, given that 1 ft^3 = 7.48 gal, 1 min = 60 s, and that a discharge is reported to be 0.5 cfs (0.5 ft^3/s), determine the value of the discharge in gallons per minute (gpm). This unit conversion can be accomplished as follows:

$$0.5\frac{ft^3}{s} \times 7.48\frac{gal}{ft^3} \times 60\frac{s}{min} = 0.5 \times 7.48 \times 60\ gpm = 224.4\ gpm$$

B. Exhibit B in Section 634.0107 provides a list of commonly used conversion factors for the ES and SI of units. Many unit conversion programs and spreadsheets are available for quick unit conversions.

634.0103 Dimensional Homogeneity in Equations

A. In the analysis of hydraulic systems, it is necessary to use a number of equations. Most equations are dimensionally homogeneous, meaning that the dimensions of both sides of the equation are the same. Equations that define a derived quantity (for example, Newton's second law of motion, F = M·• a), are, by definition, dimensionally homogeneous. For other equations, replacing the dimensions of the different variables using either length, time, and mass (L, T, M) or length, time, and force (L, T, F) will verify the dimensional homogeneity of the expression.

B. The following example verifies the dimensional homogeneity of the equation used to define power in pipe flow (see section 634.0406 Pumps in Pipelines). The power (P) required to transport a discharge (Q) of water through a pipeline, with an energy head loss (H), is given by:

$$P = \omega \cdot Q \cdot H \qquad \text{(eq. 1-1)}$$

where ω is the specific weight of water. Exhibit C in Section 634.0107 presents the letters of the Greek alphabet, indicating those most commonly used in hydraulic equations.

C. The specific weight of any material is defined as the weight per unit volume of the material:

$$\omega = \frac{W}{Vol} \qquad \text{(eq. 1-2)}$$

where W represents weight (in the ES, the pound (lb) is commonly used to measure weight), and Vol represents volume. In dimensional terms, using L, T, and F as basic dimensions, one can write:

$$[\omega] = \frac{[W]}{[Vol]} = \frac{F}{L^3} = FL^{-3}$$

while $[Q] = L^3 / T = L^3 \bullet T^{-1}$, and $[H] = L$. Thus, from the equation defining power, one can write:

$$[P] = [\omega]\,[Q]\,[H] = (F \cdot L^{-3})\,(L^3T^{-1})\,(L) = F \cdot L \cdot T^{-1}$$

D. Exhibit A in Section 634.0107 shows the dimensions of $[P] = F \bullet L \bullet T^{-1}$; thus, the equation P = ω•Q•H is shown to be dimensionally homogeneous.

E. Manning's equation (section 635.0306) illustrates an equation that is not dimensionally homogeneous. The equation is given by:

$$V = \frac{C}{n} \cdot R^{2/3} \cdot S^{1/2} \qquad \text{(eq. 1-3)}$$

where V is the velocity, C is a constant 1.486 in ES and 1.0 in SI, R is the hydraulic radius and has dimensions of length, S is the channel bed longitudinal slope and is a dimensionless quantity, and n is Manning's resistance coefficient, another dimensionless quantity.

(1) From the equation, one may obtain the dimensions of V as:

$$[V] = L^{2/3}$$

(2) However, from Exhibit A in Section 634.0107, $[V] = L\,T^{-1}$. Thus, Manning's equation is not dimensionally homogeneous. Although not dimensionally homogeneous, the empirical Manning's equation has proven to be very successful in modeling flow in open channels and pipelines.

634.0104 Physical Properties of Water

Exhibit D in Section 634.0107 presents tables with physical water properties (values may be interpolated for different temperatures) defined as follows:

(1) Density is the mass per unit volume:

$$\rho = M/Vol \qquad \text{(eq. 1-4)}$$

Units of density in the SI are kg / m^3, while in the ES, they are slug / ft^3.

(2) Specific weight is weight per unit volume (see equation 1.2):

$$\omega = W/Vol$$

(i) Units of specific weight in the SI are N / m^3, while in the ES, they are lb / ft^3 or pcf (pounds per cubic feet).

