FLOW OF WATER 5

5.1 INTRODUCTION

Pollutant removal efficiency derives from and is dependent upon the efficient movement of water through a treatment system. As illustrated in Figure 5.1 the efficiency of the flow of water, hydraulic efficiency, is particularly important for treatment systems employing wet pools and vegetated channels. The importance of hydraulic efficiency is recognized in design criteria such as the length-to-width ratio for wet ponds and vaults.[1173,1198] The effect of design configuration on hydraulic efficiency and in turn performance efficiency is the focus of Chapter 5.

FIGURE 5.1
Relationship of hydraulic to performance efficiency

5.2 PROPERTIES OF WATER

Properties relevant to stormwater treatment are density, specific weight, viscosity, specific gravity, diffusion, and advection. The density of water, ρ, is the mass of water per unit volume (lb-s^2/ft^4, Kg-s^2/m^4). The specific weight, g, is the weight per unit volume (lb/ft^3, Kg/m^3). The two are related by $g = \rho g$.

Water density is maximum at 4^{o}C, decreasing above and below this temperature. It decreases with increasing temperature above 4^{o}C but only slightly between 5 to 30^{o}C (about 0.5 percent), the upper value of interest with stormwater. Density increases with increasing solids concentration.

Viscosity of water is a property which defines its resistance to shear forces. It occurs from the interaction between the water molecules and affects the movement of molecules or packets of water relative to each other as well as the settling rate of particles. Viscosity of water decreases by about 50 percent with a rise in temperature from 5 to 30^{o}C. Engineers define two viscosities: kinematic (ft^2/s; m^2/s) and absolute (dynamic) (lb-s/ft^2; N/m^2). The definition of absolute viscosity and its relationship to kinematic viscosity is presented below.

$$\text{Absolute viscosity } (\mu) = \frac{\text{shear force } (\tau)}{dV/dy} \qquad (5.1a)$$

$$\text{Kinematic viscosity } (\nu) = \frac{\text{absolute viscosity } (\mu)}{\text{mass density, } (\rho)} \qquad (5.1b)$$

The specific gravity of a substance is the ratio of its weight to the weight of an equal volume of water. Sand weighs 2.65 times as much as water of an equivalent volume. Therefore, the specific gravity of water is 1 and the specific gravity of sand is 2.65. The specific gravity of organic matter ranges from less than 1 to about 1.5. If two particles are of the same size and shape, the one with a higher specific gravity will settle more rapidly.

Diffusion is the random motion of chemical species in water. Where a concentration gradient exists the random motion causes migration to areas of lesser concentration. Advection is the movement of chemical species via the movement of the water itself.

5.3 FLOW REGIMES

The flow of water is described by several complementary characterizations: steady and unsteady, uniform and non-uniform, laminar and turbulent, and supercritical and subcritical.[25,114,1200] Steady flow is understood by considering a point of interest in a pipe, channel, or water body. If at the point of interest the flow rate, depth, and velocity are constant with time, the flow is considered steady. Uniformity considers flow over a distance in a pipe, channel, or water body. It requires that flow rate, depth and velocity be constant over a distance of interest. If these three attributes are constant over the distance of interest, the flow is uniform.

Laminar flow describes the condition when all water molecules move along parallel lines, visualized as layers (laminae) as shown in Figure 5.2. As the forces associated with viscosity dominate the laminar flow regime, the condition is also called viscous flow. The tendency for water to depart from the layered condition is dampened by the water's viscosity. Because of strict movement of water molecules, any change in the vertical concentrations of substances only occurs by diffusion.

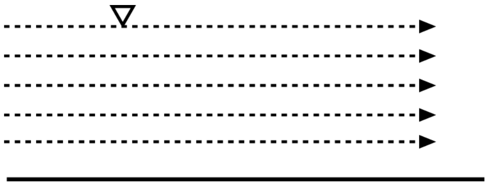

FIGURE 5.2
Laminar flow

At some point determined in part by velocity and depth, the shear forces overcome the molecular forces of viscosity and the flow regime becomes turbulent. In turbulent flow the particles of water move in all directions in a haphazard manner. Inertial forces, defined by the flow velocities, dominate the viscous forces. Movement occurs in the form of eddies, distinct packets of moving water of various sizes as illustrated in Figure 5.3. Eddies vary in size and intensity by feet in streams and rivers, inches at the inlets of stormwater ponds, and fractions of inches in flash mixers that disperse chemicals into water. Although irregular in space and time, the motion of eddies can be described statistically.[510]