(ii) Because weight is defined as W = M g, where g is the acceleration of gravity, one can also write $\omega = (W / Vol) = (M \cdot g / Vol) = (M / Vol) \cdot g = \rho \cdot g$:

$$\omega = \rho \cdot g \qquad \textit{(eq. 1-5)}$$

(3) Specific gravity is the ratio of the density of any fluid to that of water at 39.2º F (4º C).

(i) Water density tends to increase with decreasing temperature to a maximum value at 39.2º F (4º C). As the temperature decreases further, the density of water decreases until the water turns into ice at 32º F or 0º C. Referring to the density of water at 39.2º F or 4º C as ρ_w = 1,000 kg / m^3 = 1.94 slug / ft^3, or to its corresponding specific weight as ω_w = 9,806 N / m^3 = 62.4 lb / ft^3, the specific gravity of any fluid of density (ρ) or specific weight (ω), is defined as:

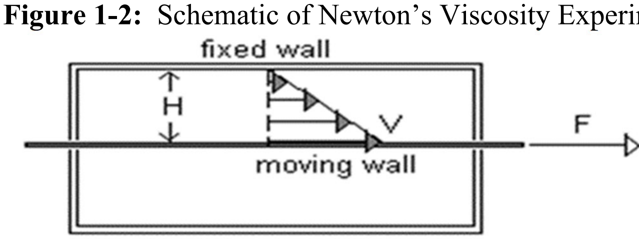
$$S = \frac{\rho}{\rho_w} = \frac{\omega}{\omega_w} \qquad \textit{(eq. 1-6)}$$

(ii) For example, mercury (chemical symbol = Hg), a liquid metal often used in pressure measurements in hydraulic laboratories, has a specific weight, ω = 846.14 lb / ft^3. Therefore, the specific gravity of mercury is:

$$S = \frac{\omega}{\omega_w} = \frac{846.16 \ {}^{lb}/_{ft^3}}{62.4 \ {}^{lb}/_{ft^3}} = 13.6$$

(4) Viscosity is a property that measures the ability of water to resist shear deformation. The definition of viscosity can be understood by referring to an experiment that was first conducted by Newton, in which a moving wall is driven at a constant velocity (V) through a quiescent water tank. A schematic top view is shown below in figure 1-2:

Figure 1-2: Schematic of Newton's Viscosity Experiment



(i) Measurements indicate that the local velocity varies linearly from zero at the fixed wall to V at the moving wall. Let F represent the force required to pull the moving wall, and A be the area of the wall in contact with the fluid. The shear stress on the moving wall is defined as:

$$\tau = \frac{F}{A} \qquad \textit{(eq. 1-7)}$$

(ii) Newton discovered that the shear stress is related to the velocity (V) and to the length (H) in the tank through the following relationship:

$$\tau = \mu \frac{V}{H} \qquad \textit{(eq. 1-8)}$$

(iii) In this equation, the quantity (μ) is referred to as the absolute or dynamic viscosity of water. The kinematic viscosity is defined by:

$$\vartheta = \frac{\mu}{\rho} \qquad \textit{(eq. 1-9)}$$

(iv) The units of absolute or dynamic viscosity are N s / m^2 = kg / (m•s) in the SI and (lb) s / ft^2 in the ES. And kinematic viscosity units are m^2 / s in the SI and ft^2 / s in the ES. Notice that the units of kinematic viscosity are those of area per unit time. The dimensions of kinematic viscosity are $[\upsilon] = L^2 \bullet T^{-1}$, i.e., they involve only kinematic quantities (area, which is length squared, and time), hence the name kinematic viscosity.

(v) For example, at a temperature of 70º F, the kinematic viscosity of water is $\upsilon = 1.059 \times 10^{-5}$ ft^2 / s, and its specific weight is ω = 62.3 lb / ft^3. To determine the absolute or dynamic viscosity of water at that temperature, we use the formulas ρ = ω / g and μ = ρ υ = (ω / g) υ = (ω υ) / g, where g = 32.2 ft / s^2:

$$\mu = \frac{\omega\vartheta}{g} = \frac{\left(62.3 \frac{lb}{ft^3}\right)\left(1.059 \times 10^{-5} \frac{ft^2}{s}\right)}{32.2 \frac{ft}{s^2}} = 2.05 \times 10^{-5} \frac{lb \cdot s}{ft^2}$$

(vi) In the technical literature, there are references to two old units of viscosity, the poise (P), a unit of dynamic viscosity, and the Stokes (St), a unit of kinematic viscosity. The conversion factors for these units into ES units are:

$$1 \cdot P = 2.0885 \times 10^{-3}\ lb \cdot s/ft^2$$

$$1 \cdot St = 1.076 \times 10^{-3}\ ft^2/s$$

(vii) In pipe flow, viscosity is used to define a quantity known as the Reynolds number:

$$R_e = \frac{\rho VD}{\mu} = \frac{VD}{\nu} \qquad \text{(eq. 1-10)}$$

- For example, to determine the Reynolds number in pipe flow in which water at 80º F is flowing at a velocity V = 0.3 ft / s through a pipeline of 6-inch diameter (D = 6 in = (6 in) / (12 in / ft) = 0.5 ft), the value of the kinematic viscosity from Exhibit D in Section 634.0107 is $\upsilon = 9.30 \times 10^{-6}$ ft^2 / s. The Reynolds number is calculated as:

$$R_e = \frac{VD}{\nu} = \frac{\left(0.3 \frac{ft}{s}\right)(0.5\, ft)}{\left(9.30 \times 10^{-6} \frac{ft^2}{s}\right)} = 16{,}129.03$$

- The Reynolds number is a dimensionless number, i.e., a number without units or dimensions.

(5) Vapor pressure and cavitation.

(i) Vapor pressure is the ambient (air) pressure at which water boils. For example, at sea level, where the atmospheric pressure is 14.697 psi (pounds per square inch), water boils at 212º F. However, at an elevation of 5,000 ft (1,524 m), where the atmospheric pressure is 12.23 psi, water boils at a temperature of approximately 203º F. Thus, at 212º F, the vapor pressure of water is 14.697 psi, whereas at 203º F, the vapor pressure of water is 12.23 psi. Exhibit E in Section 634.0107 provides a table of vapor pressures for water at different temperatures and a table of the atmospheric pressure variation with elevation.

(ii) In some pipe flows or within valves and other appurtenances, the local pressure may fall below that of the vapor pressure of water at a given temperature. In such locations, it is possible to develop small vapor cavities that, when swept by the flow towards locations of higher pressure, may collapse onto themselves generating such force in the process that it may chip away at the pipe or valve walls. This condition is known as cavitation (see 210-NEH-634, Chapter 4, Section 634.0411); it should be avoided to prevent damage to pipes or appurtenances. Figure 1-3 shows cavitation damage on the propeller of a Francis turbine.

Figure 1-3: Cavitation Damage on the Propeller of a Francis Turbine

(6) Modulus of elasticity and water hammer.

(i) Bulk modulus of elasticity is a measure of resistance of water to volume change under the effect of pressure. Water and liquids, in general, are referred to as incompressible fluids because they experience very small volume changes when subject to very large pressure changes. Gases, on the other hand, have large volume changes when pressure changes, and are, therefore, referred to as compressible fluids. For any material, the bulk modulus of elasticity is defined as:

$$E = -\frac{\Delta p}{\Delta V/V} \qquad \text{(eq. 1-11)}$$

where Δp is the change in pressure applied to the material with initial volume (V), and ΔV is the resulting change in volume. The negative sign in the equation signifies that an increase in pressure (positive Δp) will produce a decrease in volume (negative ΔV). Thus, the bulk modulus of elasticity can be defined as the change in pressure per unit change in volume of a fluid.

(ii) For example, at a temperature of 60º F, the modulus of elasticity of water is E = 311,000 psi = 44,784,000 psf. If we wanted to reduce the volume of a water mass by ΔV = -0.1 ft^3, and given that the original volume is V = 1 ft^3, the equation above indicates that the required pressure increase is extremely large, namely:

$$\Delta p = -E \ \frac{\Delta V}{V} = -311{,}000\,psi\left(\frac{-0.1ft^3}{1ft^3}\right) = 31{,}100\,psi$$

(iii) This calculation illustrates that water (and liquids, in general) are, for most practical purposes, incompressible. The incompressibility of water is a factor in producing a phenomenon known as water hammer (see 210-NEH-634, Chapter 4, Section 634.0410).