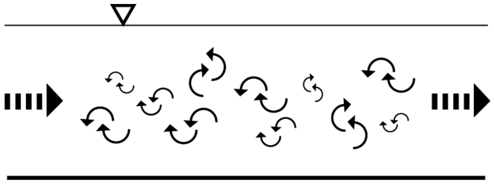

FIGURE 5.3
Turbulent flow

The degree of turbulence is described by the Reynolds Number (R_e).[5] It is a dimensionless parameter defined by Equation 5.2.

$$R_e = \frac{\rho V L_C}{\mu} = \frac{V L_C}{\nu} \qquad (5.2)$$

Where: = density of water
μ = absolute viscosity
V = mean velocity
L_c = characteristic length
ν = kinematic viscosity

For pipes, channels, and basins the characteristic length is defined by the hydraulic radius: the ratio of the cross-sectional area of flow divided by the wetted perimeter of flow.[5] Equation 5.2 shows that R_e is the ratio of the inertial to the viscous forces. Hence, the greater the value of R_e, the more turbulent the condition. Figure 5.4 illustrates the relationships between R_e, the flow regime, and friction in pipes.[5] As resistance to flow increases the R_e decreases; there is greater resistance in laminar flows.

Laminar conditions exist at R_e values below several hundred. Turbulent conditions begin to become significant at a R_e of about 3,000. Values of R_e between 3,000 and 10,000 are called smooth or transitional turbulence conditions.[204] Above 10,000 the condition is rough or fully turbulent. However, with shallow flows in vegetated channels and wetlands, full turbulence does not occur until the R_e exceeds about 10,000.[582, 1122]

Hence, laminar conditions likely exist in vegetated swales and wetlands when the water flow is shallow and slow. Flows become transitional when flow depth is significant relative to the height of the grass. R_e in wastewater treatment lagoons are laminar to transitional.[371,700,1039] A similar condition likely exists in stormwater wet ponds.

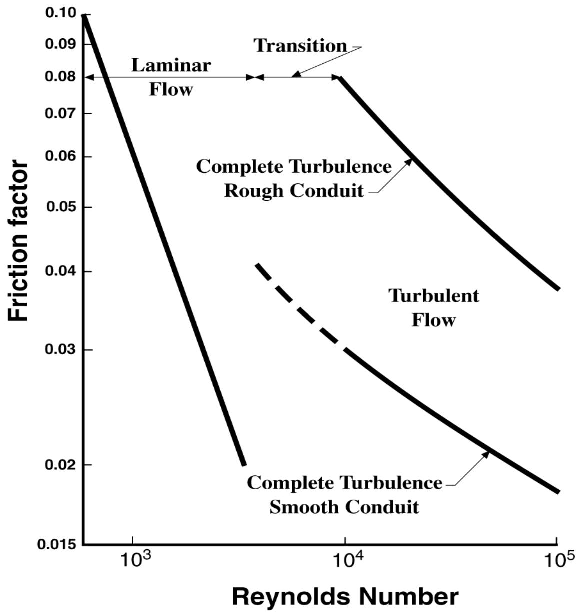

FIGURE 5.4
Reynolds Number and the hydraulic condition

Flow in pipes and open channels is described as subcritical or supercritical. Subcritical flow is characterized by low velocities and high depths. It occurs where the slope of the conduit is generally less than 15 percent with relatively smooth surfaces. Supercritical flow is characterized by high velocity and shallow depth, occurring where the slope of the conduit is greater than 15 percent. The point of delineation between subcritical and supercritical flow occurs at the critical depth (D_c).

The relationship between the two conditions is related to the specific energy (H_c) as shown in Figure 5.5. H_c is minimum at the critical depth. Elsewhere, H_c is the same at two different water depths, one in the subcritical flow regime and the second in the supercritical regime. H_c includes the depth of flow and energy due to the flow of water, expressed as $V^2/2g$. The flow rate, Q, is constant for each particular relationship. Whether a flow is sub- or supercritical is also related to a hydraulic term known as the Froude Number, F. If F is greater than 1, the flow is supercritical. If less than one, the flow is subcritical. Equation 5.3 shows that F increases with increasing water velocity, V, and/or decreasing water depth, D.

$$F = \frac{V}{(gD)^{0.5}} \qquad (5.3)$$