634.0105 References

The following references are applicable to all chapters in 210-NEH-634.

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634.0106 Acknowledgements

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634.0107 Exhibits

A. Dimensions and Units of Measurement

(1) The table in figure 1-4 shows the dimensions of a variety of physical quantities in terms of the basic units *mass, length, time* (M, L, T) or *force, length, time* (F, L, T). The table also shows the preferred units for those quantities in both the SI and ES of units. Additional units commonly used for the quantities listed are shown in the last column of the table.

(2) Figure 1-5 lists abbreviations for commonly used units.

Figure 1-4: Dimensions and Units of Measurement

Quantity	Dimensions		Preferred Units		Other Units
	(M, L, T)	(F, L, T)	SI	ES	
Length (L)	L	L	m	ft	in, mi
Time (T)	T	T	s	s	h, d, min
Mass (M)	M	$F\ T^2 / L$	kg	slug	---
Area (A)	L^2	L^2	m^2	ft^2	ac
Volume (Vol)	L^3	L^3	m^3	ft^3	ac-ft
Velocity (V)	L / T	L / T	m / s	ft / s or fps	---
Acceleration (a)	L / T^2	L / T^2	m / s^2	ft / s^2	---
Discharge (q)	L^3 / T	L^3 / T	m^3 / s	ft^3 / s or cfs	---
Kinematic viscosity (ν)	L^2 / T	L^2 / T	m^2 / s	ft^2 / s	St
Force (F)	$M\ L / T^2$	F	N	lb	---
Pressure (p)	$M / L\ T^2$	$F\ L^2$	Pa	lb / ft^2	psi, atm
Shear Stress (τ)	$M / L\ T^2$	$F\ L^2$	Pa	lb / ft^2	psi
Density (ρ)	$M\ L^3$	$F\ T^2$ / L4	kg / m^3	$slug / ft^3$	---
Specific weight (ω)	$M / L^2\ T^2$	F / L^3	N / m^3	lb / ft^3	---
Energy / Work / Heat (E)	$M\ L^2 / T^2$	F L	J	lb / ft	---
Power (P)	$M\ L^2 / T^3$	F L / T	W	lb ft / s	hp
Dynamic Viscosity (μ)	M / L T	$F\ T / L^2$	$N\ s / m^2$	$lb\ s / ft^2$	P

Figure 1-5: Abbreviations for Commonly Used Units

Abbreviation	Units	Abbreviation	Units
ac	acre (unit of area)	kW	kilowatt (1,000 Watts, power)
ac-ft	acre × feet		
atm	Atmosphere (unit of pressure)	kWh	kilowatt hour (work, energy, or heat)
bar	bar (unit of pressure)	l	liter (unit of volume)
Btu	British thermal unit (unit of work, energy, or heat)	lb	pound (unit of force)
cal	calorie (work, energy, or heat)	m	meter
cfs	cubic feet per second		
cm	centimeter (1/100 of a meter)	mH_2O	meters or water (pressure)
cP	centipoise (1/100 of a poise)	mi	mile
cSt	centistoke (1/100 of a stoke)	min	minute
d	day	ml	milliliter (1/1,000 of a liter)
dyn	dyne = $g \cdot cm/s^2$ (unit of force)	mm	millimeter (1/1,000 of a meter)
fps	feet per second		
ft	foot or feet	mmHg	millimeters of mercury (pressure)
ftH_2O	feet of water (unit of pressure)	mph	miles per hour
g	gram (unit of mass)	N	Newton (unit of force)
gal	gallon (unit of volume)	°	degree for angular measurement
h	hour	°C	Centigrade degree (temperature)
ha	hectare (an SI unit of area)	°F	Fahrenheit degree (temperature)
hp	horsepower (unit of power)	°R	Rankine degree (absolute temperature)
in	inch	oz	ounce (1/16 pound, force)
inH_2O	inches of water (pressure)	P	Poise (dynamic viscosity)
inHg	inches of mercury (pressure)	Pa	Pascal (unit of pressure)
J	Joule (work, energy, or heat)	psf	pounds per square foot (lb/ft^2, pressure)
K	Kelvin (absolute temperature)	psi	pounds per square inch (lb/in^2 or psi, pressure)
kcal	kilocalorie (1,000 calories, heat)	r	Radian (dimensionless, angle)
kg	kilogram (1,000 grams, mass)	s	second
kip	kip (1,000 lb, force)	slug	slug unit of mass = $lb \cdot s^2/ft$)
km	kilometer (1,000 meters)	St	Stokes (kinematic viscosity)
kN	kiloNewton (1,000 Newtons)	W	Watt (unit of power)
kPa	kiloPascal (1,000 Pascals)	yd	yard
kph	kilometers per hour	yr	year

B. Conversion Factors for Units of Measurement

Figure 1-6 shows selected conversion factors for many units of measurement in both the ES and SI. Figure 1-6 groups the conversion factors by dimensions.

Figure 1-6: Selected Conversion Factors for Units of Measurement

Dimensions	Basic Conversion Factors	
LENGTH	1 ft = 0.3048 m	1 m = 3.2808 ft
MASS	1 slug = 14.5939 kg	1 kg = 0.0685 slug
FORCE	1 lb = 4.4482 N	1 N = 0.2248 lb
TIME	(same basic units) 1 s = 1 s 1	
ABSOLUTE TEMP	1 °R = 5/9 K	K = 9/5 °R
Dimensions	**Other Conversion Factors**	
LENGTH	1 ft = 0.3048 m 1 ft = 30.48 cm 1 in = 2.54 cm 1 mi = 1.609 km	1 m = 3.2808 ft 1 cm = 0.0328 ft 1 cm = 0.3937 in 1 km = 0.6214 mi
AREA	1 ft^2 = 0.0929 m^2 1 ha = 104 m^2 1 ha = 2.4710 ac 1 in2 = 6.4516 cm^2	1 m^2 = 10.7639 ft^2 1 ac = 43,560 ft^2 1 ac = 0.4047 ha 1 cm^2 = 0.1550 in^2
VOLUME	1 ft^3 = 0.0283 m^3 1 in^3 = 16.3871 cm^3 1 ft^3 = 28.3168 l 1 ft^3 = 7.4805 gal 1 l = 1,000 cm^3 1 ac-ft = 43,560 ft^3	1 m^3 = 35.3147 ft^3 1 cm^3 = 0.0610 in^3 1 l = 0.0353 ft^3 1 gal = 0.1337 ft^3 1 l = 0.001 m^3 1 ft^3 = 2.2957×10^{-5} ac-ft
VELOCITY	1 ft/s = 0.3048 m/s 1 mph = 0.4470 m/s 1 mph = 1.6093 kph	1 m/s = 3.2808 ft/s 1 m/s = 2.2369 mph 1 kph = 0.6214 mph
ACCELERATION	acceleration of gravity, g = 32.174 ft/s^2 = 9.8067 m/s^2 1 ft/s^2 = 0.3048 m/s^2 1 m/s^2 = 3.2808 ft/s^2	
DISCHARGE	1 ft^3/s = 0.0283 m^3/s 1 ft^3/s = 7.4805 gal/s 1 ft^3/s = 448.8312 gal/min 1 ft^3/s = 28.3168 l/s 1 l/s = 15.8503 gal/min	1 m^3/s = 35.3147 ft^3/s 1 m^3/s = 264.1720 gal/s 1 m^3/s = 15850.3231 gal/m 1 m^3/s = 1,000 l/s 1 l/s = 0.001 m^3/s

Figure 1-6: Selected Conversion Factors for Units of Measurement (continued)

Dimension	Other Conversion Factors (continued)	
MASS	1 slug = 14.5939 kg 1 slug = 14593.9029 g 1 g = 0.0000685 slug	1 kg = 0.0685 slug 1 kg = 1,000 g 1 g = 0.001 kg
FORCE	1 lb = 4.4482 N 1 lb = 16 oz 1 lb = 0.001 kip 1 kip = 1,000 lb	1 N = 0.2248 lb 1 N = 10^5 dyn 1 N = 0.0002 kips 1 dyn = 2.2480×10^{-6} lb
ENERGY WORK HEAT TORQUE	1 ft-lb = 1.3558 J 1 ft-lb = 0.0013 Btu 1 ft-lb = 0.3238 cal 1 Btu = 778.1693 ft-lb 1 Btu = 251.9958 cal 1 Btu = 1055.0559 J	1 J = 0.7376 ft-lb 1 J = 0.0009 Btu 1 kW-h = 3600000 J 1 kW-h = 3412.1416 Btu 1 J = 10^7 ergs 1 J = 0.2388 cal
POWER	1 ft-lb/s = 1.3558 W 1 hp = 550 ft-lb/s 1 hp = 745.6999 W	1 W = 0.7376 ft-lb/s 1 kW = 737.5621 ft-lb/s
PRESSURE SHEAR STRESS	1 atm = 2116.2166 psf 1 psf = 0.0069 psi 1 psf = 47.8803 Pa 1 mmHg = 0.0193 psi 1 inHg = 0.4912 psi	1 bar = 10^5 Pa = 14.5038 psi 1 kPa = 10^3 Pa = 0.1450 psi 1 ft$H_2$0 = 0.4331 psi 1 in$H_2$0 = 0.0361 psi 1 m$H_2$0 = 0.9102 kPa
DENSITY	1 slug/ft^3 = 515.3788 kg/m^3 1 slug/ft^3 = 0.5154 g/cm^3 1 kg/m^3 = 0.001 g/cm^3	1 kg/m^3 = 0.0019 slug/ft^3 1 g/cm^3 = 1.9403 slug/ft^3 1 g/cm^3 = 1,000 kg/m^3
SPECIFIC WEIGHT	1 lb/ft^3 = 157.0875 N/m^3 1 kip/ft^3 = 157087.4638 N/m^3 1 lb/ft^3 = 15.7087 dyn/cm^3	1 N/m^3 = 0.0064 lb/ft^3 1 N/m^3 = 0.1 dyn/cm^3 1 N/m^3 = 6.3658×10^{-6} kip/ft^3
KINEMATIC VISCOSITY	1 ft^2/s = 0.0929 m^2/s 1 ft^2/s = 929.0304 St 1 St = 0.0001m^2/s	1 m^2/s = 10.7639 ft^2/s 1 St = 0.001 ft^2/s 1 m^2/s = 10000 St
DYNAMIC VISCOSITY	1 lb-s/ft^2 = 47.8803 N-s/m^2 1 lb-s/ft^2 = 478.8026 P 1 P = 0.1 N-s/m^2	1 N-s/m^2 = 0.0209 lb-s/ft^2 1 P = 0.0021 lb-s/ft^2 1 N-s/m^2 = 10 P
TEMPERATURE	1 °R = 5/9 K °R = °F + 459.67 °F = 9/5 °C + 32	1 K = 9/5 °R K = °C + 273.15 °C = 5/9 (°F - 32)

C. The Greek Alphabet

(1) Figure 1-7 shows the letters of the Greek alphabet in their lower- and upper-case forms, their name, and the closest English equivalent.

Figure 1- 7: The Greek Alphabet

Lower Case	Upper Case	Letter Name	English Equivalent
α	Α	Alpha	a
β	Β	Beta	b
γ	Γ	Gamma	g
δ	Δ	Delta	d
ε	Ε	Epsilon	e
ζ	Ζ	Zeta	z
η	Η	Eta	h
θ	Θ	Theta	th
ι	Ι	Iota	i
κ	Κ	Kappa	k
λ	Λ	Lambda	l
μ	Μ	Mu	m
ν	Ν	Nu	n
ξ	Ξ	Xi	x
ο	Ο	Omicron	o
π	Π	Pi	p
ρ	Ρ	Rho	r
σ	Σ	Sigma	s
τ	Τ	Tau	t
υ	Υ	Upsilon	u
φ	Φ	Phi	ph
χ	Χ	Chi	ch
ψ	Ψ	Psi	ps
ω	Ω	Omega	o

(2) Many of the letters of the Greek alphabet are used as symbols for variables used in hydraulics equations. Some common examples are:
(i) ρ (rho) Density
(ii) ω (omega) Specific weight (some references use γ (gamma) for specific weight)
(iii) μ (mu) Dynamic viscosity
(iv) τ (tau) Shear stress
(v) ε (epsilon) Absolute roughness in pipes
(vi) π (pi) Ratio of circumference of circle to its diameter, constant value, $\pi = 3.1416$

(3) In reference to angular measurements, the letters α (alpha), β (beta), γ (gamma), and θ (theta) are commonly used.
(4) The letter Δ (upper case delta) is typically used to indicate an increment of a quantity, thus, Δh may represent, for example, an increment on a depth (h).
(5) The letter ε (epsilon) is typically used to indicate a very small quantity in solution of equations.

D. Physical Properties of Water

(1) The following tables (Figure 1-8 and Figure 1-9) show values of the following physical properties of water at different temperatures:
(i) Density
(ii) Specific weight
(iii) Kinematic viscosity
(iv) Dynamic viscosity
(v) Vapor pressure
(vi) Bulk modulus of elasticity
(2) Figure 1-8 shows the properties of water in ES units, while Figure 1-9 shows the same properties in SI units.

Figure 1-8: Physical Properties of Water in ES Units

Temp. ^{o}F	**Density, ρ slug/ft^3**	**Specific weight, ω lb/ft^3**	**Kinematic viscosity, ν ft^2/s**	**Dynamic viscosity, μ lb-s/ft^2**	**Vapor pressure, p_v psi-abs**	**Bulk Modulus of Elasticity, E psi**
32	1.940	62.42	1.931×10^{-5}	3.746×10^{-5}	0.09	2.93×10^{5}
40	1.940	62.43	1.664×10^{-5}	3.229×10^{-5}	0.12	2.94×10^{5}
50	1.940	62.41	1.410×10^{-5}	2.735×10^{-5}	0.18	3.05×10^{5}
60	1.938	62.37	1.217×10^{-5}	2.359×10^{-5}	0.26	3.11×10^{5}
70	1.936	62.30	1.059×10^{-5}	2.050×10^{-5}	0.36	3.20×10^{5}
80	1.934	62.22	9.300×10^{-6}	1.799×10^{-5}	0.51	3.22×10^{5}
90	1.931	62.11	8.260×10^{-6}	1.595×10^{-5}	0.70	3.23×10^{5}
100	1.927	62.00	7.390×10^{-6}	1.424×10^{-5}	0.95	3.27×10^{5}
110	1.923	61.86	6.670×10^{-6}	1.284×10^{-5}	1.27	3.31×10^{5}
120	1.918	61.71	6.090×10^{-6}	1.168×10^{-5}	1.69	3.33×10^{5}
130	1.913	61.55	5.580×10^{-6}	1.069×10^{-5}	2.22	3.34×10^{5}
140	1.908	61.38	5.140×10^{-6}	9.810×10^{-6}	2.89	3.30×10^{5}
150	1.902	61.20	4.760×10^{-6}	9.050×10^{-6}	3.72	3.28×10^{5}
160	1.896	61.00	4.420×10^{-6}	8.380×10^{-6}	4.74	3.26×10^{5}
170	1.890	60.80	4.130×10^{-6}	7.800×10^{-6}	5.99	3.22×10^{5}
180	1.883	60.58	3.850×10^{-6}	7.260×10^{-6}	7.51	3.18×10^{5}
190	1.876	60.36	3.620×10^{-6}	6.780×10^{-6}	9.34	3.13×10^{5}
200	1.868	60.12	3.410×10^{-6}	6.370×10^{-6}	11.52	3.08×10^{5}
212	1.860	59.83	3.190×10^{-6}	5.930×10^{-6}	14.70	3.00×10^{5}

Figure 1-9: Physical Properties of Water in SI Units

Temp. ^{o}C	Density, ρ kg/m^3	Specific weight, ω kN/m^3	Kinematic viscosity, ν m^2/s	Dynamic viscosity, μ N·s/m^2	Vapor pressure, p_v kPa-abs	Bulk Modulus of Elasticity, E kPa
0	999.8	9.805	1.785×10^{-6}	1.781×10^{-3}	0.61	2.02×10^{6}
5	1000.0	9.807	1.519×10^{-6}	1.518×10^{-3}	0.87	2.06×10^{6}
10	999.7	9.804	1.306×10^{-6}	1.307×10^{-3}	1.23	2.10×10^{6}
15	999.1	9.798	1.139×10^{-6}	1.139×10^{-3}	1.70	2.15×10^{6}
20	998.1	9.789	1.000×10^{-6}	1.002×10^{-3}	2.34	2.18×10^{6}
25	997.0	9.777	8.930×10^{-7}	8.900×10^{-4}	3.17	2.22×10^{6}
30	995.7	9.764	8.000×10^{-7}	7.980×10^{-4}	4.24	2.25×10^{6}
35	994.0	9.747	7.290×10^{-7}	7.300×10^{-4}	5.81	2.27×10^{6}
40	992.2	9.730	6.580×10^{-7}	6.530×10^{-4}	7.38	2.28×10^{6}
45	990.1	9.710	6.055×10^{-7}	6.000×10^{-4}	9.86	2.29×10^{6}
50	988.0	9.689	5.530×10^{-7}	5.530×10^{-4}	12.33	2.29×10^{6}
55	985.6	9.666	5.135×10^{-7}	5.135×10^{-4}	16.13	2.29×10^{6}
60	983.2	9.642	4.740×10^{-7}	4.740×10^{-4}	19.92	2.28×10^{6}
65	980.5	9.620	4.435×10^{-7}	4.435×10^{-4}	25.54	2.27×10^{6}
70	977.8	9.589	4.130×10^{-7}	4.130×10^{-4}	31.16	2.25×10^{6}
75	974.8	9.560	3.885×10^{-7}	3.885×10^{-4}	39.25	2.23×10^{6}
80	971.8	9.530	3.640×10^{-7}	3.640×10^{-4}	47.34	2.20×10^{6}
85	968.6	9.498	3.395×10^{-7}	3.395×10^{-4}	58.75	2.17×10^{6}
90	965.3	9.466	3.150×10^{-7}	3.150×10^{-4}	70.10	2.14×10^{6}
95	961.9	9.433	3.045×10^{-7}	2.990×10^{-4}	85.72	2.1110^{6}
100	958.4	9.399	2.940×10^{-7}	2.820×10^{-4}	101.33	2.0710^{6}

E. Variation of Atmospheric Pressure with Elevation

(1) Figure 1-10 shows the variation of atmospheric pressure with elevation.

Figure 1-10: Variation of Atmospheric Pressure with Elevation

English System		International System	
Elevation above sea level (ft)	**Atmospheric pressure p_{atm} (psia)**	**Elevation above sea level (m)**	**Atmospheric pressure p_{atm} (kPa)**
0	14.69	0	101.32
1,000	14.18	300	97.78
2,000	13.67	600	94.34
3,000	13.18	900	90.98
4,000	12.70	1,200	87.73
5,000	12.23	1,500	84.56
6,000	11.78	1,800	81.49
7,000	11.34	2,100	78.51
8,000	10.92	2,400	75.62
9,000	10.50	2,700	72.83
10,000	10.10	3,000	70.12

Based on the International Civil Aviation Organization (ICAO) Standard Atmosphere

(2) The tables are based on the following data fitting of the *atmospheric pressure*-vs-*elevation* data:

(i) ES units: p_{atm} (psia) = atmospheric pressure, z (ft) = elevation

$$p_{atm} = 14.69 - 0.000525\, z + (6.563 \times 10^{-9}10)z^2$$

(ii) SI units: p_{atm} (kPa) = atmospheric pressure, z (m) = elevation

$$p_{atm} = 101.32 - 0.01195z + (5.172 \times 10^{-7})z^2$$